GEORG-AUGUST-UNIVERSITÄT
GÖTTINGEN

ATLAS
EXPERIMENT

Using associated production of top quarks and neutral bosons to probe Standard Model couplings and search for new physics

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on behalf of the ATLAS Collaboration

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Top Quark and Electroweak
Physics: Session III

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Introduction to top+boson processes

- Unique role in the SM due to its large mass (173 GeV)
  - Yukawa coupling-strength parameter close to unity
  - Short lifetime (ca. 10^{-25} s) → decay before hadronisation
- Generalised, effective Lagrangian for the $t\bar{t}V$ coupling vertex:

$$\Gamma_\mu^V(q^2) = \gamma_\mu F_1^V(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2m_t} F_2^V(q^2) + \gamma_\mu\gamma_5 F_3^V(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2m_t}\gamma_5 F_4^V(q^2)$$

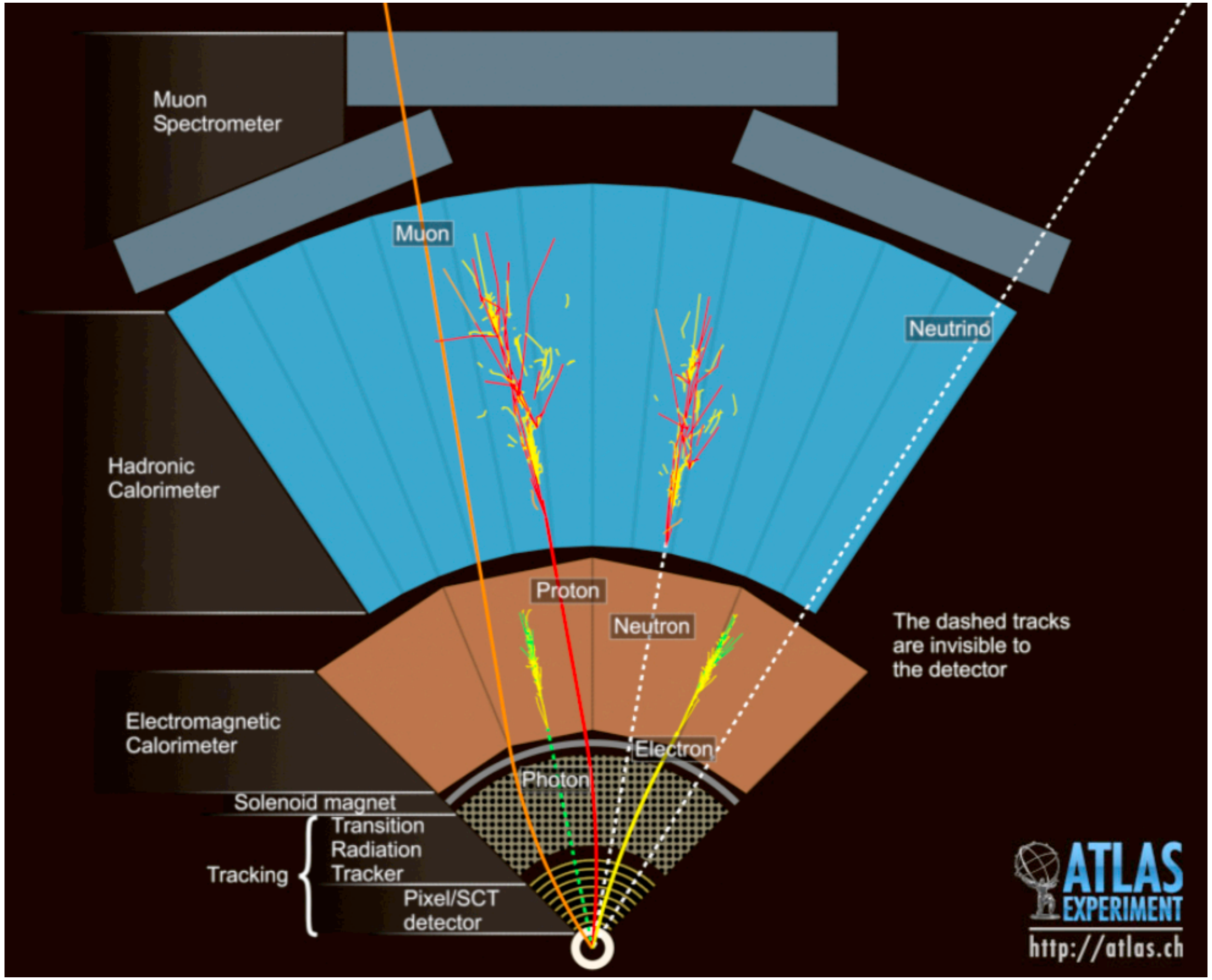
  - Photon coupling: purely "vectorial" coupling at tree level in the SM
  - Z boson coupling: components from EW mixing (hypercharge, weak isospin)
  - Both: only minor tensor-like components with higher-order loop corrections

- Couplings accessible through: top quarks in association with photon or Z boson
- First ATLAS papers with full Run 2 data: stringent tests of theory predictions

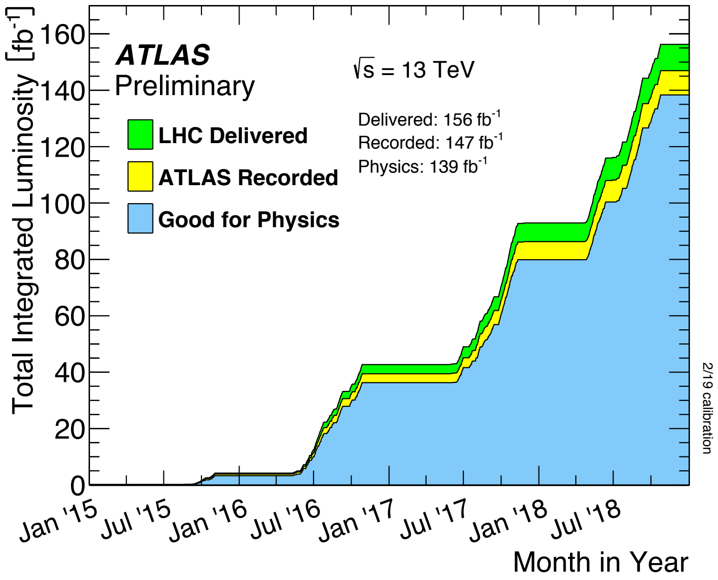
→ Presented here: ATLAS measurements of $t\bar{t}\gamma$, $t\bar{t}Z$ and tZq production

$t\bar{t}\gamma$: arXiv:2007.06946 | $t\bar{t}Z$: ATLAS-CONF-2020-028 | tZq: arXiv:2002.07546

Detection with the ATLAS detector

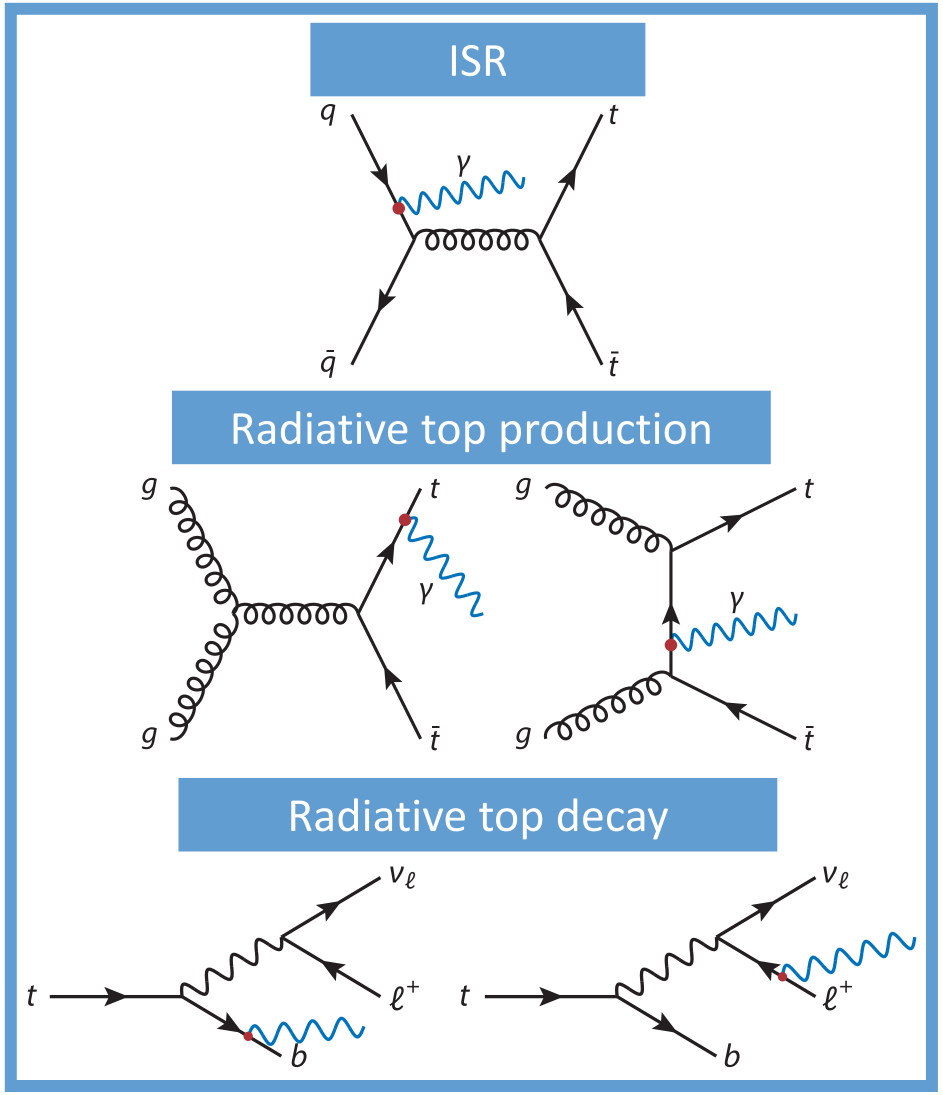


- Onion-shell-like structure
- High-precision components: tracker, calorimeters, muon spectrometer
- Large coverage up to $|\eta| < 5.0$
- 139 fb^{-1} of data “good for physics”



$t\bar{t}\gamma$ production in the $e\mu$ channel

- Top-photon coupling accessible in production of $t\bar{t}\gamma$ final states
- $t\bar{t}\gamma$: photon radiation possible by any of the charged particles involved → Combination is measured experimentally as "$t\bar{t}\gamma$ production"
- Earlier measurements (36 fb^{-1}) with Run 2 data published by ATLAS EPJC 79 (2019) 382
  - Both lepton+jets and dilepton channels
  - Fiducial inclusive and differential cross-sections
- Now: precision measurement in $e\mu$ channel
  - Fiducial inclusive and differential cross-sections in several observables to test theory prediction
  - Comparison with fixed-order calculation (NLO in QCD): JHEP 1810 (2018) 158



$t\bar{t}\gamma$ production in the $e\mu$ channel

- Fixed-order computation includes all off-shell contributions and interference effects

  → Perform combined $t\bar{t}\gamma + tW\gamma$ measurement

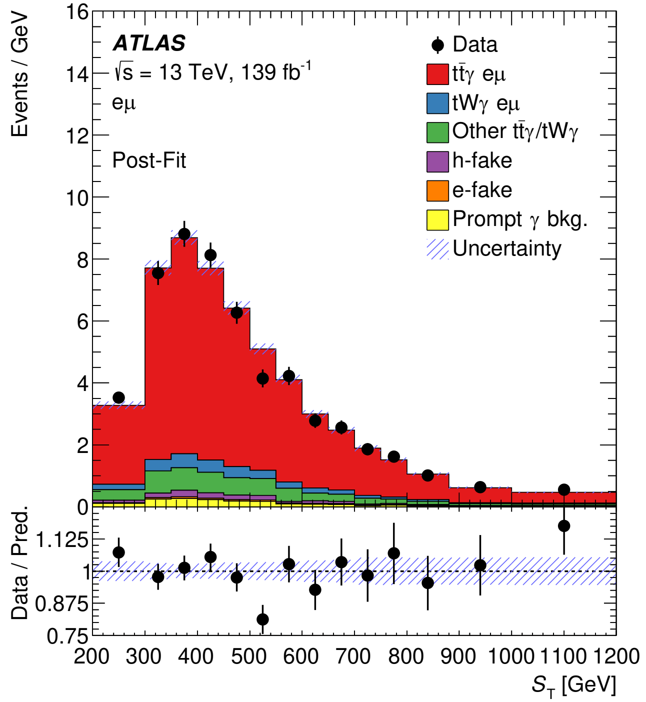
  → Fiducial phase space aligned with computation
- Binned profile likelihood fit of observable S_{T} (scalar sum of all transverse momenta, incl. $E_{\mathrm{T}}^{\mathrm{miss}}$)
- Measured fiducial cross-section (approx. 6% unc.):

$$\sigma^{\mathrm{fid}}(t\bar{t}\gamma \to e\mu) = 39.6 \pm 0.8\ (\mathrm{stat})\ ^{+2.6}_{-2.2}\ (\mathrm{syst})\ \mathrm{fb}$$

- To be compared against theory value:

$$\sigma^{\mathrm{fid}}_{\mathrm{NLO}} = 38.50\ ^{+0.56}_{-2.18}\ (\mathrm{scale})\ ^{+1.04}_{-1.18}\ (\mathrm{PDF})\ \mathrm{fb}$$

- Dominant uncertainties: signal and background modelling, luminosity



	***eμ* signal region**
Leptons	1 electron, p_{T} > 25 GeV
	1 muon, p_{T} > 25 GeV
	opposite electric charge
	M_{ll} > 15 GeV
Jets	2 or more (*R*=0.4)
b-tags	1 or more (85% efficiency)
Photons	1 photon, p_{T} > 20 GeV

