Searches for rare single top quark associated production processes at the LHC

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on behalf of the ATLAS and CMS collaborations

Top 2022 Conference

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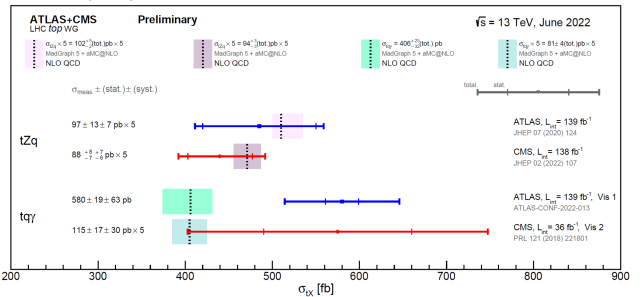
Single top + V processes

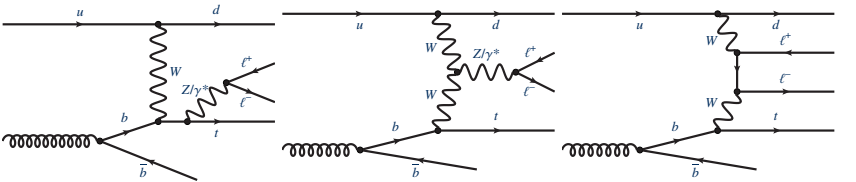
- Properties that make the top-quark interesting:
  - Highest mass of SM particle (173 GeV)
  - Decays before hadronization ($\tau \sim 10^{-25}$s), can study the bare quark.
  - Yukawa coupling close to 1
- Studying tVq production probes the fundamental properties of the top quark
- Z/γ coupling sensitive to EW parameters (hypercharge and weak isospin)



tZq

Searches for *tZq*

- *tZq* is a rare process predicted by the SM
- t-channel production with an associated *Z* boson
- probes both *ttZ* and *WWZ* couplings
- Also contributions from $t\ell^{\pm}\ell^{\mp}q$
- *tZq* has been observed by both ATLAS (JHEP 07(2020) 124) and CMS (Phys. Rev. Lett. 122 (2019) 132003).
- Precision measurement by CMS JHEP 02 (2022) 107



tZq - ATLAS

tZq - Signal regions

2 SRs defined by:

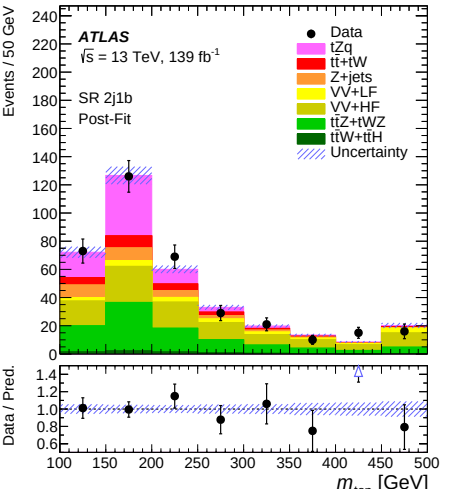
- 3 leptons (e or μ)
- 1 b-tagged jet @ 70% WP
- 1 (2j1b SR) or 2 (3j1b SR) untagged jets

Major backgrounds are primarily from processes with prompt leptons:

- Diboson
- $t\bar{t}Z$

Smaller nonprompt contribution:

- Zjets
- $t\bar{t}$

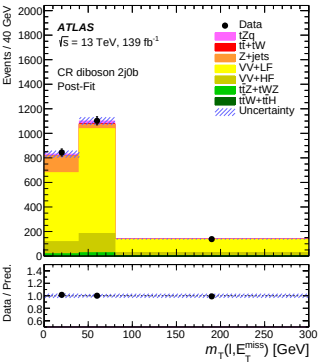


tZq - Background estimation

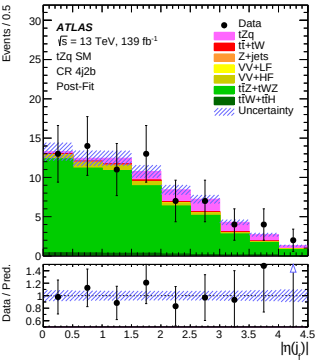
Prompt backgrounds:

- The largest background contributions come from prompt lepton sources: $t\bar{t}Z$ and diboson
- CRs are constructed that are enriched in these backgrounds and included in the likelihood fit to determine their normalization and constrain associated systematic uncertainties

Diboson CR

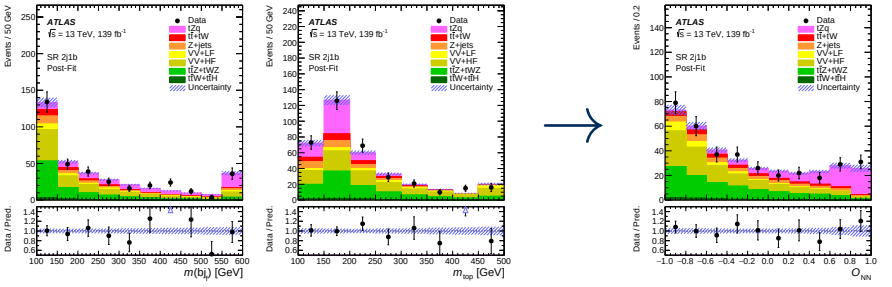


$t\bar{t}Z$ CR



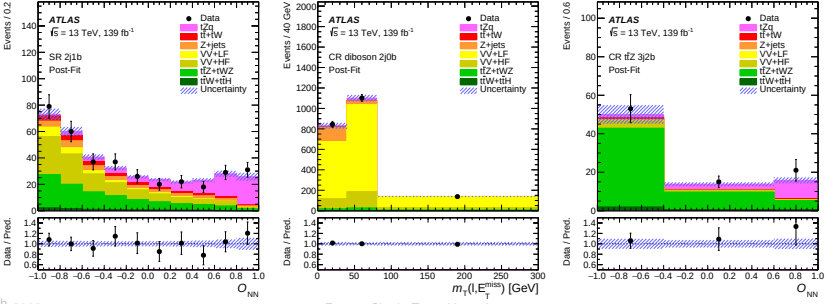
tZq - **MVA**

- A neural network is used to separate signal and background
- Combines several variables to form an optimal variable, *O*(NN)
- Variables are required to be well modeled