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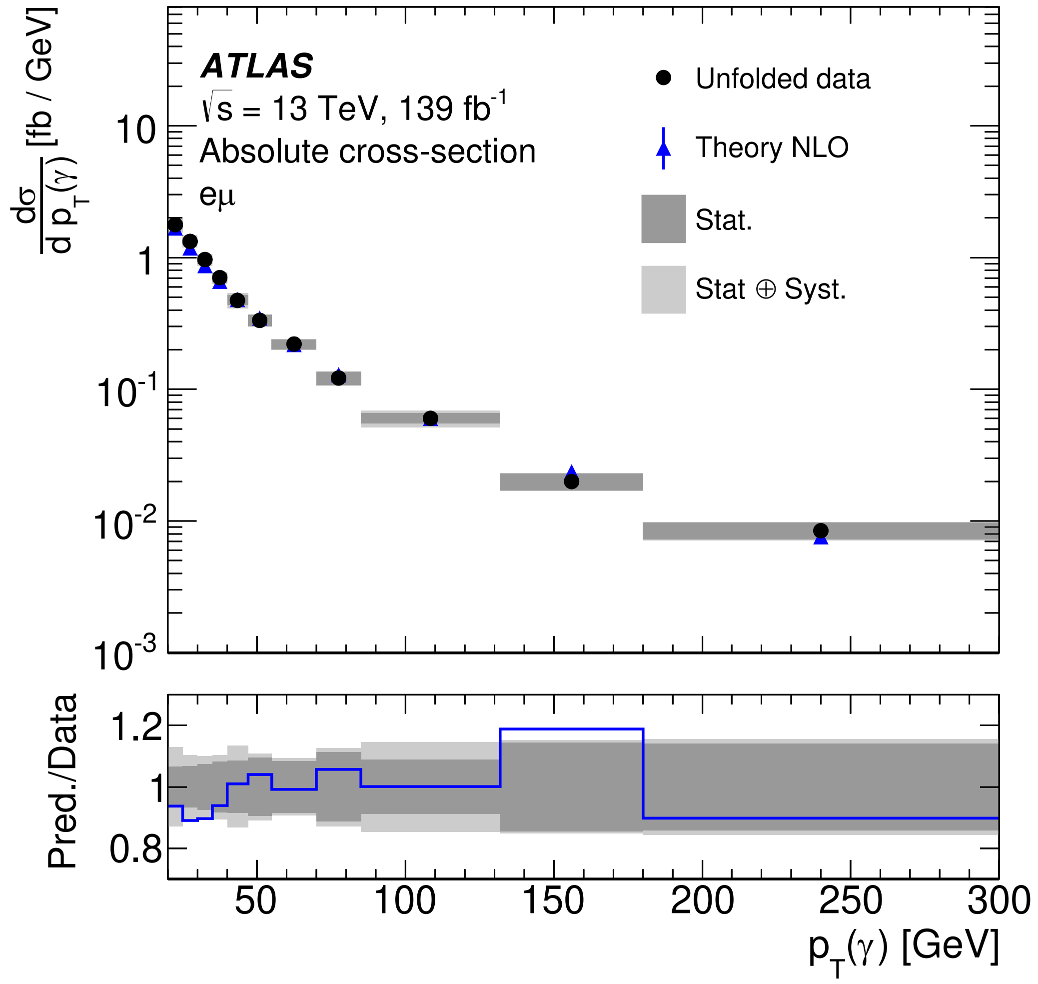
$t\bar{t}\gamma$ production in the $e\mu$ channel

- ATLAS data unfolded to parton level
- Compared against fixed-order NLO theory and LO+PS Monte Carlo simulation:
  - p_T and absolute rapidity of the photon
  - $|\Delta\eta|$ and $|\Delta\phi|$ between the two leptons
  - ΔR between photon and closest lepton
- NLO theory in good agreement with data

Absolute cross-section as a function of $p_\mathrm{T}(\gamma)$



$t\bar{t}\gamma$ production in the $e\mu$ channel

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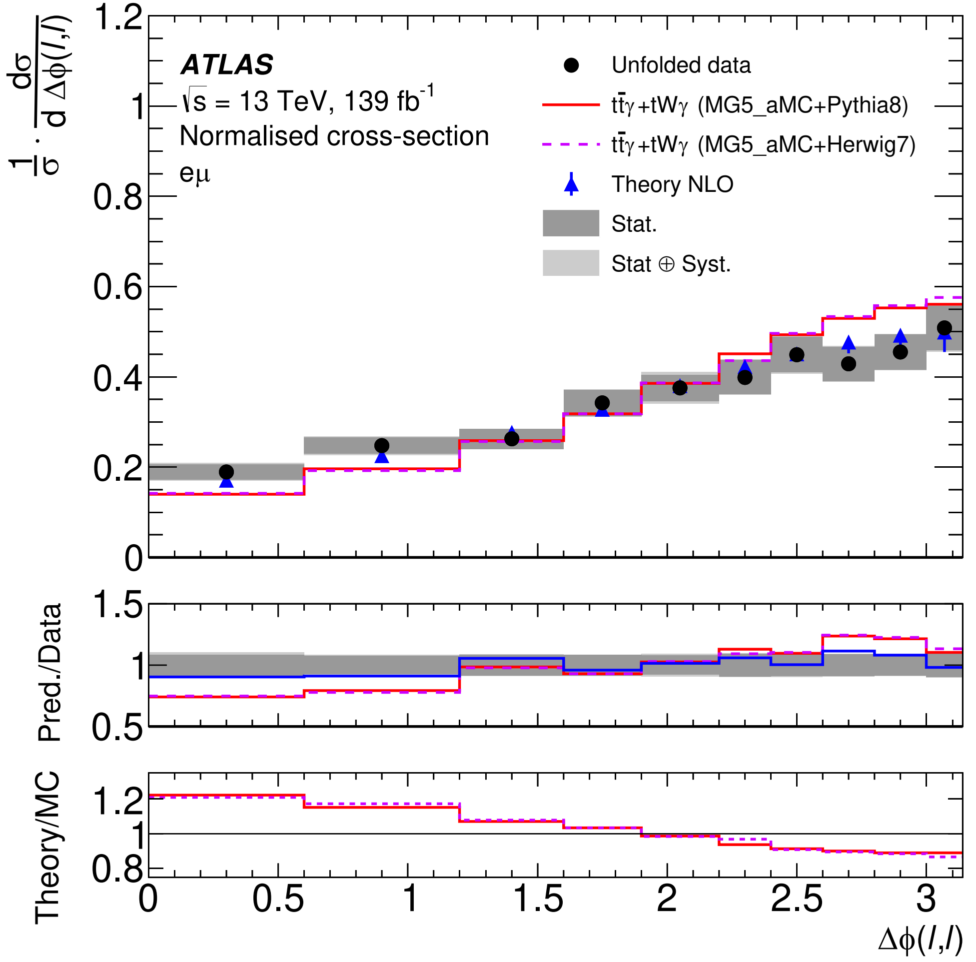
  - $|\Delta\eta|$ and $|\Delta\phi|$ between the two leptons
  - ΔR between photon and closest lepton
- NLO theory in good agreement with data
- LO+PS MC simulation with difficulties to describe some of the observables

	χ^2/ndf	p-value
MG5 + Pythia8	30.8/9	< 0.01
MG5 + Herwig7	31.6/9	< 0.01
Fixed-order NLO	5.8/9	0.76

Normalised cross-section as a function of $\Delta\phi(\ell,\ell)$

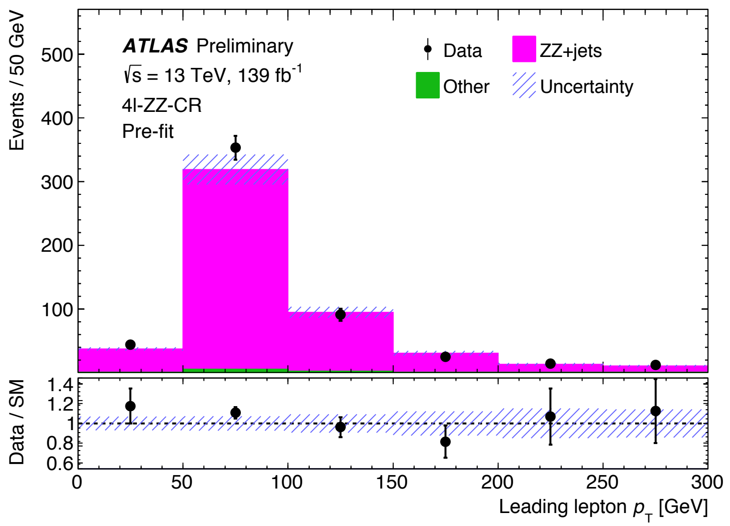


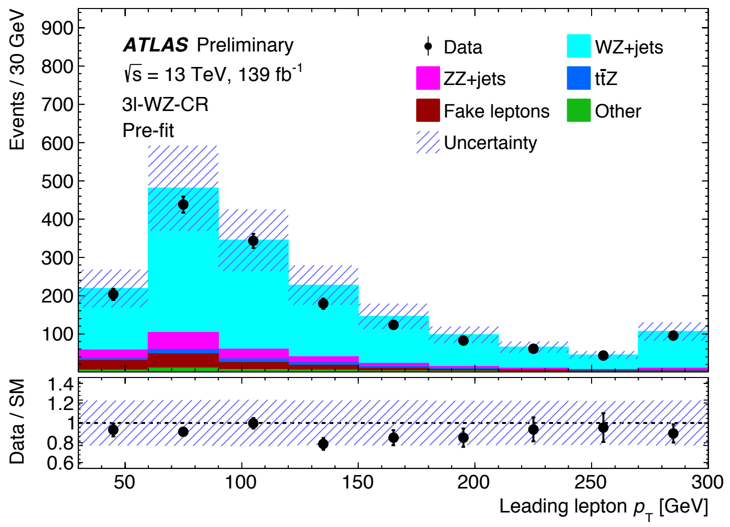
$t\bar{t}Z$ production in $3\ell/4\ell$ final states

- Earlier ATLAS measurements at 13 TeV (36 fb^{-1}): inclusive cross-sections of $t\bar{t}W/t\bar{t}Z$ production

PRD 99 (2019) 072009

→ Measurement of $t\bar{t}Z$ with full Run 2 data
  - Focus on trilepton and tetralepton final states
  - Inclusive & differential cross-section measurements in several observables (parton and particle level)
- Trilepton channels – different usage in incl./diff.:
  - One region for unfolding → maximum statistics
  - Two b-tag regions for inclusive measurement → maximum precision & WZ background suppression
- Tetralepton channels – four signal regions:
  - Same-flavour/opposite-flavour lepton pairing
  - Different b-tag multiplicities
- Control regions for ZZ and WZ backgrounds



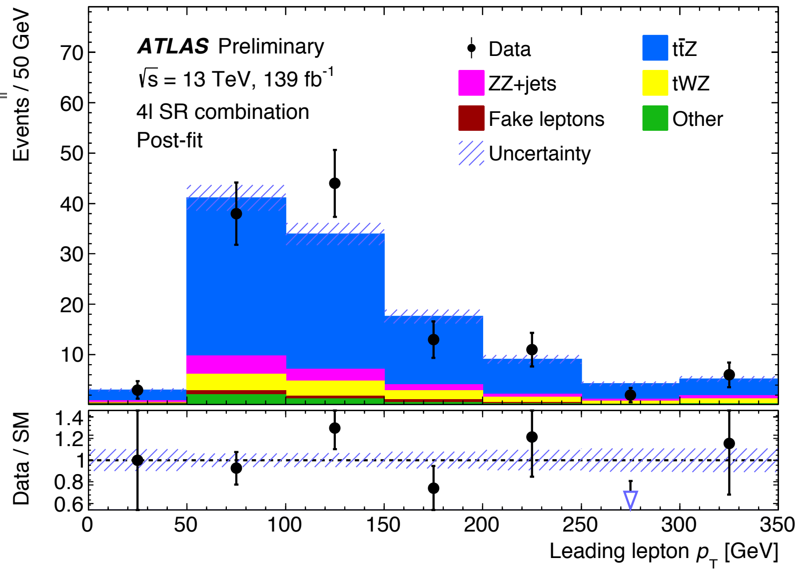


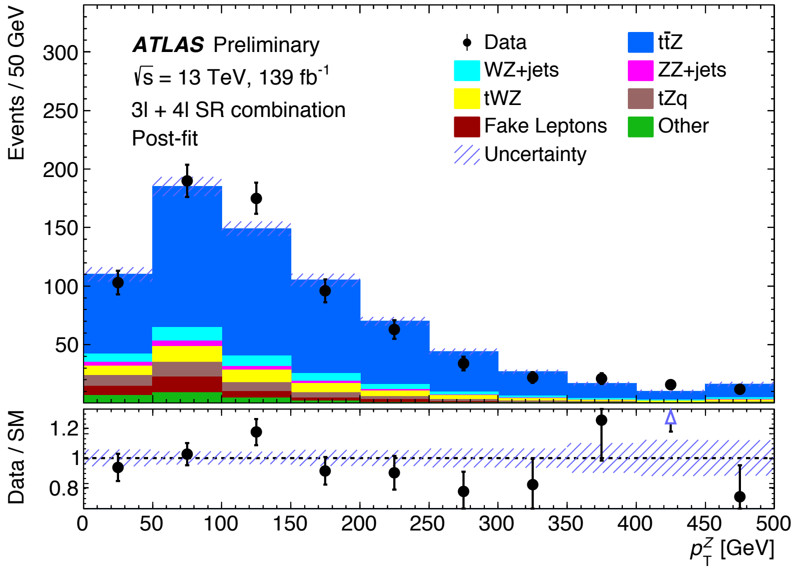
$t\bar{t}Z$ production in $3\ell/4\ell$ final states

- Simultaneous profile likelihood fit of all trilepton and tetralepton signal regions + WZ and ZZ control regions
- Cross-check of fit results with individual channel fits

Fit configuration	$\mu_{t\bar{t}Z}$
Trilepton	$1.17 \pm 0.07\,(\text{stat.})\,^{+0.12}_{-0.11}\,(\text{syst.})$
Tetralepton	$1.21 \pm 0.15\,(\text{stat.})\,^{+0.11}_{-0.10}\,(\text{syst.})$
Combined	$1.19 \pm 0.06\,(\text{stat.}) \pm 0.10\,(\text{syst.})$

- Measured inclusive $t\bar{t}Z$ cross-section:
  $\sigma(t\bar{t}Z) = 1.05 \pm 0.05\text{ (stat)} \pm 0.09\text{ (syst) pb}$
- In agreement with NLO+NNLL prediction: EPJC 79 (2019) 249
  $\sigma(t\bar{t}Z) = 0.863\,^{+0.07}_{-0.09}\text{ (scale)} \pm 0.03\text{ (PDF+}\alpha_S\text{) pb}$

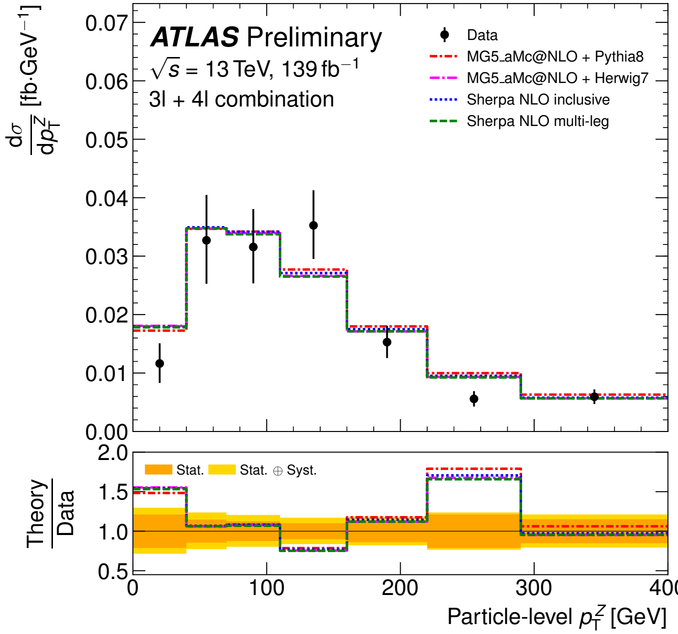




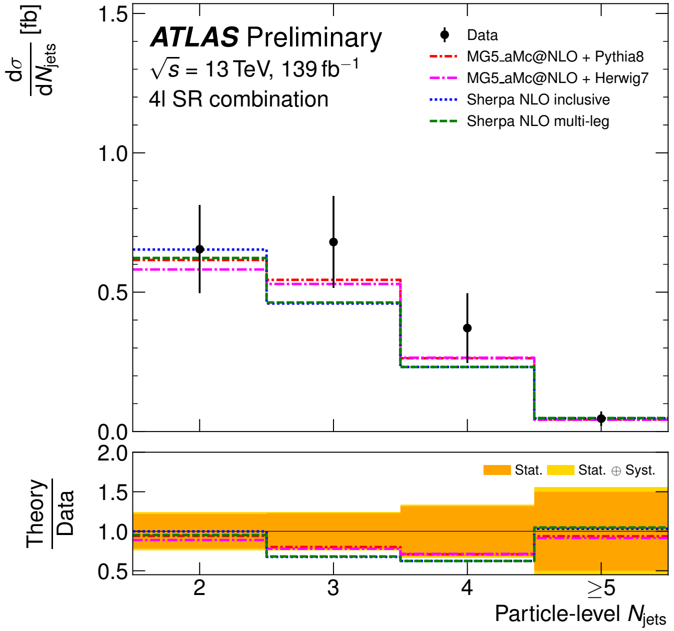
$t\bar{t}Z$ production in $3\ell/4\ell$ final states

- Unfolding done to both parton and particle level
- Differential results dominated by statistical uncertainties and those on signal modelling and b-tagging

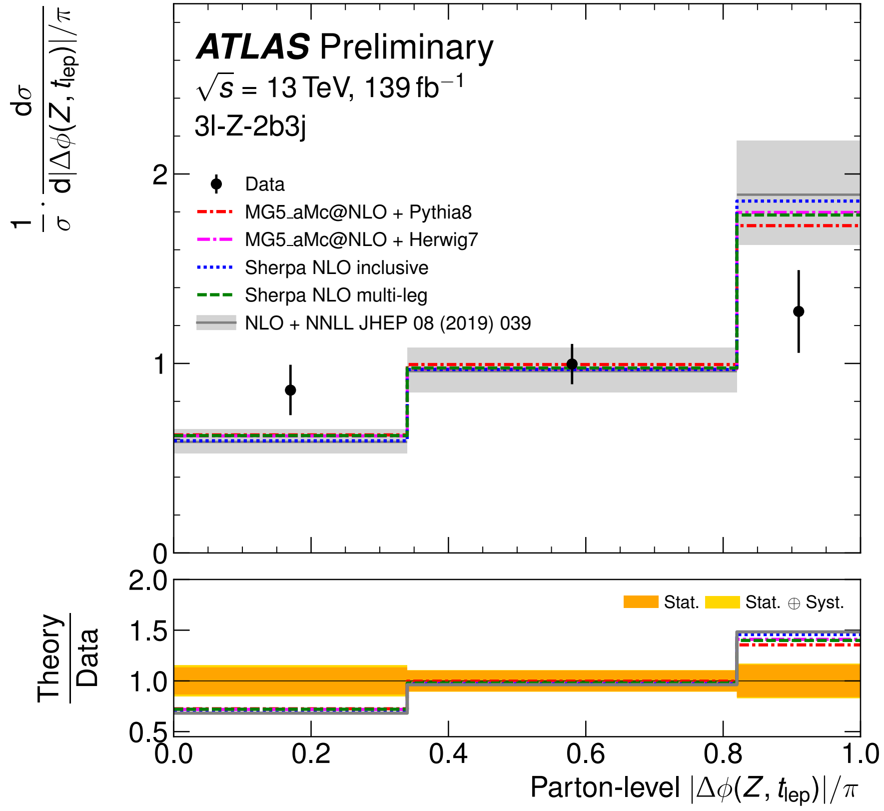
$p_\mathrm{T}(Z)$ at particle level (combined $3\ell/4\ell$ regions)



$\mathrm{N_{jets}}$ at particle level (combined 4ℓ regions)

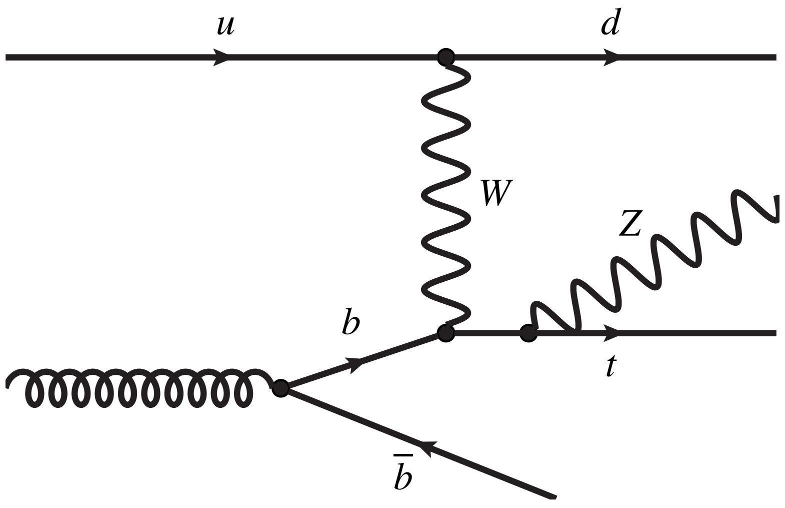


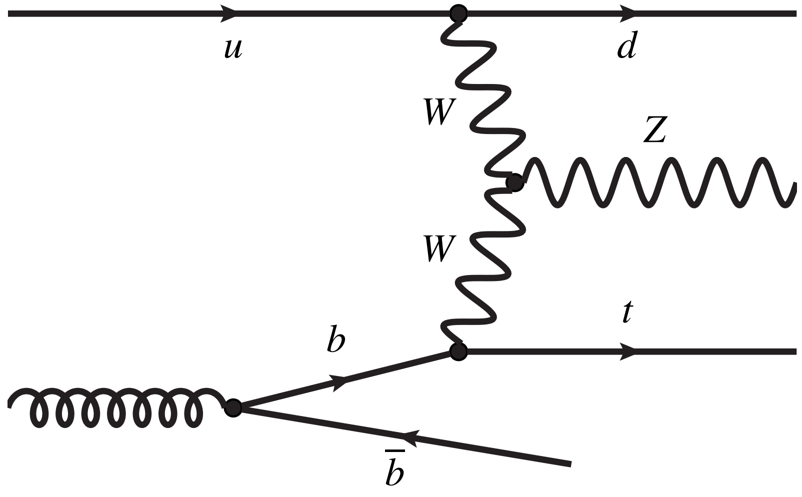
$\Delta\phi(Z, t_{\mathrm{lep}})$ at parton level, normalised (3ℓ– $2b3j$ region)



Observation of tZq production

- Measurement of a single top quark in association with a Z boson (tZq production)
  - Evidence seen by ATLAS (2015/16 data) PLB 780 (2018) 557
  - Observed by CMS (2016/17 data) PRL 122 (2019) 132003
- Best signal significance in the trilepton channel → Use only this channel!
- Include non-resonant lepton pairs ($t\ell^+\ell^-q$)
- Multiple tree-level diagrams, measurement includes both $t-Z$ and $Z-W$ couplings
- Two signal regions (2j1b, 3j1b) plus additional control regions for the largest backgrounds ($t\bar{t}Z$, diboson, $t\bar{t}$)



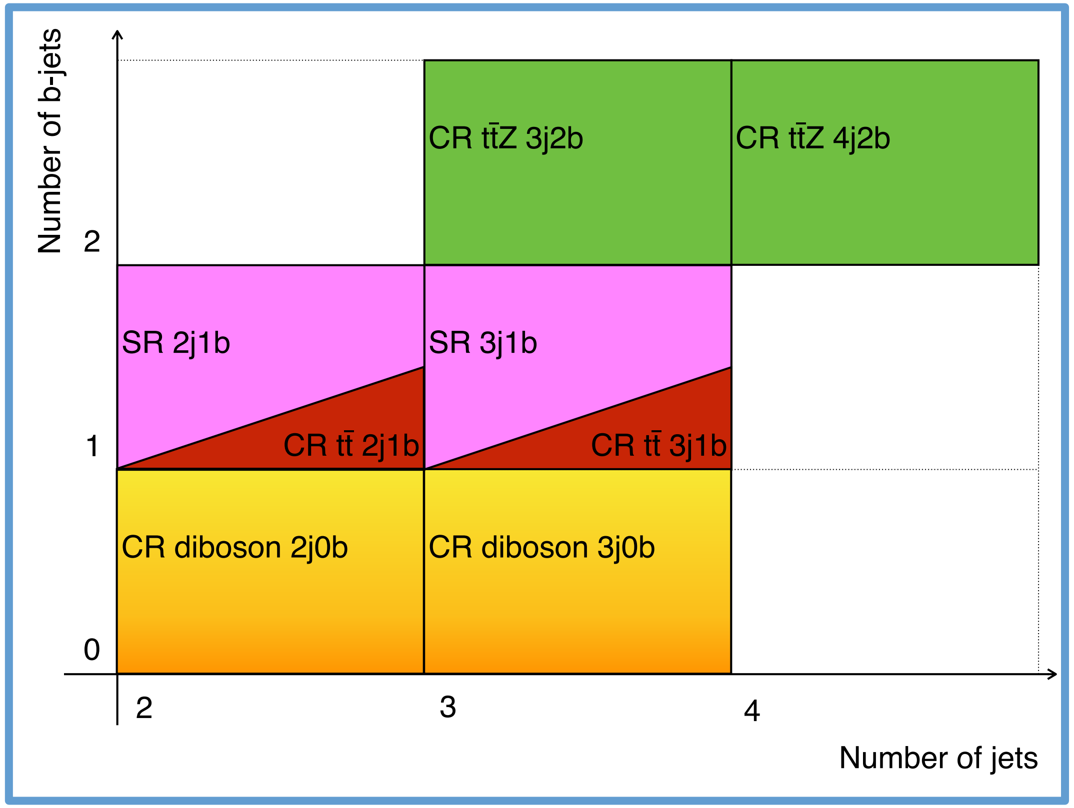


Observation of tZq production

Basic pre-selection:

- Three leptons with large p_T
  - ≥ one OSSF lepton pair
  - $|m_{ll} - m_Z| < 10$ GeV

  → $\mu\mu e$ and $ee\mu$ unambiguous, for $\mu\mu\mu$ and eee take pair with the smallest difference to the Z mass
- Signal regions: additional forward jet with large $|\eta|$

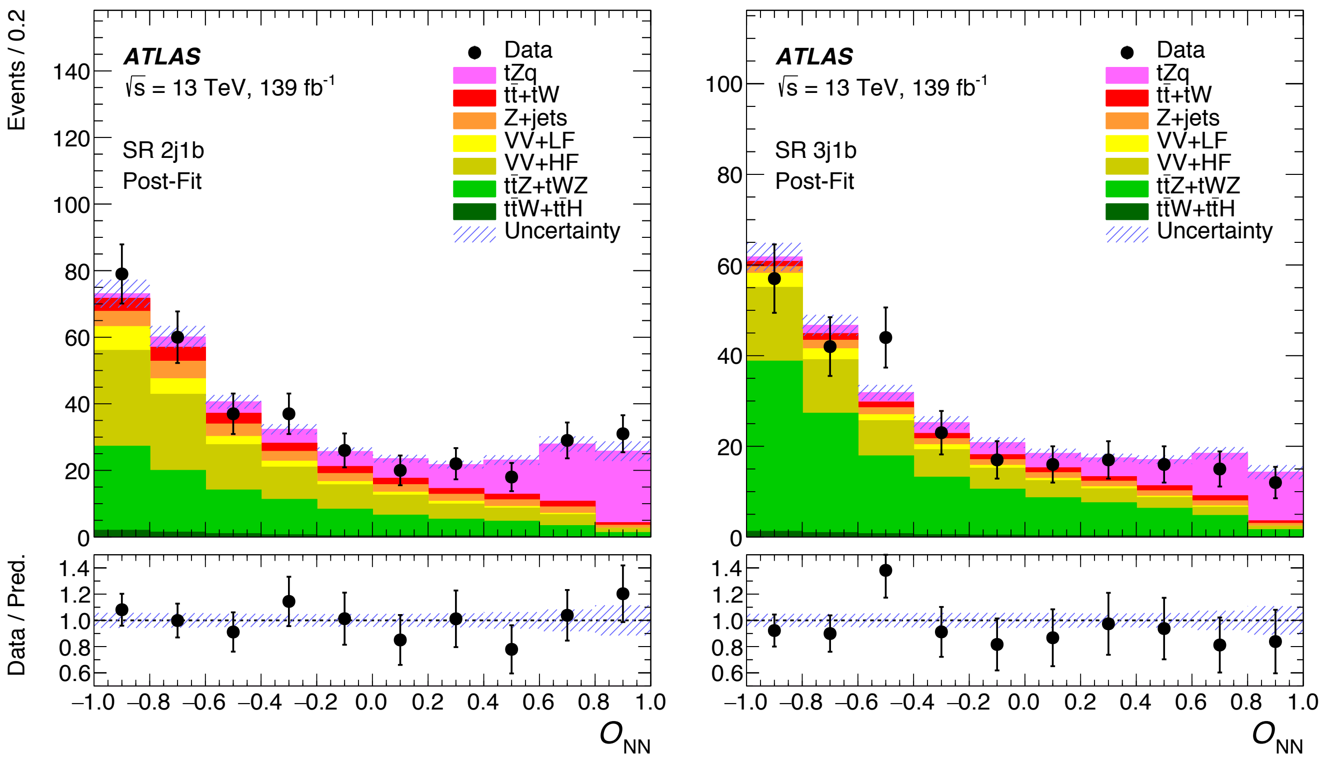


- Normalisation of backgrounds determined through control regions in the fit → free floating
- Statistics of fake-lepton estimate (e.g. $t\bar{t}$, $Z+$ jets) enriched from dilepton + two b-tag regions → replace one of the b-jets with a lepton (+ energy and polar angle replacement)