tZq - Results

- Binned maximum-likelihood fit using SRs and CRs
- $> 5\sigma$ significance
- Inclusive $\sigma_{tZq}^{\text{fid.}} = 97 \pm 13(\text{stat.}) \pm 7(\text{syst.})\text{fb}$ ($\sim 15\%$)
- Agrees with SM prediction: $\sigma_{tZq}^{\text{SM, fid.}} = 102^{+5}_{-2}\text{fb}$ calculated at NLO in QCD including non-resonant contributions with $m_{\ell\ell} > 30\text{GeV}$
- Statistically limited ($\sim 14\%$)
- Dominant systematic related to prompt backgrounds modeling



tZq - CMS

tZq - Signal regions

Common SR selection

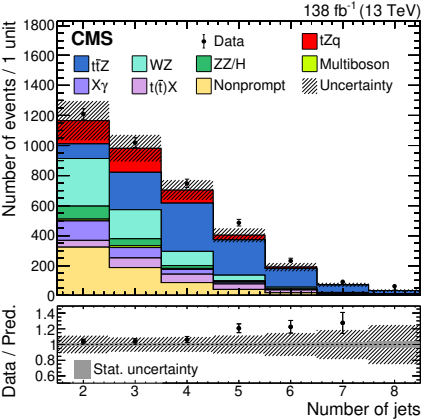
- 3 leptons (e or μ)
- an OSSF lepton pair close to Z boson mass

Split into 3 subregions:

- 1 b-jet, 2-3 jets
- 1 b-jet, $\geq$4 jets
- $\geq$2 b-jets

Major backgrounds:

- $t\bar{t}Z$
- WZ
- nonprompt



tZq - Background estimation

Prompt:

- Include CRs in likelihood fit to constrain normalization

CR	N(leptons)	N($\lvert m_{\ell^\pm \ell^\mp} - m_Z \rvert < 15$GeV)	b-jet veto
ttZ	4	exactly 1	no
ZZ	4	2	no
WZ	3	1	yes
$Z\gamma$	3	0, $m(\ell\ell\ell)$ instead	no

Nonprompt:

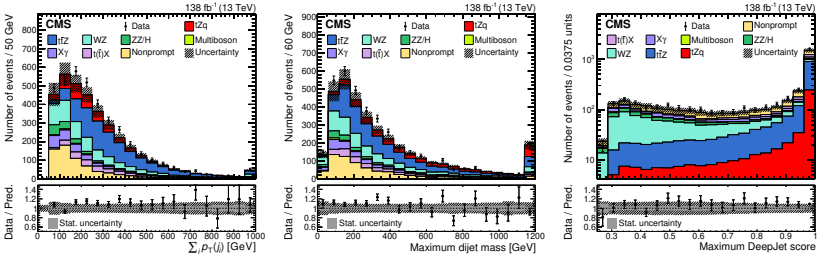
- Calculate transfer fxn as a fxn of p_T and $|\eta|$ in region enriched in nonprompt:

$$\frac{\text{N(Tight | multijet CR)}}{\text{N(Loose | multijet CR)}} \cdot \text{N(Loose | close to SR)}$$

- Include nonprompt CR (fail OSSF mass requirement) in likelihood fit

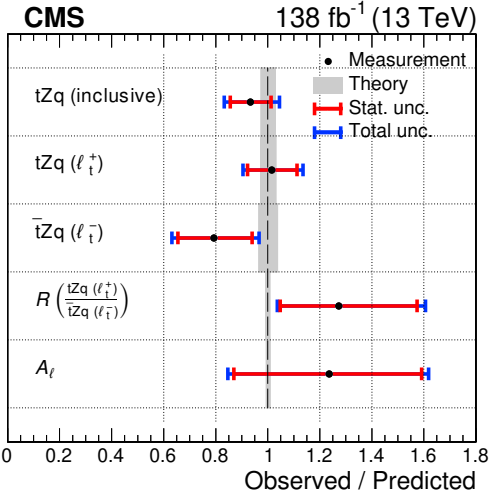
tZq - **MVA**

- A BDT is used to separate signal and background
- Combines several variables to form an optimal variable, *O*(BDT)
- Variables are required to be well modeled



Results

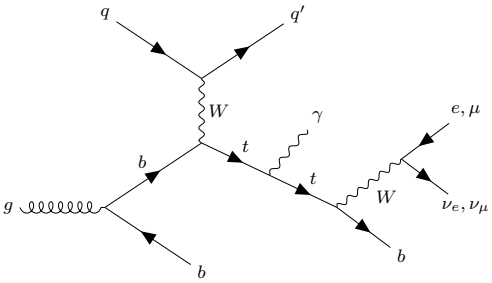
- Reduced uncertainty compared to previous ATLAS measurements: $\sim 15\% \rightarrow \sim 11\%$
- First time $tZq(\ell_t^+)$ and $\bar{t}Zq(\ell_t^-)$ measured separately as well as their ratio.
- First differential measurement of tZq production.
- Differential measurement performed for several variables.
- The differential measurement performed with $cos\theta^*_{pol}$ used to measure spin asymmetry



tqy

Top-quark with an associated photon ($tq\gamma$)

- $tq\gamma$ is a rare process predicted by the SM
- t-channel production with associated photon
- $tq\gamma$ probes
  - top-quark electroweak couplings
  - electric and dipole moments of the top quark
- CMS provided evidence for $tq\gamma$ using 35.9fb^{-1} of data at 13 TeV (Phys. Rev. Lett. 121, 221802 (2018))
- Observed by ATLAS (ATLAS-CONF-2022-013) using the full 139 fb^{-1} run-2 data set



tqy - CMS

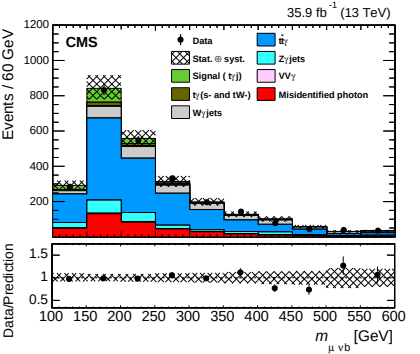
$tq\gamma$ - Signal regions

SR defined by:

- 1 muon
- 1 photon
- $E_T^{\text{miss}} > 30\text{GeV}$
- at least 2 jets
- exactly 1 b-tagged jet @ 70% WP

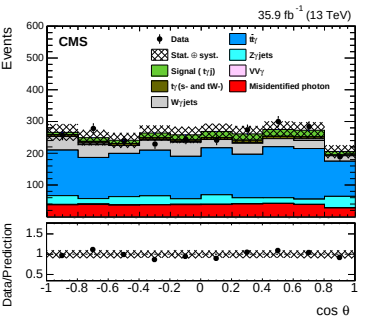
Major backgrounds:

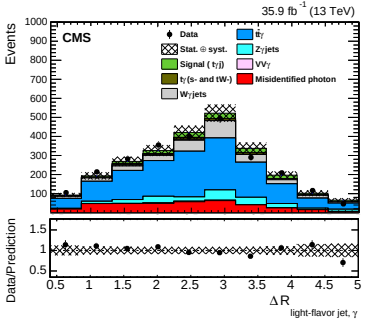
- $t\bar{t}y$, $W\gamma$, $Z\gamma$ (prompt photon)
- $t\bar{t}$, Wjets, Zjets (nonprompt photon)

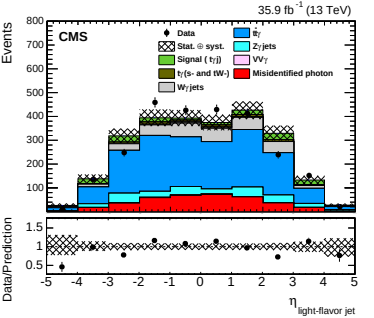


$tq\gamma$ - MVA

- A BDT is used to separate signal and background.
- Combines several variables to form an optimal variable, O(BDT)
- Variables are required to be well modeled

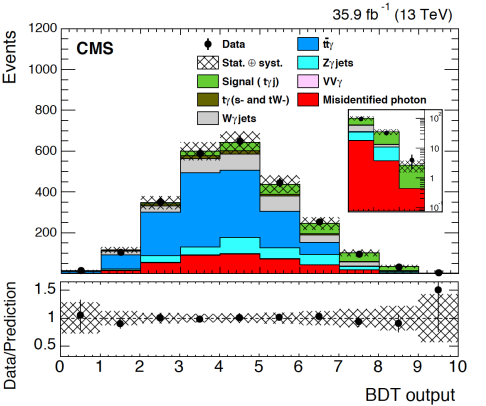






$tq\gamma$ - Fit and results

- Binned maximum-likelihood fit performed by simultaneously fitting the O(BDT) distribution and the $t\bar{t}\gamma$ CR.
- Normalization of $tq\gamma$, $t\bar{t}\gamma$ unconstrained
- Inclusive $\sigma^{\text{fid.}}_{tq\gamma}$ = $115 \pm 17(\text{stat.}) \pm 30(\text{syst.})\text{fb}$
- Agrees with the NLO SM prediction: $\sigma^{\text{SM, fid.}}_{tq\gamma} = 81 \pm 4\text{fb}$.
- Provides evidence for $tq\gamma$ process
- Observed (expected) significance is 4.4σ (3.0σ)



tqy - ATLAS

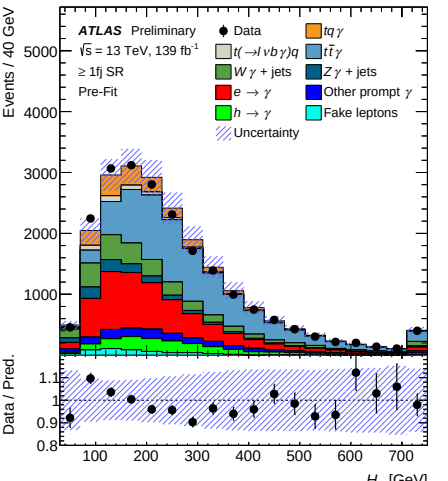
$tq\gamma$ - Signal regions

2 SRs defined by:

- 1 lepton (e or μ)
- 1 photon
- $E_T^{\text{miss}} > 30\text{GeV}$
- $|m(e\gamma) - 90\text{GeV}| > 10\text{GeV}$
- 1 b-tagged jet @ 70% WP
- 0 (0fj SR) or ≥ 1 ($\geq 1fj$ SR) forward jets

Major backgrounds:

- $t\bar{t}y$, $W\gamma$, $Z\gamma$ (prompt photon)
- $t\bar{t}$, Zjets (nonprompt photon)

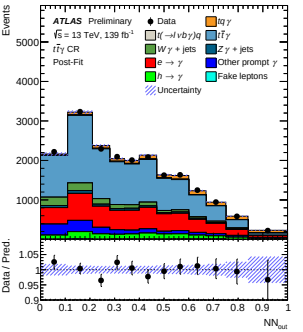


$tq\gamma$ - Prompt background estimation

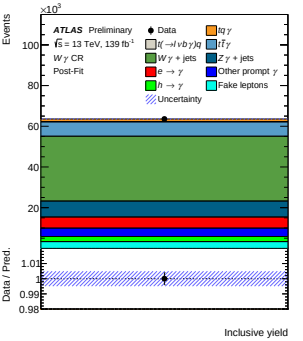
Prompt backgrounds:

- Primarily from: $t\bar{t}y$, $W\gamma$, and $Z\gamma$
- CRs are constructed that are enriched in these backgrounds and included in the likelihood fit to determine their normalization and constrain associated systematic uncertainties