Observation of tZq production

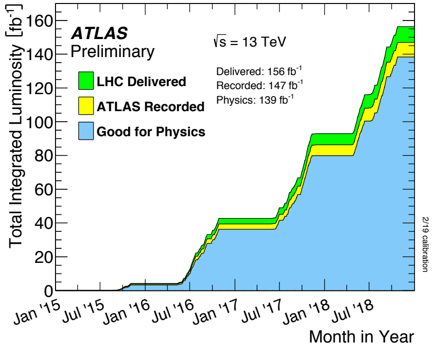
- Fitted cross-section: 97 $\pm$ 13 (stat.) $\pm$ 7 (syst.) fb
- Compatible with NLO theory prediction: 102^{+5}_{-2} fb

- Neural networks employed in both signal regions to perform binary event classification
  - 15 input variables
  - One hidden layer with 25 nodes
- Best separating input variables:
  - Inv. mass of b-jet and untagged jet
  - Reconstructed top-quark mass
- Simultaneous profile-likelihood fit of all signal and control regions
- Dominant uncertainties: statistics, modelling + rate of prompt-lepton background

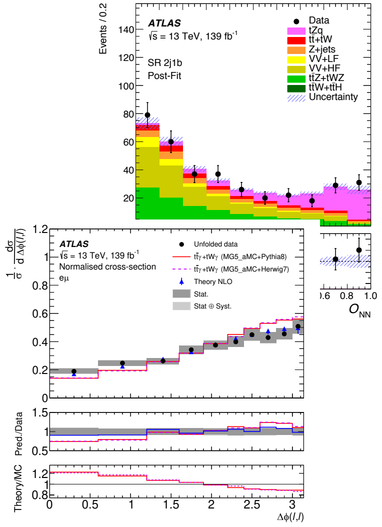


Summary & Conclusions

- Run 2 dataset enables precision measurements in top+boson topologies
- Rich program of ATLAS top-quark analyses: full list of public results
- Analyses presented today (using full Run 2 data):
  - $t\bar{t}\gamma$ production measurements in $e\mu$ final states
  - $t\bar{t}Z$ production measurements in trilepton and tetralepton final states
  - Observation of single top-quark production with a Z boson (tZq)



- Good agreement in inclusive and differential spectra with SM predictions
  - State-of-the-art fixed-order computations and NLO+PS Monte Carlo simulations provide good description of data spectra
  - LO+PS MC simulations describe some of the observables insufficiently



- First round of ATLAS Run 2 measurements = stringent tests of SM prediction

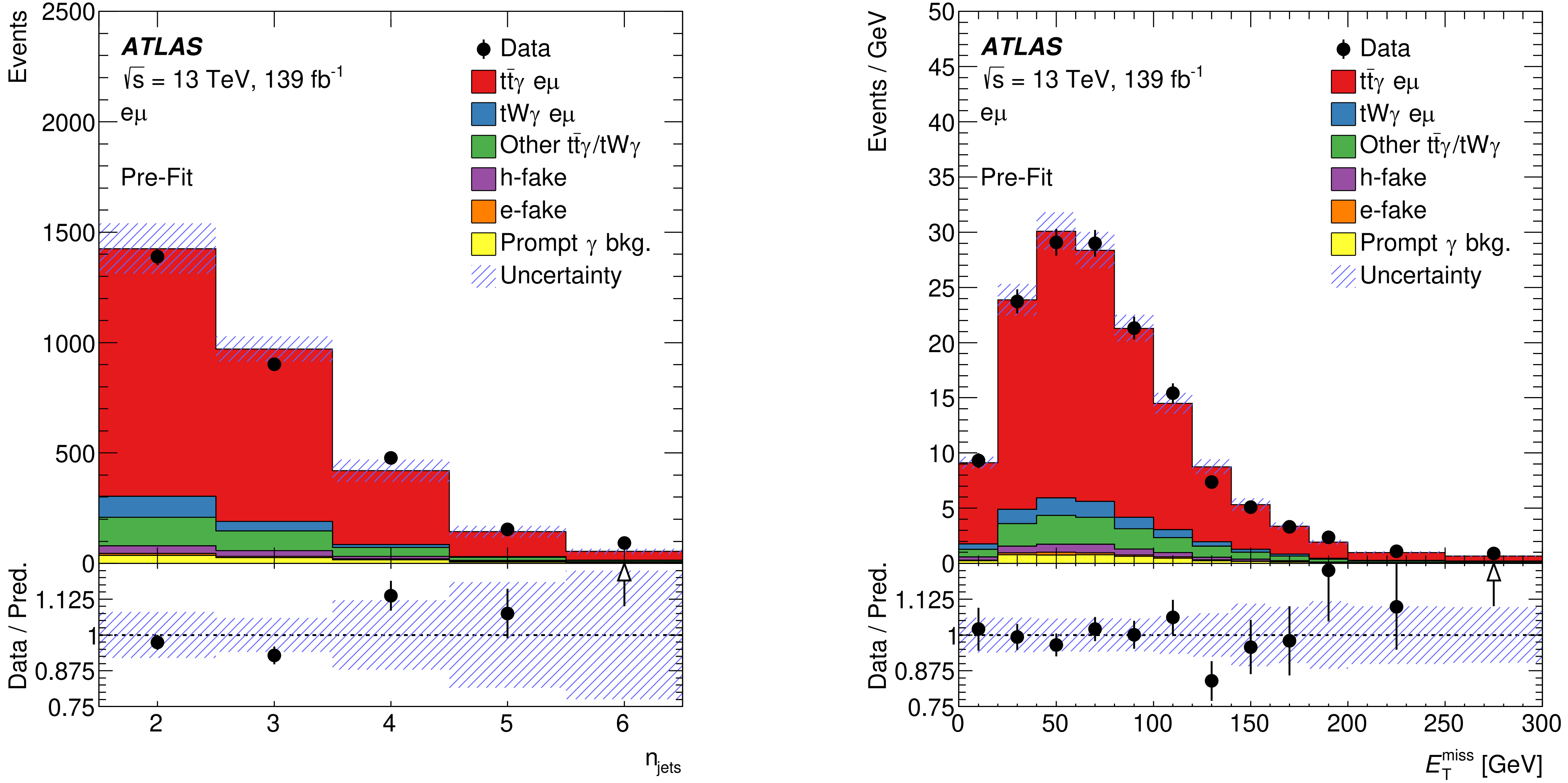
→ More ATLAS Run 2 measurements to come in the top-quark sector!

$t\bar{t}\gamma$: arXiv:2007.06946 | $t\bar{t}Z$: ATLAS-CONF-2020-028 | tZq: arXiv:2002.07546

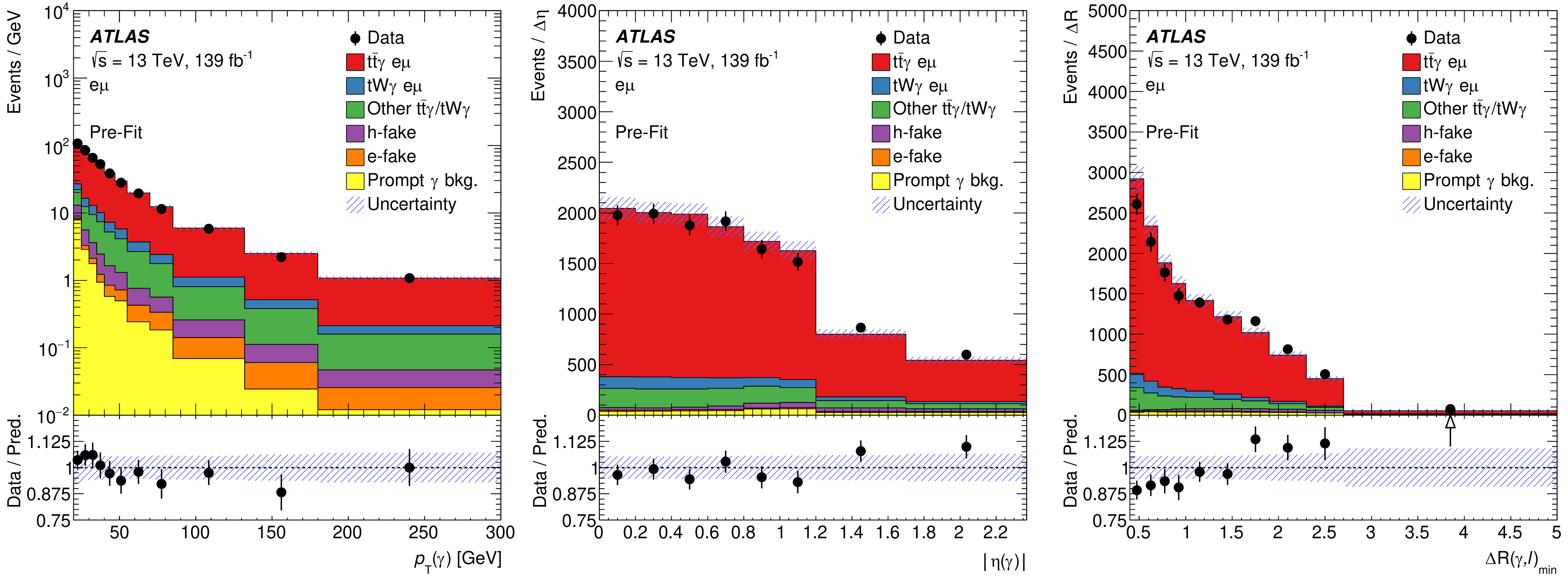
Backup

$t\bar{t}\gamma$ production in the $e\mu$ channel

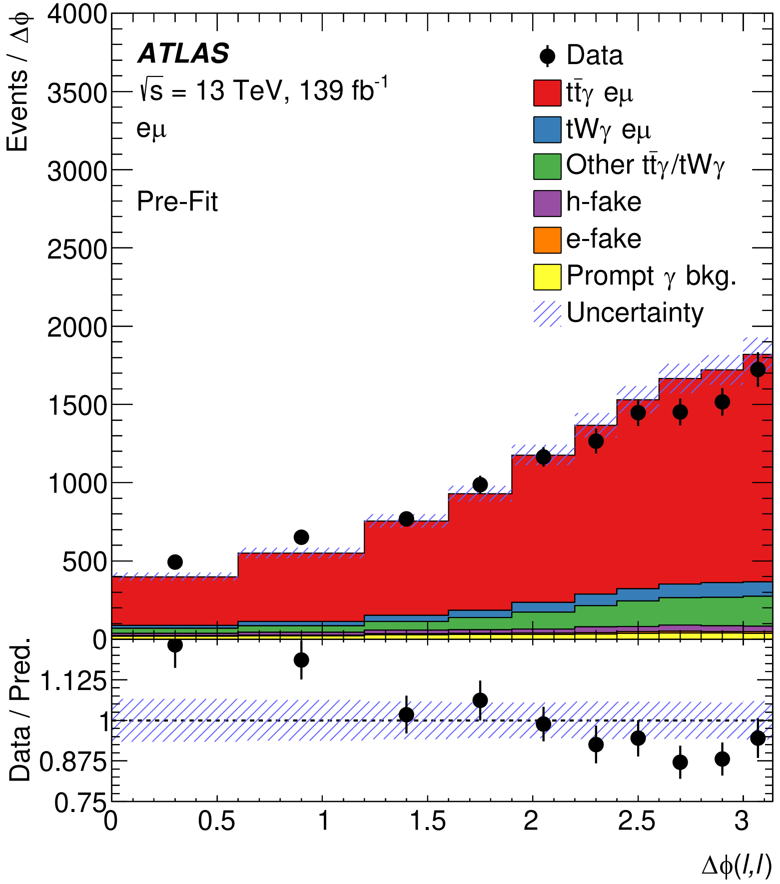
$t\bar{t}\gamma$ – pre-fit control plots