$t\bar{t}\gamma$ CR



$W\gamma$ CR

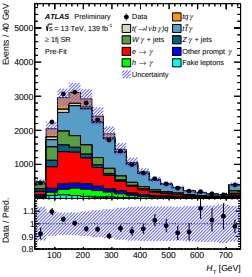


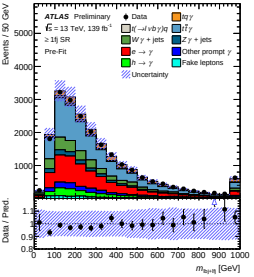
$tq\gamma$ - Nonprompt background estimation

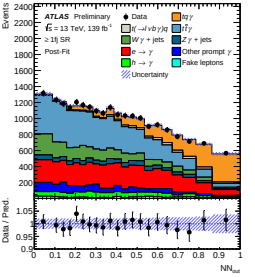
- $e \to \gamma$ fakes:
  - Mainly dilepton $t\bar{t}$ and Z+jets
  - MC correction scale factors are calculated using the tag and probe method: $N(Z \to e(e \to \gamma))/N(Z \to ee)$
  - Use $e^{\pm}e^{\mp}$ and $e\gamma$ events close to the Z mass
  - MC is corrected in bins of photon η and photon reconstruction type
- jet $\to \gamma$ fakes:
  - Mainly due to semilleptonic $t\bar{t}$ decay
  - estimated using ABCD method
  - The four ABCD regions defined using photon identification and isolation criteria
  - MC is corrected in bins of photon η, p_T, and photon reconstruction type
- Fake lepton background is estimated using matrix method

$tq\gamma$ - MVA

- A neural network is used to separate signal and background.
- Combines several variables to form an optimal variable, O(NN)
- Input features (12 for 0fj SR and 15 for $\geq$1fj SR): kinematics of final state particles and their contributions as well as b-tagging properties
- Variables are required to be well modeled

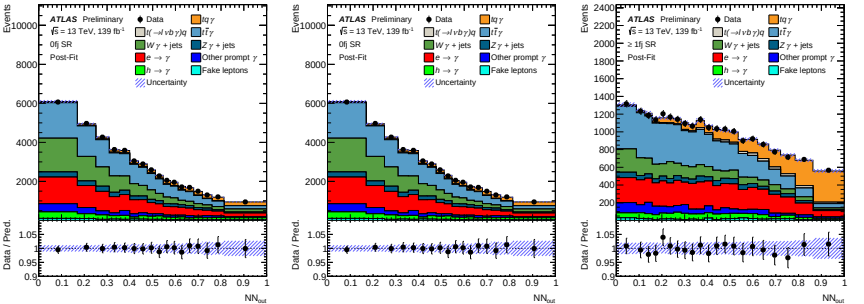






$tq\gamma$ - Results

- Binned maximum-likelihood fit using SRs and CRs
- Provides observation for the $tq\gamma$ process.
- Observed (expected) significance is 9.1σ (6.7σ)



$tq\gamma$ - Cross section at parton/particle level

At parton level:

- photon phase space requirements are:
  - $p_T(\gamma) > 20$GeV
  - $\Delta R(X, \gamma) > 0{,}4$ where X represents the leptons and jets
  - $|\eta(\gamma)| < 2{,}37$
- Measured $\sigma(tq\gamma)\ \mathcal{B}(t \to \ell\nu b) = 580 \pm 19(\text{stat.}) \pm 63(\text{syst.})$fb
- $\sim 40\%$ higher than NLO SM prediction of 406^{+25}_{-32}fb

At particle level

- Phase space definition closer to reco. level selection
- Measured $\sigma(tq\gamma)\ \mathcal{B}(t \to \ell\nu b) + \sigma(t \to \ell\nu b\gamma)q = 287 \pm 8(\text{stat.})^{+32}_{-31}(\text{syst.})$fb
- $\sim 40\%$ higher than NLO SM prediction of 207^{+26}_{-11}fb

Compatible with the SM within 2.5(1.9)σ at parton(particle) level

Summary

- *tZq* process has been observed by both the ATLAS and CMS collaborations
- using full run 2 data set, CMS provided:
  - most precise *tZq* cross section measurement
  - separate $tZq(\ell_t^+)$ and $\bar{t}Zq(\ell_{\bar{t}}^-)$ measurements as well as their ratio
  - first differential *tZq* measurement
  - Spin asymmetry measured using differential measurement
- $tq\gamma$ process has been observed for the first time with the full run-2 data collected by the ATLAS experiment
- Results are compatible with the SM withing $2.5(1.9)\sigma$ at parton(particle) level

Questions?