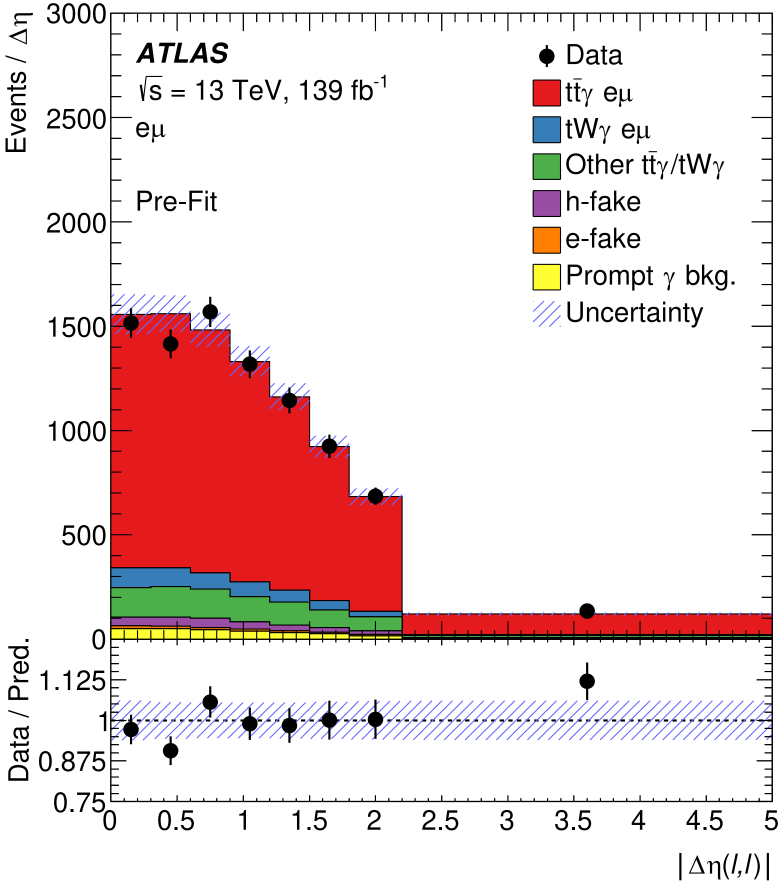


$t\bar{t}\gamma$ – pre-fit plots of unfolded variables

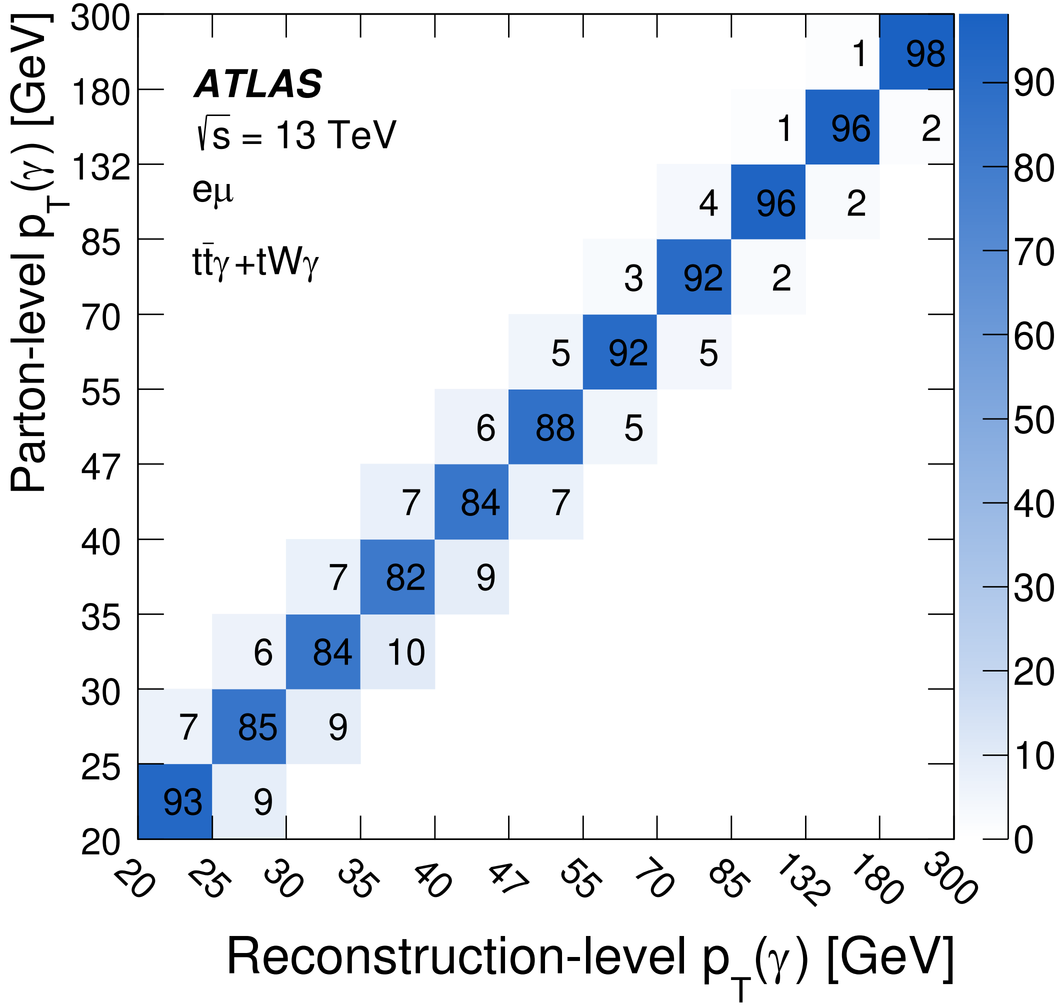


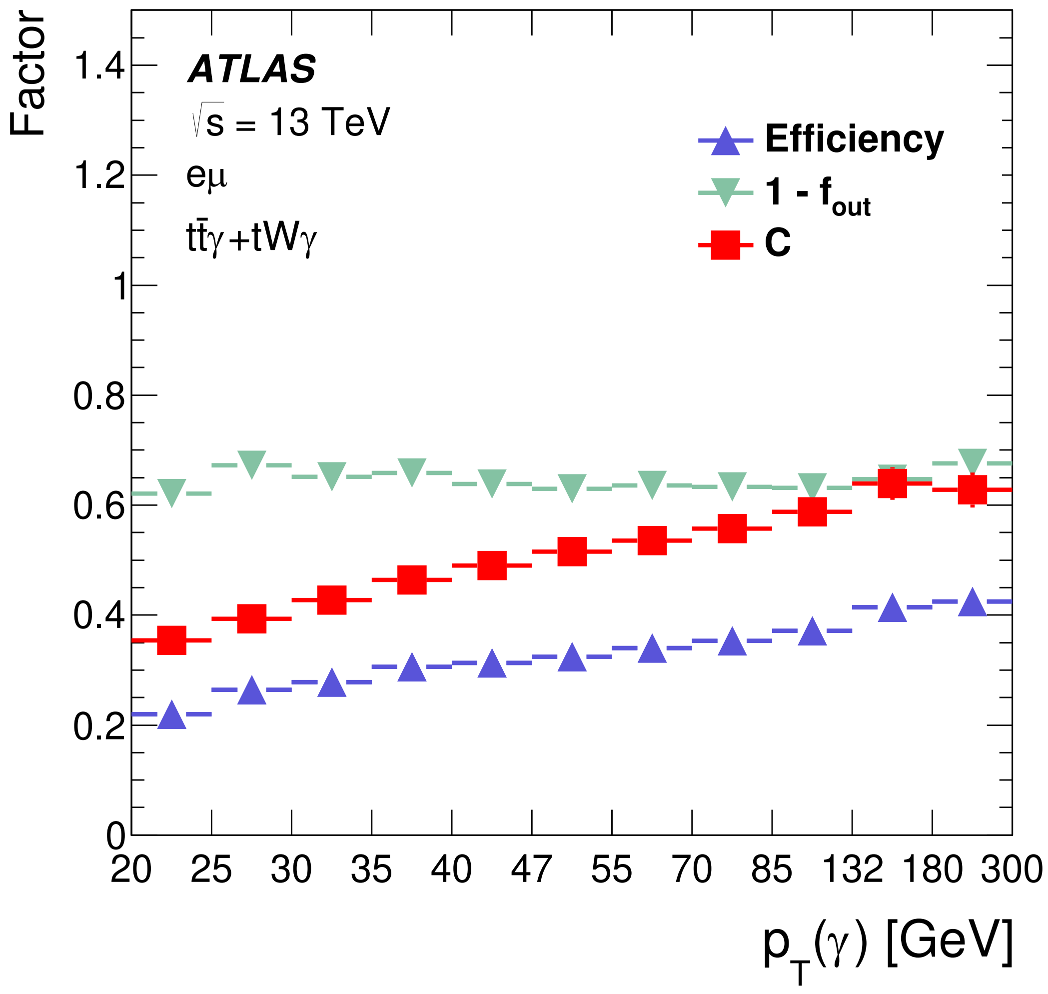
$t\bar{t}\gamma$ – pre-fit plots of unfolded variables (2)



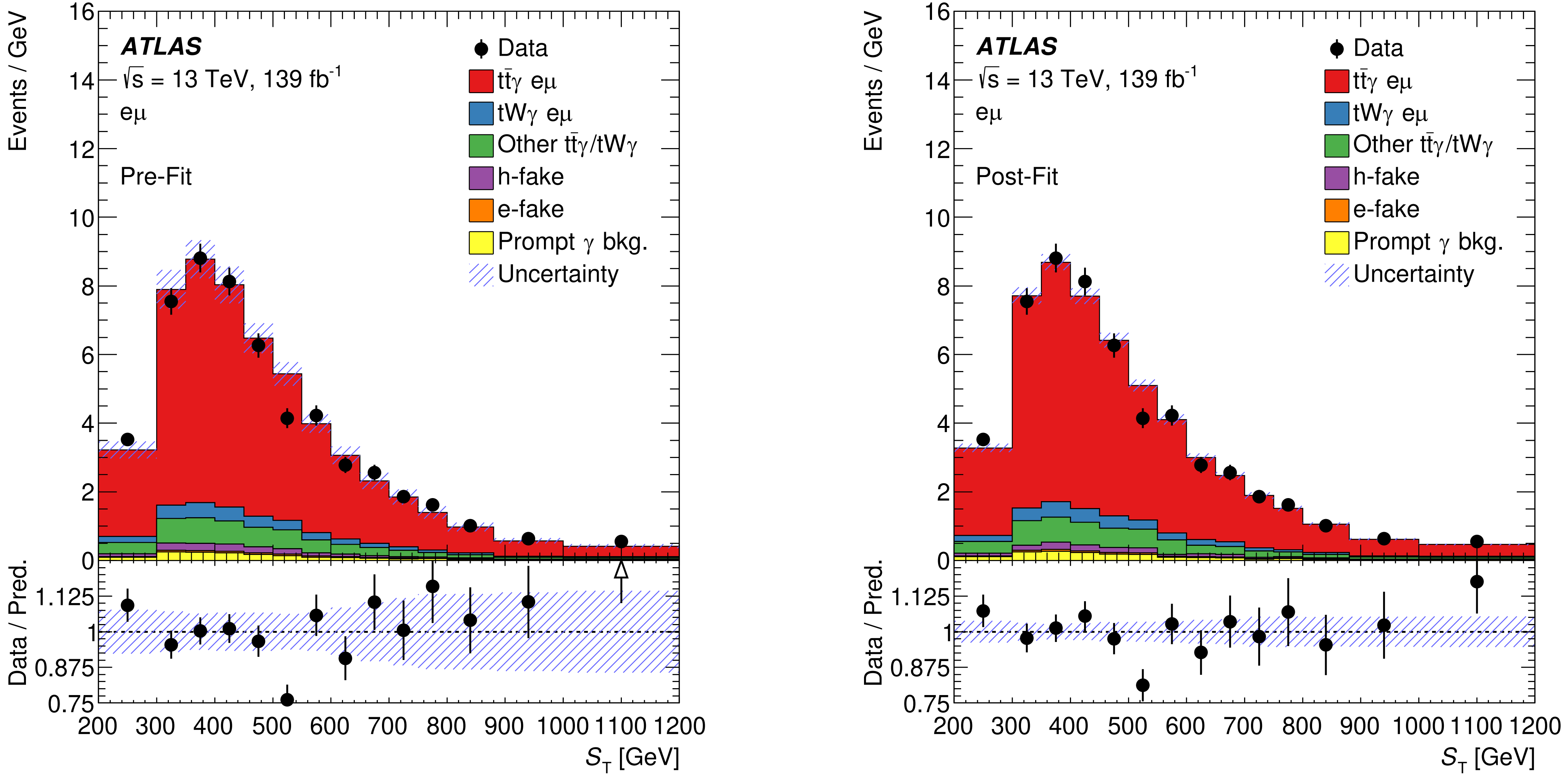


$t\bar{t}\gamma$ – migration matrix and efficiencies

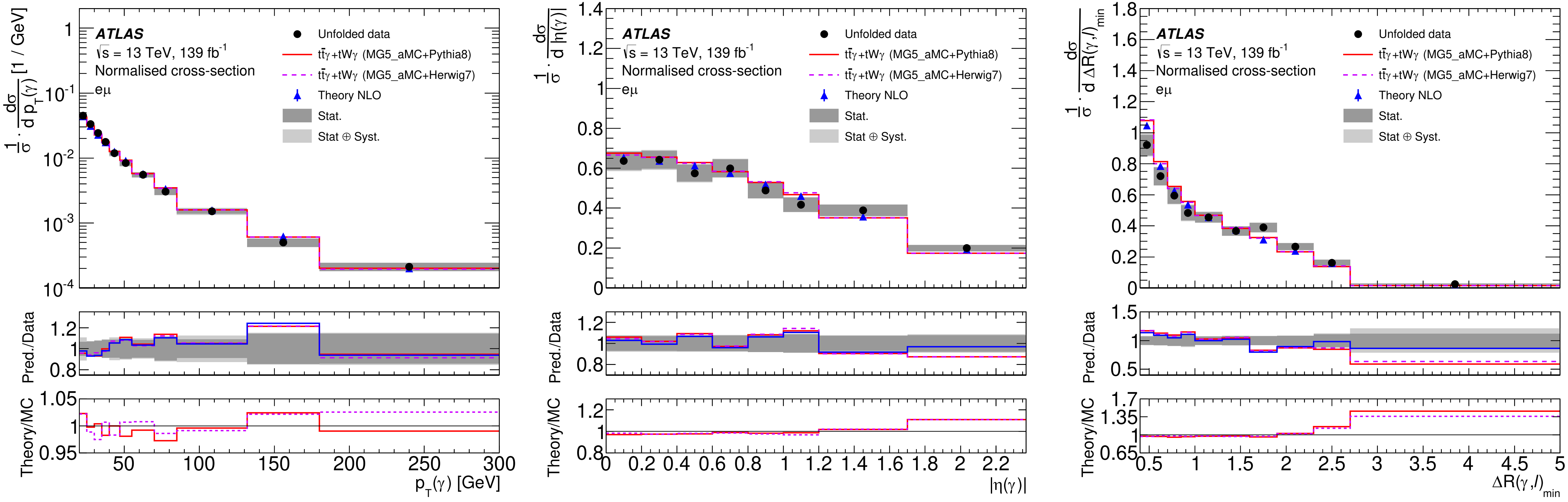




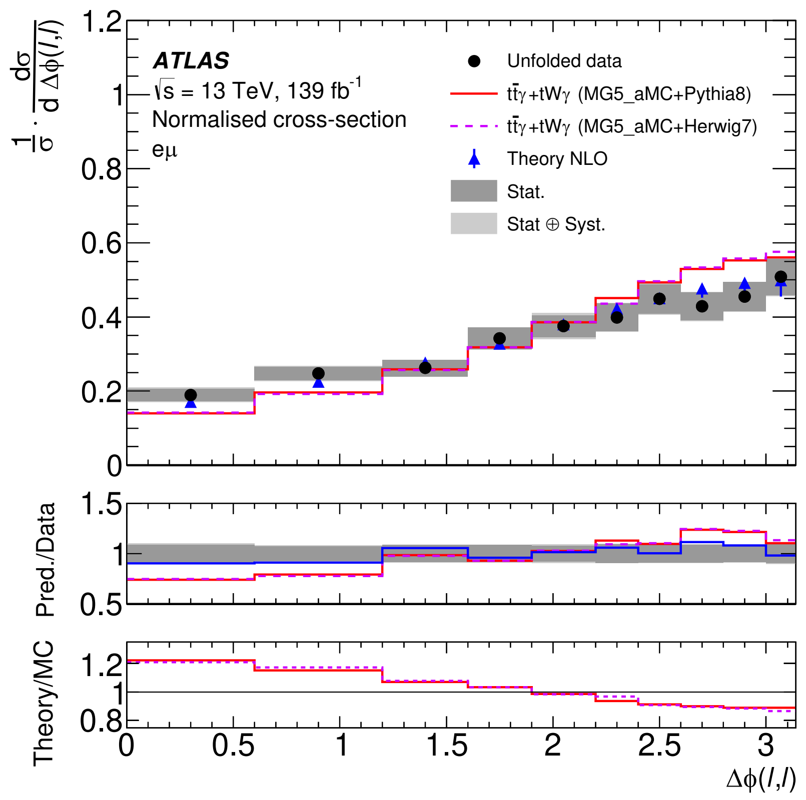
$tt\gamma$ – pre-fit/post-fit distributions of fit variable

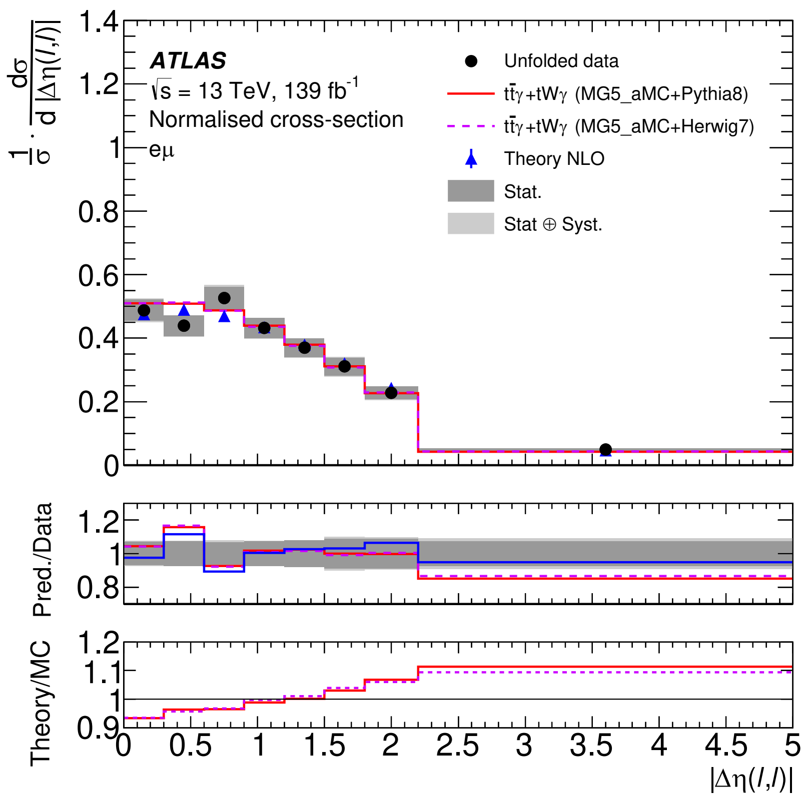


$tt\gamma$ – normalised unfolded cross-sections

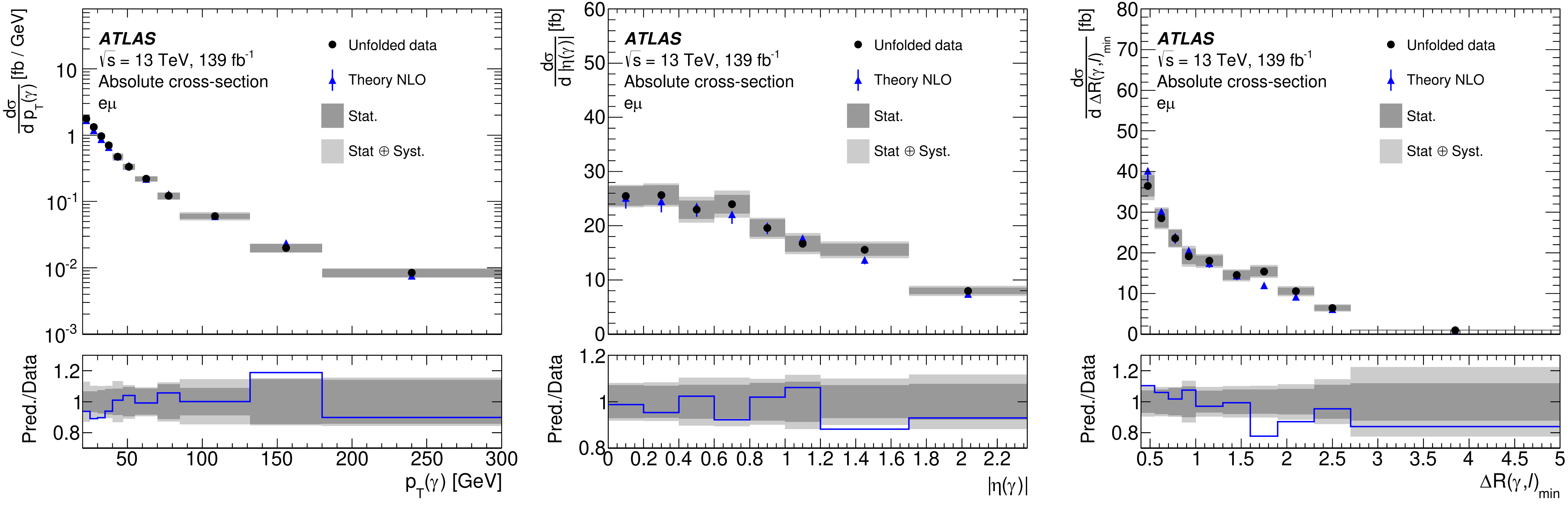


$tt\gamma$ – normalised unfolded cross-sections (2)

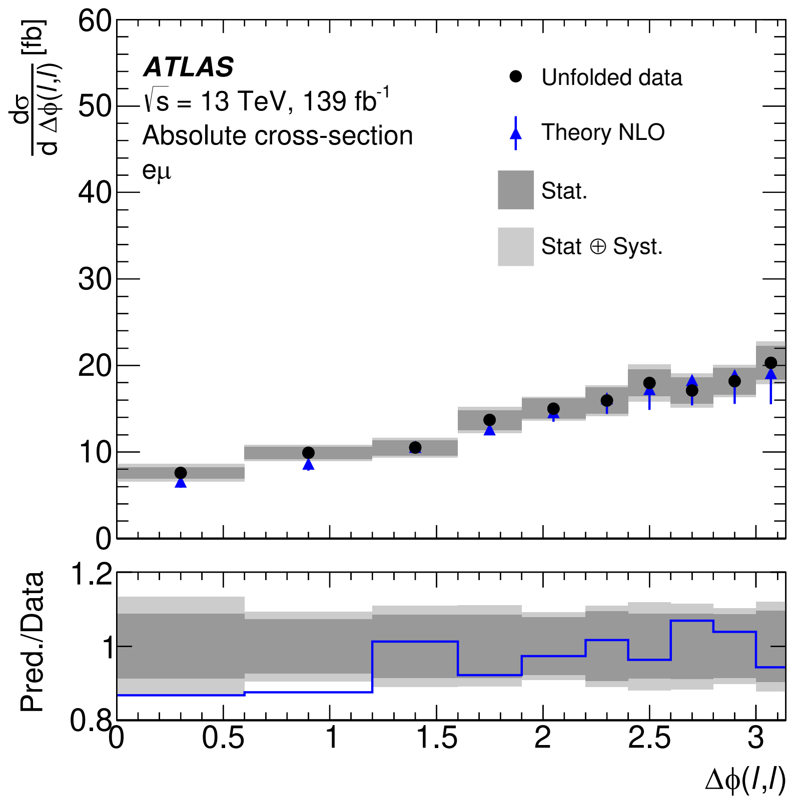


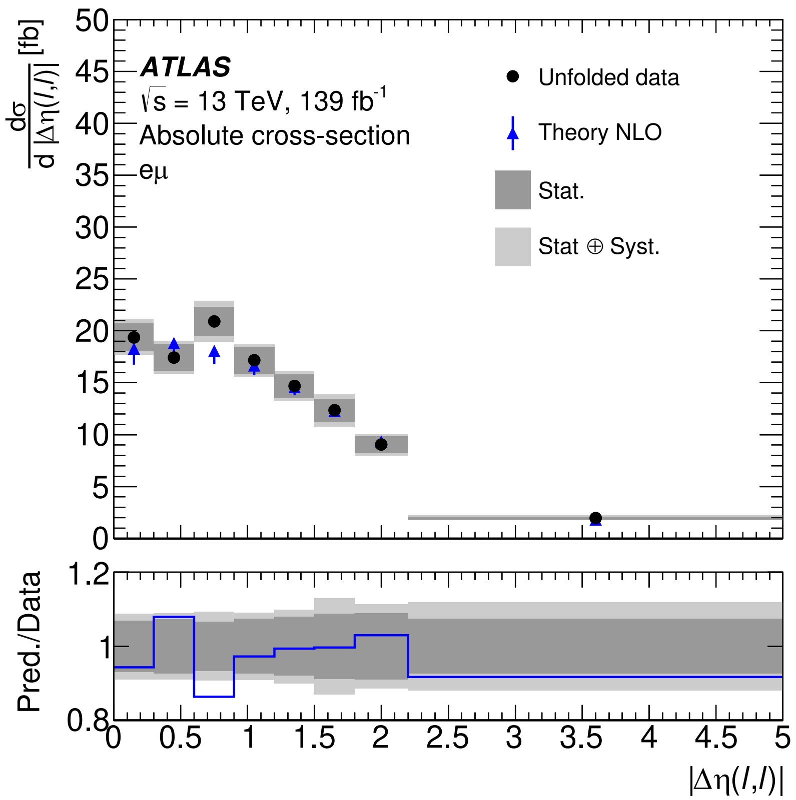


$tt\gamma$ – absolute unfolded cross-sections

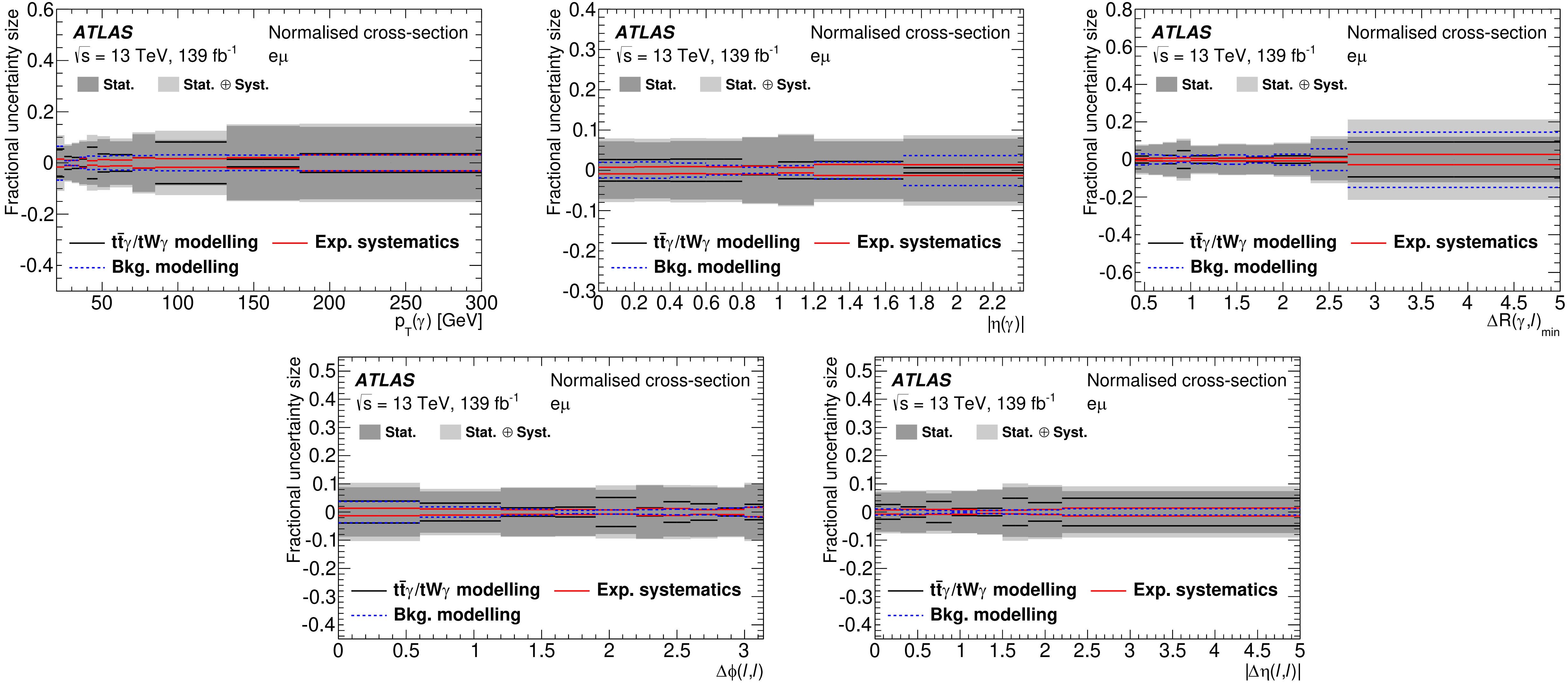


$t\bar{t}\gamma$ – absolute unfolded cross-sections (2)