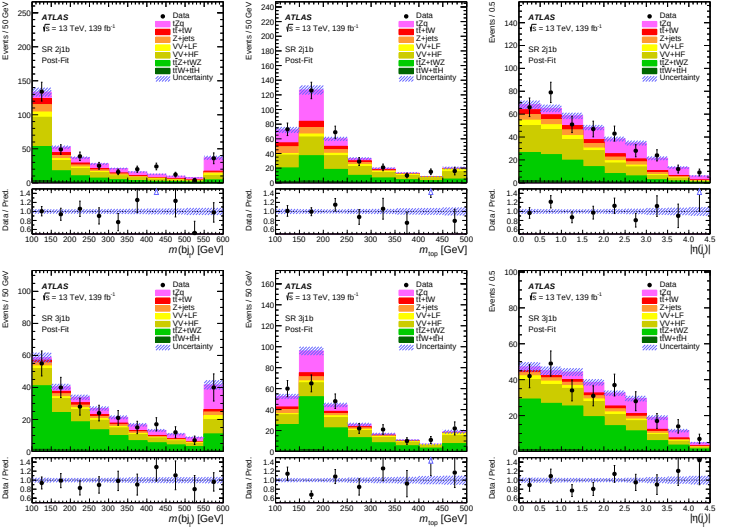
Backup

tZq - ATLAS

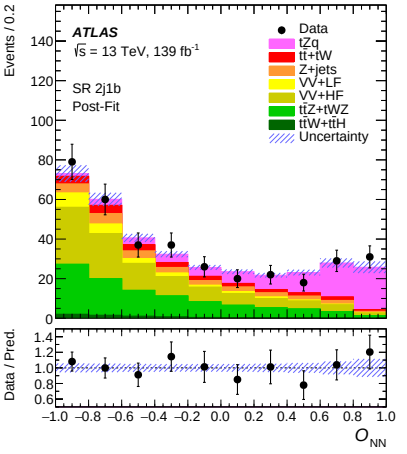
tZq - Region definitions

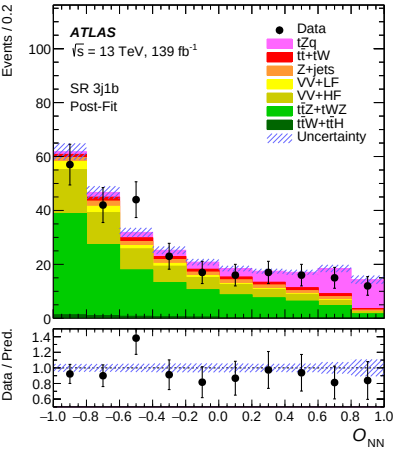
Common selections			
Exactly 3 leptons (e or μ) with $\|\eta\| < 2.5$ $p_{\mathrm{T}}(\ell_1) > 28\,\mathrm{GeV}$, $p_{\mathrm{T}}(\ell_2) > 20\,\mathrm{GeV}$, $p_{\mathrm{T}}(\ell_3) > 20\,\mathrm{GeV}$ $p_{\mathrm{T}}(\mathrm{jet}) > 35\,\mathrm{GeV}$			
SR 2j1b	CR diboson 2j0b	CR $t\bar{t}$ 2j1b	CR $t\bar{t}Z$ 3j2b
≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10\,\mathrm{GeV}$ 2 jets, $\|\eta\| < 4.5$ 1 b-jet, $\|\eta\| < 2.5$	≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10\,\mathrm{GeV}$ 2 jets, $\|\eta\| < 4.5$ 0 b-jets	≥ 1 OSDF pair No OSSF pair 2 jets, $\|\eta\| < 4.5$ 1 b-jet, $\|\eta\| < 2.5$	≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10\,\mathrm{GeV}$ 3 jets, $\|\eta\| < 4.5$ 2 b-jets, $\|\eta\| < 2.5$
SR 3j1b	CR diboson 3j0b	CR $t\bar{t}$ 3j1b	CR $t\bar{t}Z$ 4j2b
≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10\,\mathrm{GeV}$ 3 jets, $\|\eta\| < 4.5$ 1 b-jet, $\|\eta\| < 2.5$	≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10\,\mathrm{GeV}$ 3 jets, $\|\eta\| < 4.5$ 0 b-jets	≥ 1 OSDF pair No OSSF pair 3 jets, $\|\eta\| < 4.5$ 1 b-jet, $\|\eta\| < 2.5$	≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10\,\mathrm{GeV}$ 4 jets, $\|\eta\| < 4.5$ 2 b-jets, $\|\eta\| < 2.5$

tZq - NN training variables

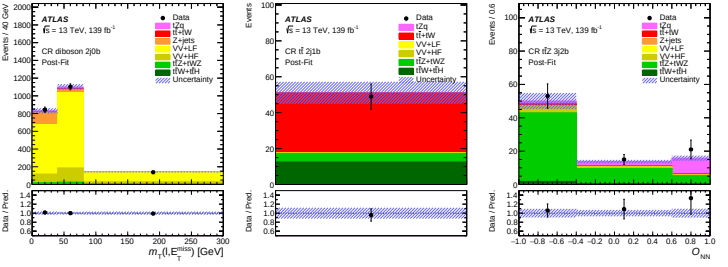


$tZ\gamma$ - Fitted SRs





$tZ\gamma$ - Fitted CRs



tZq - Postfit event yields

	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

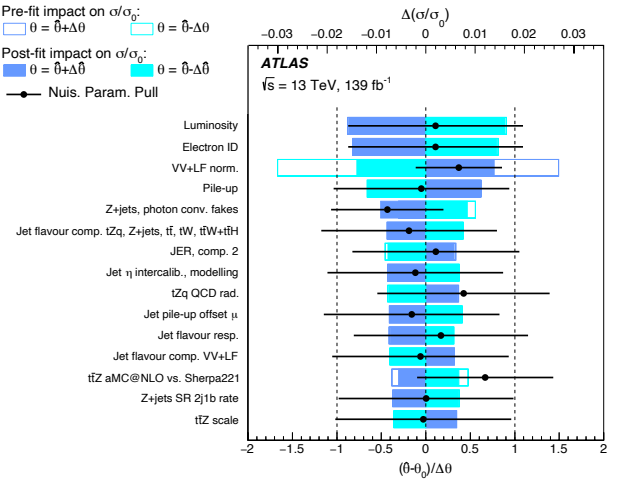
tZq - NN training variables

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 - Uncertainty breakdown

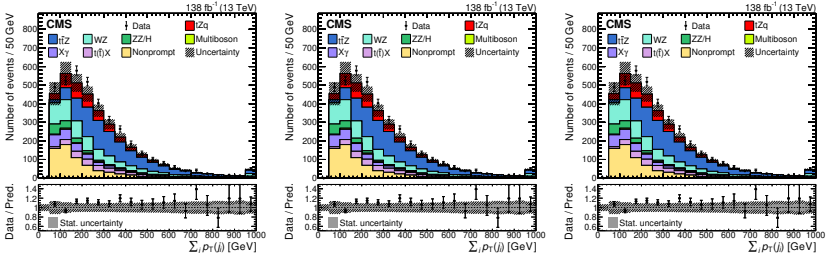
Uncertainty source	$\Delta\sigma/\sigma$ [%]
Prompt-lepton background modelling and normalisation	3.3
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction and calibration	2.0
Lepton reconstruction and calibration	2.0
Luminosity	1.7
Non-prompt-lepton background modelling	1.6
Pile-up modelling	1.2
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 - Systematic ranking