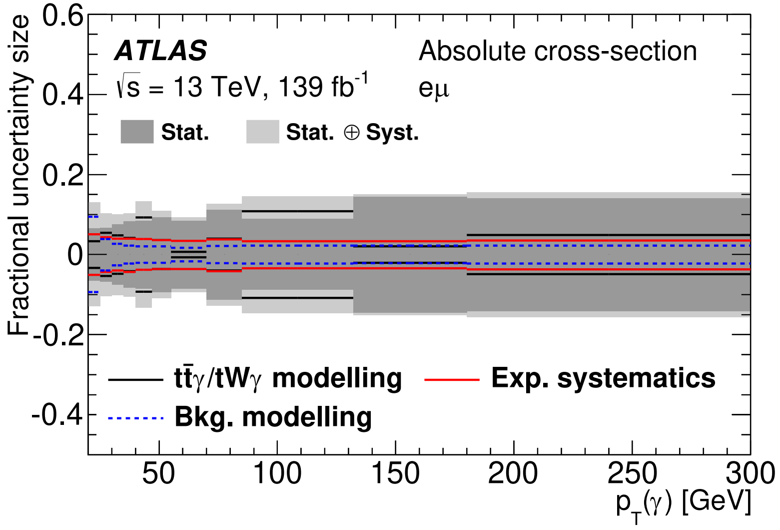


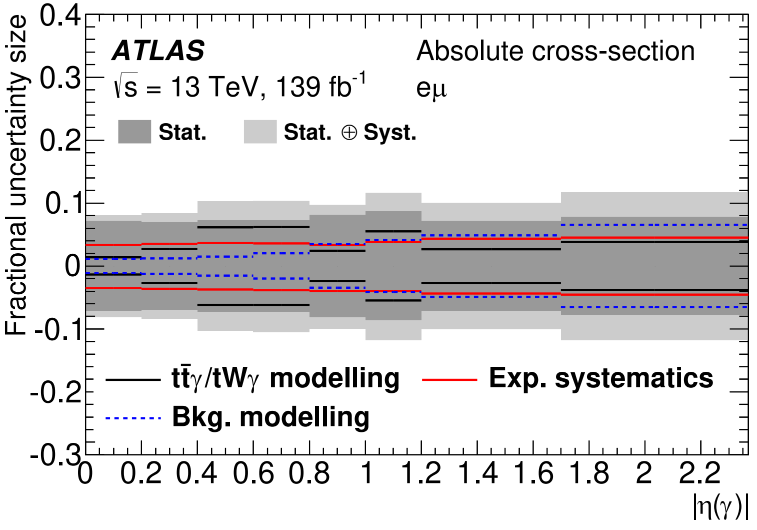


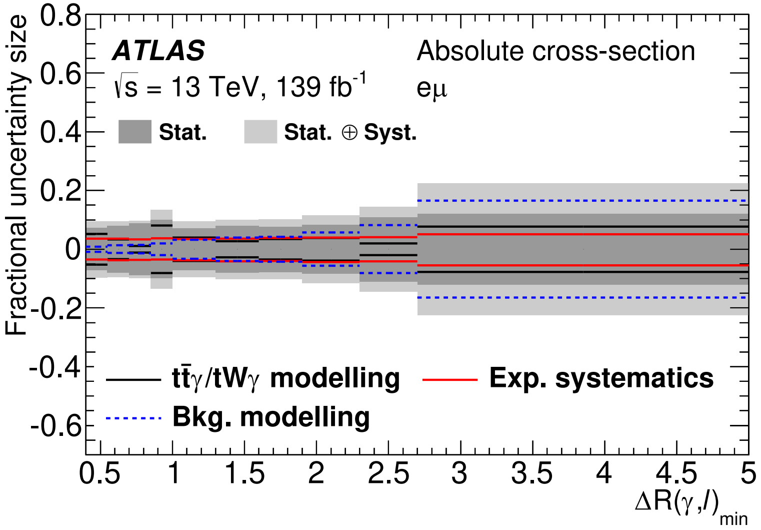
$tt\gamma$ – uncertainties on normalised cross-sections

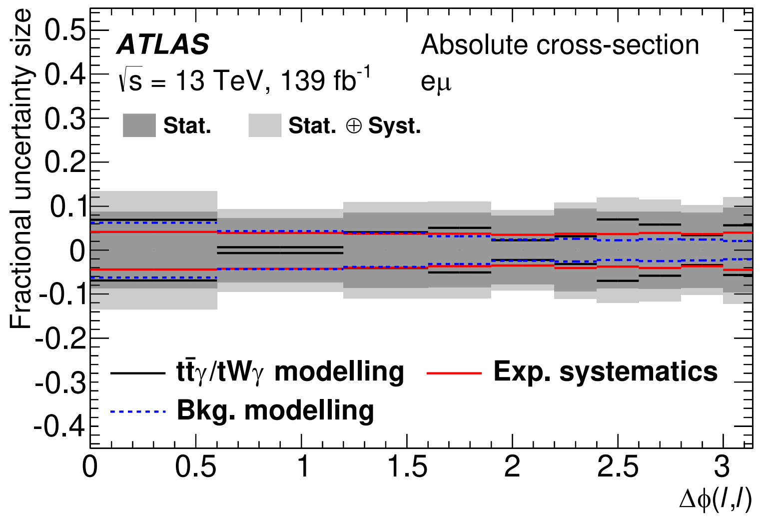


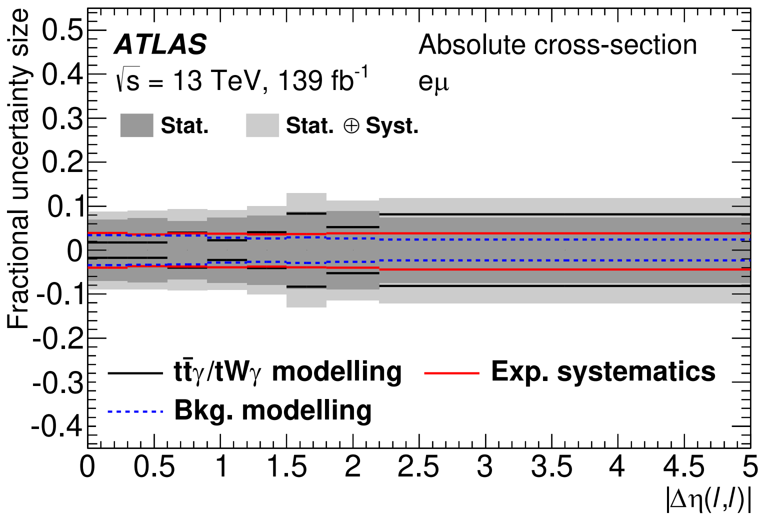
$t\bar{t}\gamma$ – uncertainties on absolute cross-sections











$tt\gamma$ – pre-fit yield table

Table 1: Event yields before the profile likelihood fit of the signal and background processes to data after the full selection. All categories are estimated from MC simulation and include correction factors for detector effects as described in Section 6. The combination of all $t\bar{t}\gamma$ and $tW\gamma$ categories is scaled to match the event yields in data. The quoted uncertainties correspond to the total statistical and systematic uncertainties (cf. Section 6) added in quadrature.

	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

$t\bar{t}\gamma$ – impact of systematic uncertainties

Table 2: Illustrative summary of the systematic uncertainties on the fiducial inclusive cross-section measurement grouped into different categories and their relative impact on the measurement (symmetrised). The categories '$t\bar{t}\gamma/tW\gamma$ modelling' and 'Background modelling' include all corresponding systematic uncertainties described in Section 6.2. The '$tW\gamma$ parton definition' uncertainty is listed separately since it does not enter the profile likelihood fit directly as described in Section 6.3. The category 'Photons' corresponds to the uncertainties related to photon identification and isolation as well as photon energy scale and resolution. 'Jets' includes the total uncertainty from the JES, JER and JVT discriminant, while the b-tagging-related uncertainties are given in a separate category ('Flavour-tagging'). The category 'Leptons' represents the uncertainties related to lepton identification, isolation and energy/momentum calibration.

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%

$t\bar{t}\gamma$ – compatibility tests for differential cross-sections

normalised cross-sections

Predictions	$p_T(\gamma)$ χ^2/ndf	$p_T(\gamma)$ p-value	$\|\eta(\gamma)\|$ χ^2/ndf	$\|\eta(\gamma)\|$ p-value	$\Delta R(\gamma,\ell)_{min}$ χ^2/ndf	$\Delta R(\gamma,\ell)_{min}$ p-value	$\Delta\phi(\ell,\ell)$ χ^2/ndf	$\Delta\phi(\ell,\ell)$ p-value	$\|\Delta\eta(\ell,\ell)\|$ χ^2/ndf	$\|\Delta\eta(\ell,\ell)\|$ 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

absolute cross-sections

Predictions	$p_T(\gamma)$ χ^2/ndf	$p_T(\gamma)$ p-value	$\|\eta(\gamma)\|$ χ^2/ndf	$\|\eta(\gamma)\|$ p-value	$\Delta R(\gamma,\ell)_{min}$ χ^2/ndf	$\Delta R(\gamma,\ell)_{min}$ p-value	$\Delta\phi(\ell,\ell)$ χ^2/ndf	$\Delta\phi(\ell,\ell)$ p-value	$\|\Delta\eta(\ell,\ell)\|$ χ^2/ndf	$\|\Delta\eta(\ell,\ell)\|$ 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

ttZ production in 3l/4l final states

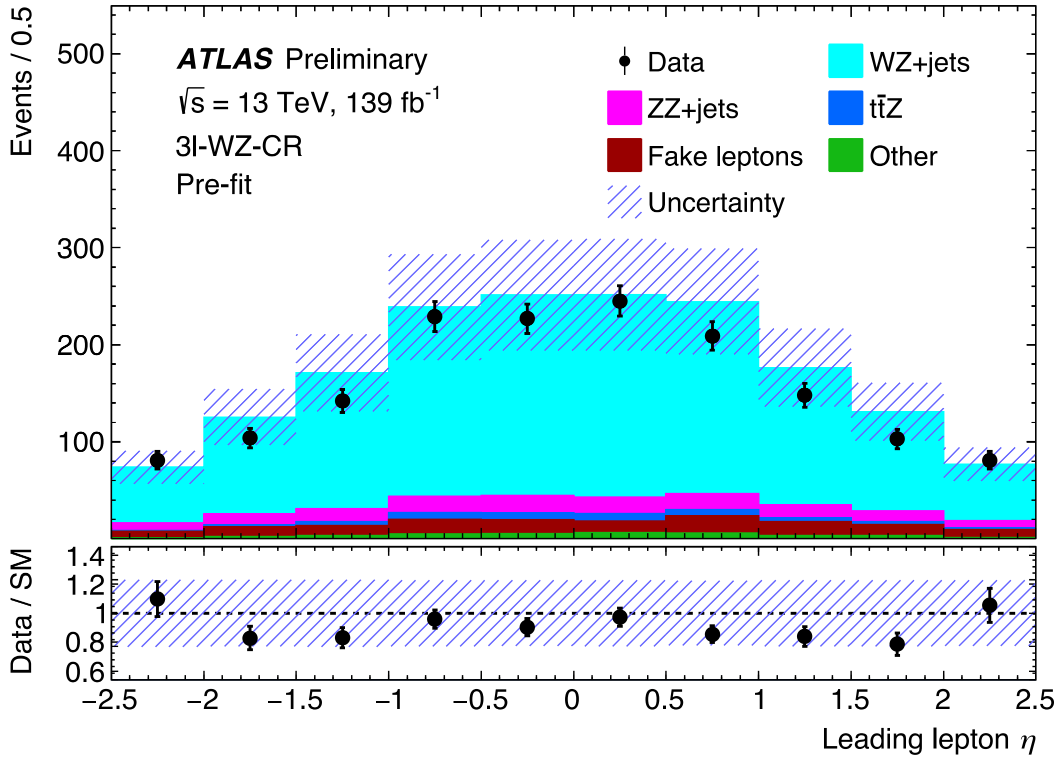
ttZ – definition of trilepton SRs

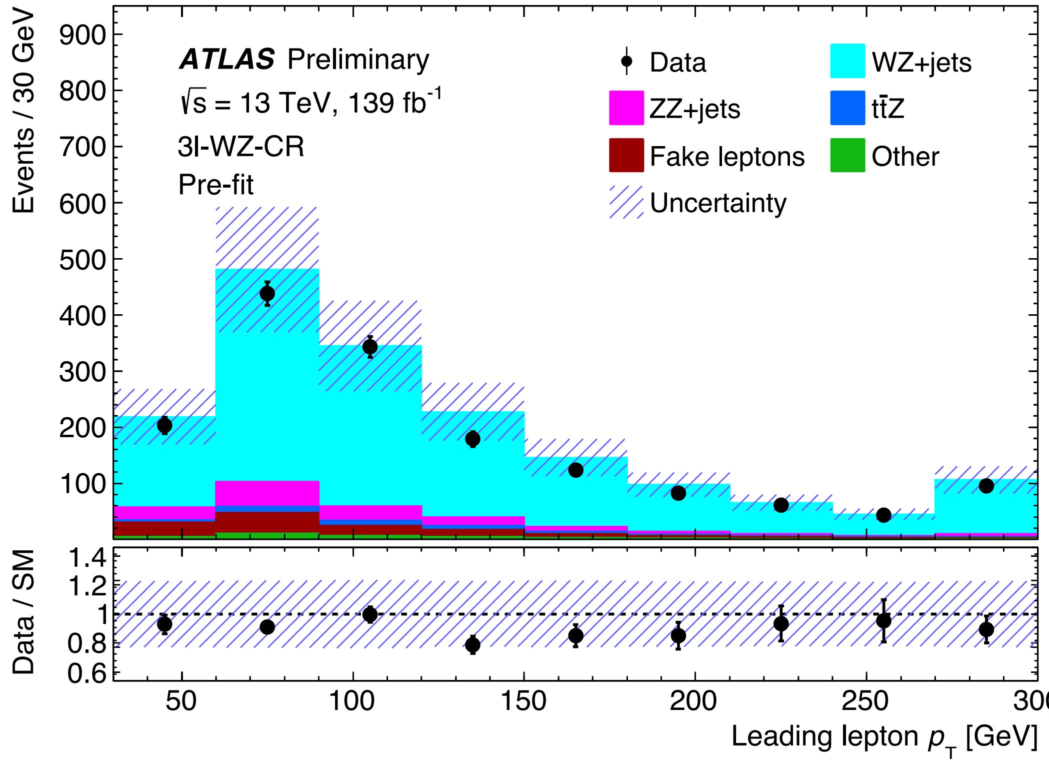
Variable	3ℓ-Z-$1b4j$-PCBT inclusive	3ℓ-Z-$2b3j$-PCBT inclusive	3ℓ-Z-$2b3j$ differential
N_ℓ ($\ell = e, \mu$)		$= 3$	
		$\geq$1 OSSF lepton pair with $\lvert m_{\ell\ell}^{Z} - m_Z \rvert < 10$ GeV	
		for all OSSF combinations: $m_{\text{OSSF}} > 10$ GeV	
p_{T} (ℓ_1, ℓ_2, ℓ_3)		$> 27,\ 20,\ 20$ GeV	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