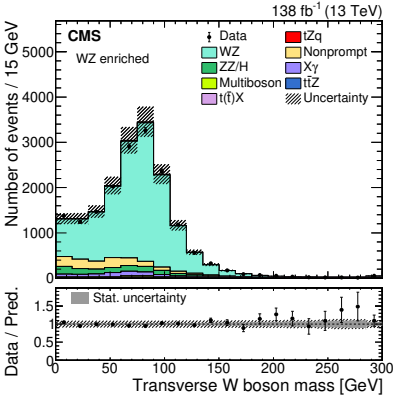


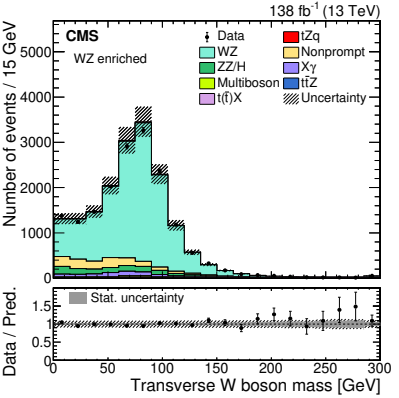
tZq - CMS

tZq - Kinematic variables

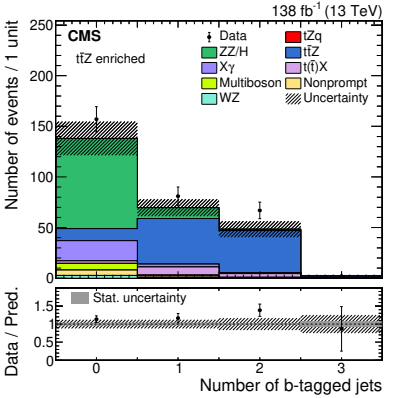


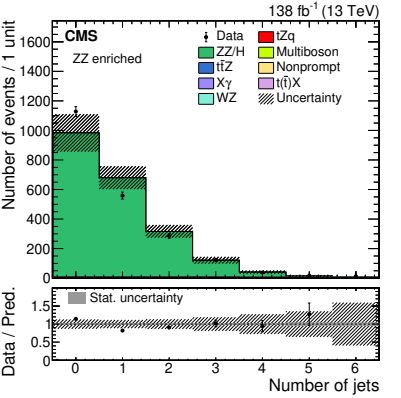
tZq - *WZ* **CR**


138 fb-1 (13 TeV)
CMS
WZ enriched
Data
tZq
WZ
Nonprompt
ZZ/H
Xγ
Multiboson
ttZ
t(t̄)X
Uncertainty
Number of events / 15 GeV
Stat. uncertainty
Data / Pred.
Transverse W boson mass [GeV]

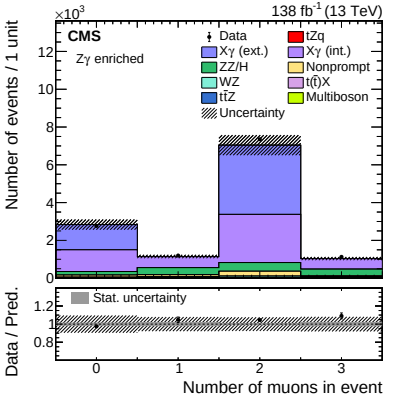

138 fb-1 (13 TeV)
CMS
WZ enriched
Data
tZq
WZ
Nonprompt
ZZ/H
Xγ
Multiboson
ttZ
t(t̄)X
Uncertainty
Number of events / 15 GeV
Stat. uncertainty
Data / Pred.
Transverse W boson mass [GeV]

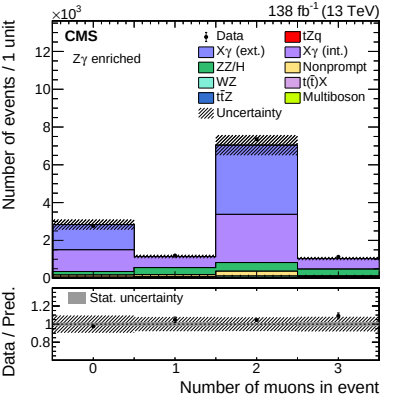
tZq - $t\bar{t}Z$ and ZZ CRs



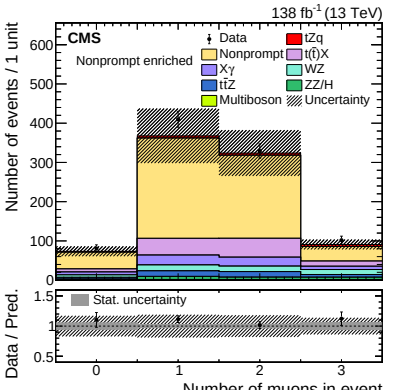


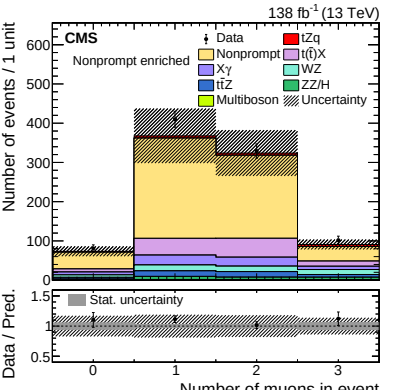
tZq - $Z\gamma$ CR



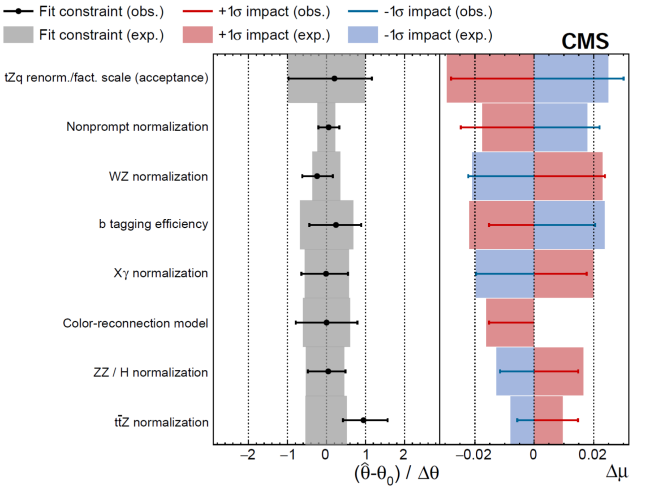


tZq - Nonprompt CR

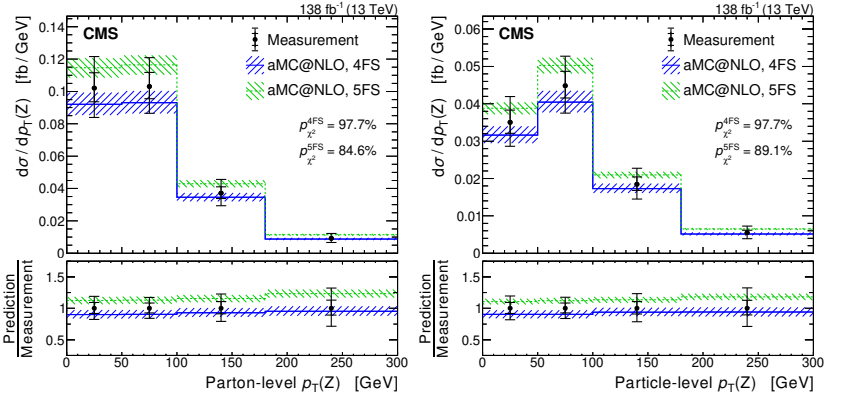




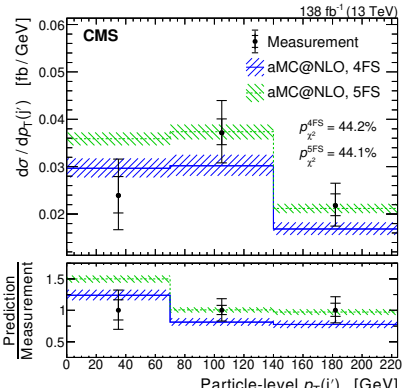
tZq - Systematic ranking

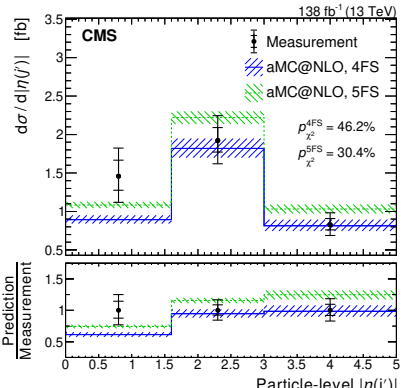


$tq\gamma$ - Differential cross section



$tq\gamma$ - Differential cross section



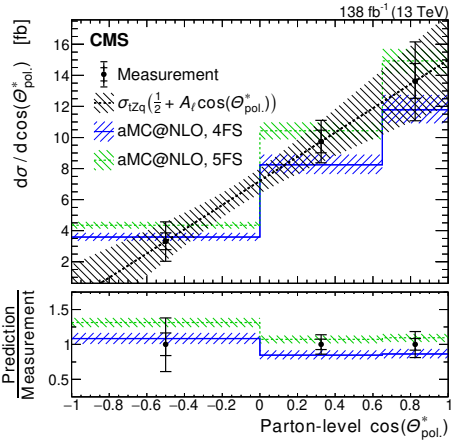


tZq - Spin asymmetry

- The polarization angle ($\cos(\theta^*_{\text{pol}})$) is defined as the anlge from angle between the recoiling quark and the lepton from the top quark decay in the top quark candate rest frame.
- $\cos(\theta^*_{\text{pol}})$ is related to the spin asymmetry (A_ℓ) by:

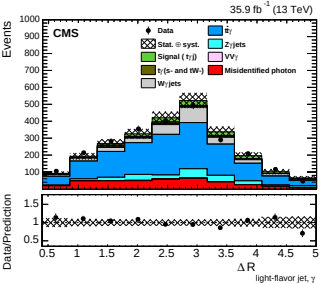
$$\frac{d\sigma}{d\cos(\theta^*_{\text{pol}})} = \sigma_{tZq}\left(\frac{1}{2} + A_\ell \cos(\theta^*_{\text{pol}})\right)$$

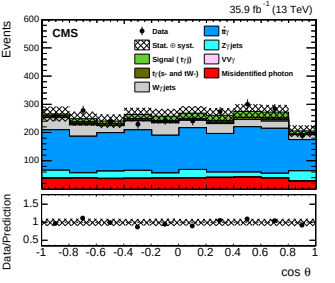
- Using the differential measurement of $\cos(\theta^*_{\text{pol}})$, the spin asymmetry is determined by the likelihood fit.

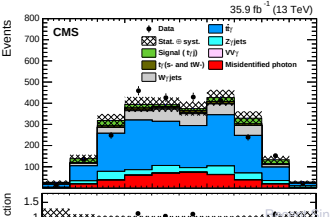


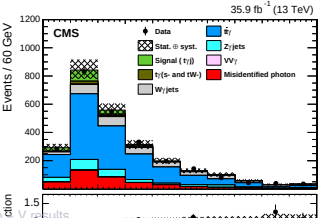
tqy - CMS

$tq\gamma$ - Kinematic variables







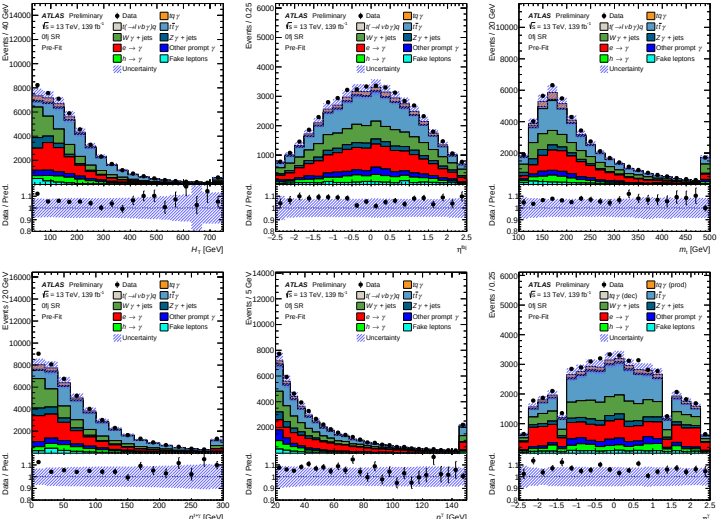


$tq\gamma$ - yields

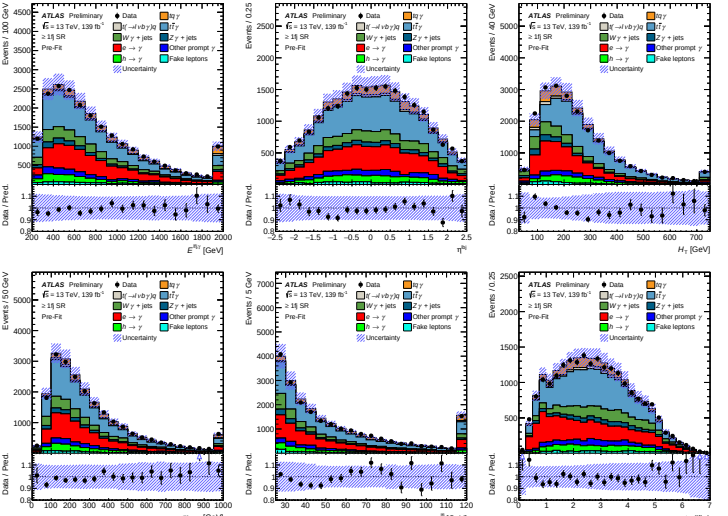
Process	Event yield
$t\bar{t}+\gamma$	1401 ± 131
$W\gamma$+jets	329 ± 78
$Z\gamma$+jets	232 ± 55
Misidentified photon	374 ± 74
$t\gamma$ (s- and tW-channel)	57 ± 8
$VV\gamma$	8 ± 3
Total background	2401 ± 178
Expected signal	154 ± 24
Total SM prediction	2555 ± 180
Data	2535

tqy - ATLAS

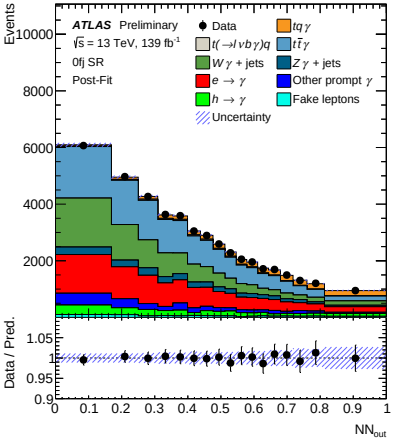
$tq\gamma$ - 0fj SR kinematic variables

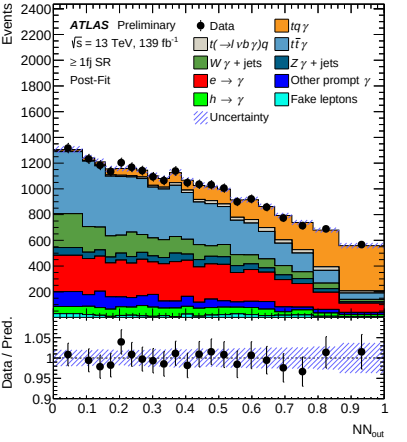


$tq\gamma$ - $\geq$1fj SR kinematic variables

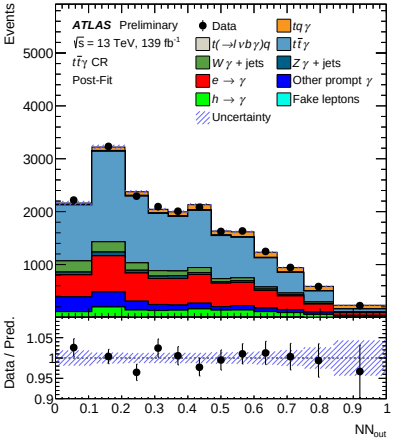


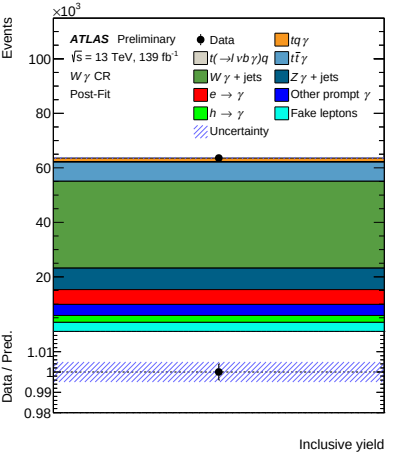
$tq\gamma$ - Fitted SRs





$tq\gamma$ - Fitted CRs





$tq\gamma$ - Parton level measurement yields

	$\geq$ 1fj SR	0fj SR	$t\bar{t}\gamma$ CR	$W\gamma$ CR
$tq\gamma$	2390 ± 260	2480 ± 320	890 ± 120	1280 ± 150
$t\,(\rightarrow \ell\nu b\gamma)\,q$	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
$e \rightarrow \gamma$ fake photons	5200 ± 500	10 300 ± 800	4800 ± 400	5400 ± 500
$h \rightarrow \gamma$ 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

$tq\gamma$ - Particle level measurement yields

	$\geq$ 1fj SR	0fj SR	$t\bar{t}\gamma$ CR	$W\gamma$ CR
$tq\gamma$	2340 ± 250	2430 ± 310	880 ± 120	1250 ± 140
$t\,(\rightarrow \ell\nu b\gamma)\,q$	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
$e \rightarrow \gamma$ fake photons	5200 ± 500	10 400 ± 800	4900 ± 400	5500 ± 500
$h \rightarrow \gamma$ 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

$tq\gamma$ - Systematic uncertainties

Parton level

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%

Particle level

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%