ttZ – definition of tetralepton SRs

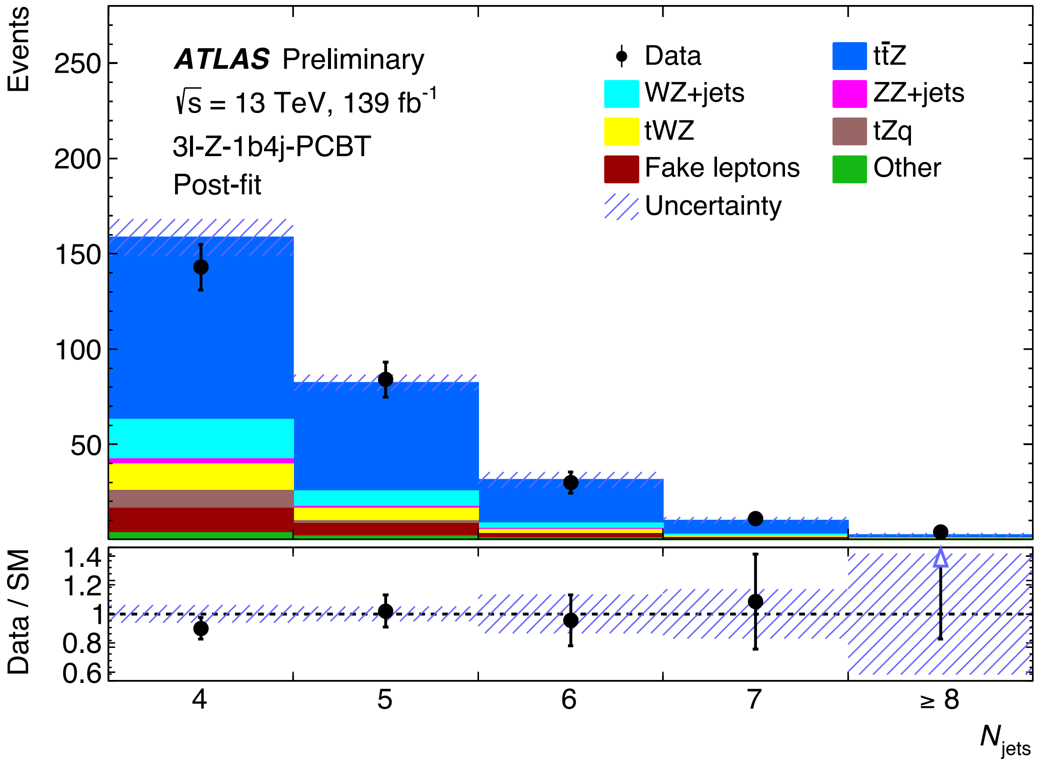
Variable	4ℓ-SF-1b	4ℓ-SF-2b	4ℓ-DF-1b	4ℓ-DF-2b
$N_{\ell}(\ell = e, \mu)$	$= 4$			
	$\geq$1 OSSF lepton pair with $\lvert m_{\ell\ell}^{Z} - m_Z \rvert < 10$ GeV			
	for all OSSF combinations: $m_{\mathrm{OSSF}} > 10$ GeV			
p_{T} $(\ell_1, \ell_2, \ell_3, \ell_4)$	$> 27, 20, 10, 7$ GeV			
$\ell\ell^{\,\mathrm{non-}Z}$	e^+e^- or $\mu^+\mu^-$	e^+e^- or $\mu^+\mu^-$	$e^{\pm}\mu^{\mp}$	$e^{\pm}\mu^{\mp}$
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 100 GeV, if $\lvert m_{\ell\ell}^{\mathrm{non-}Z} - m_Z \rvert \leq 10$ GeV	> 50 GeV, if $\lvert m_{\ell\ell}^{\mathrm{non-}Z} - m_Z \rvert \leq 10$ GeV	–	–
	> 50 GeV, if $\lvert m_{\ell\ell}^{\mathrm{non-}Z} - m_Z \rvert > 10$ GeV	–		
N_{jets}	≥ 2	≥ 2	≥ 2	≥ 2
$N_{b\mathrm{-jets}}$@85%	$= 1$	≥ 2	$= 1$	≥ 2

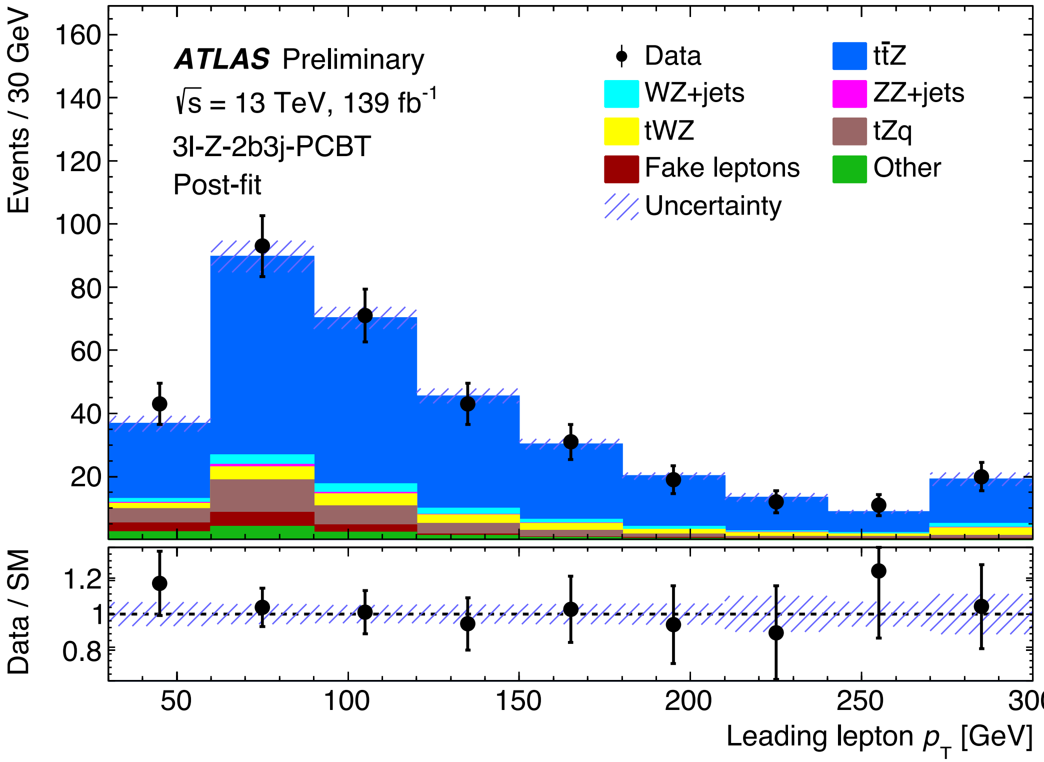
ttZ – control plots in WZ CR



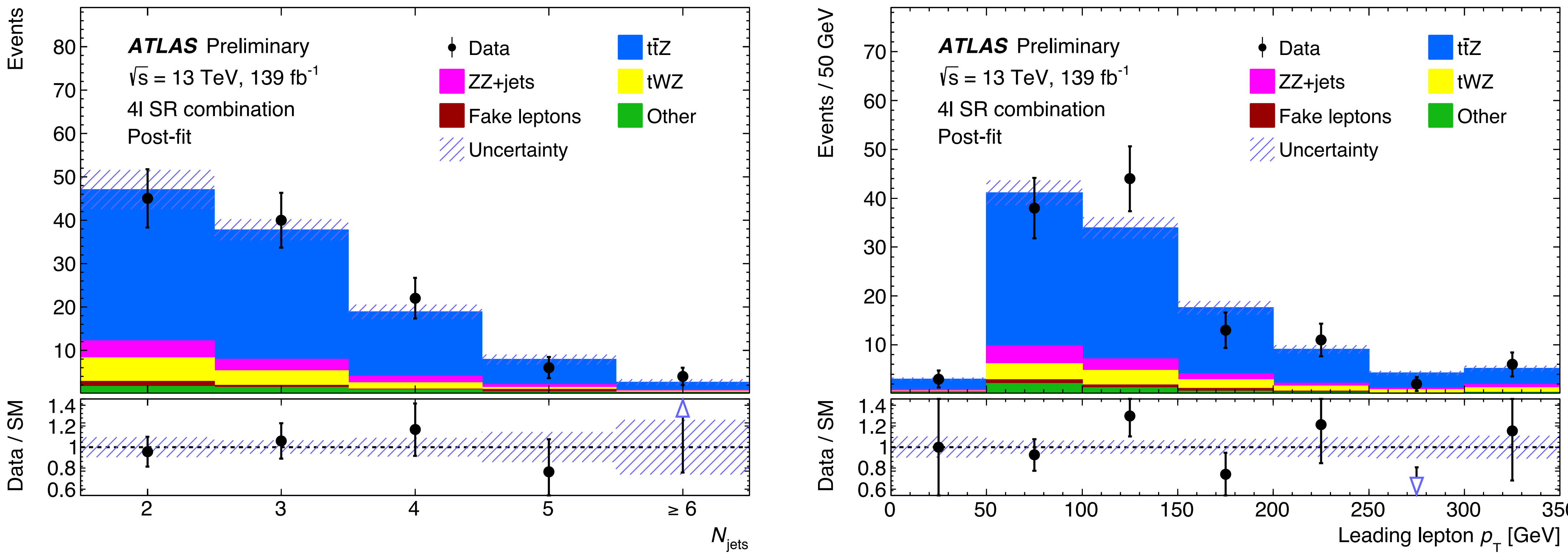


ttZ – trilepton post-fit distributions

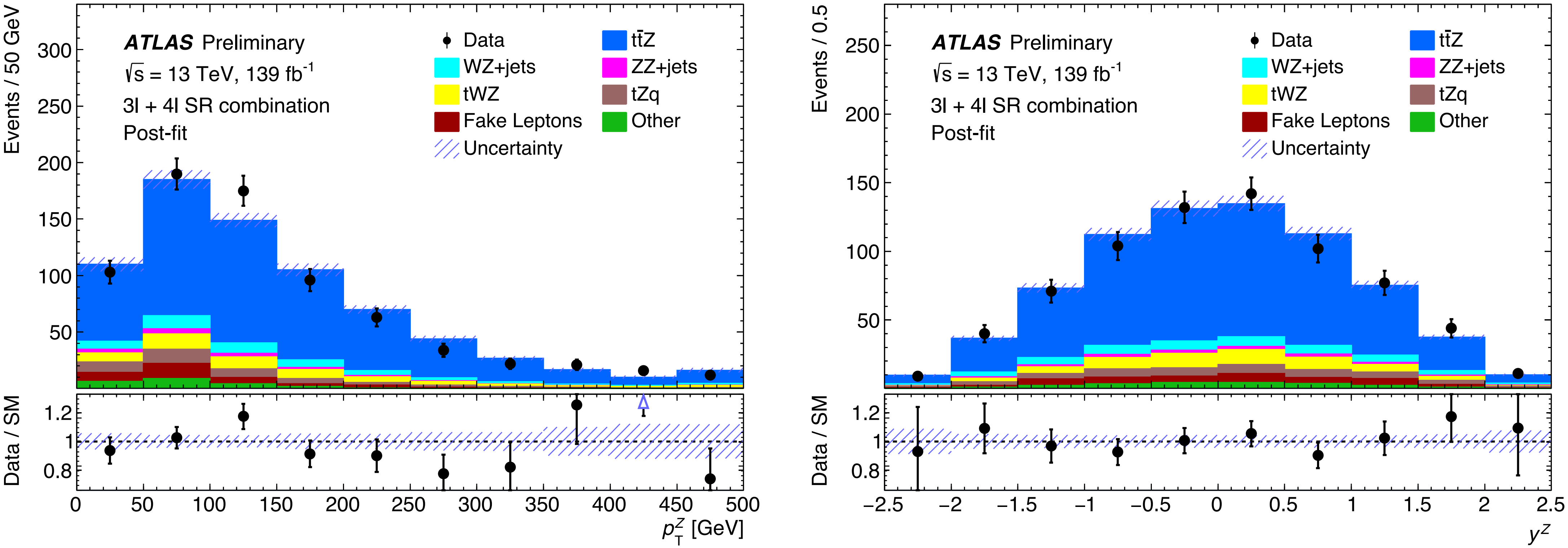




ttZ – tetralepton post-fit distributions



$t\bar{t}Z$ – combined-channel post-fit distributions



ttZ – fit results and systematic uncertainties

Fit configuration	$\mu_{t\bar{t}Z}$
Trilepton	$1.17 \pm 0.07\,(\text{stat.})\,^{+0.12}_{-0.11}\,(\text{syst.})$
Tetralepton	$1.21 \pm 0.15\,(\text{stat.})\,^{+0.11}_{-0.10}\,(\text{syst.})$
Combined	$1.19 \pm 0.06\,(\text{stat.})\,\pm 0.10\,(\text{syst.})$

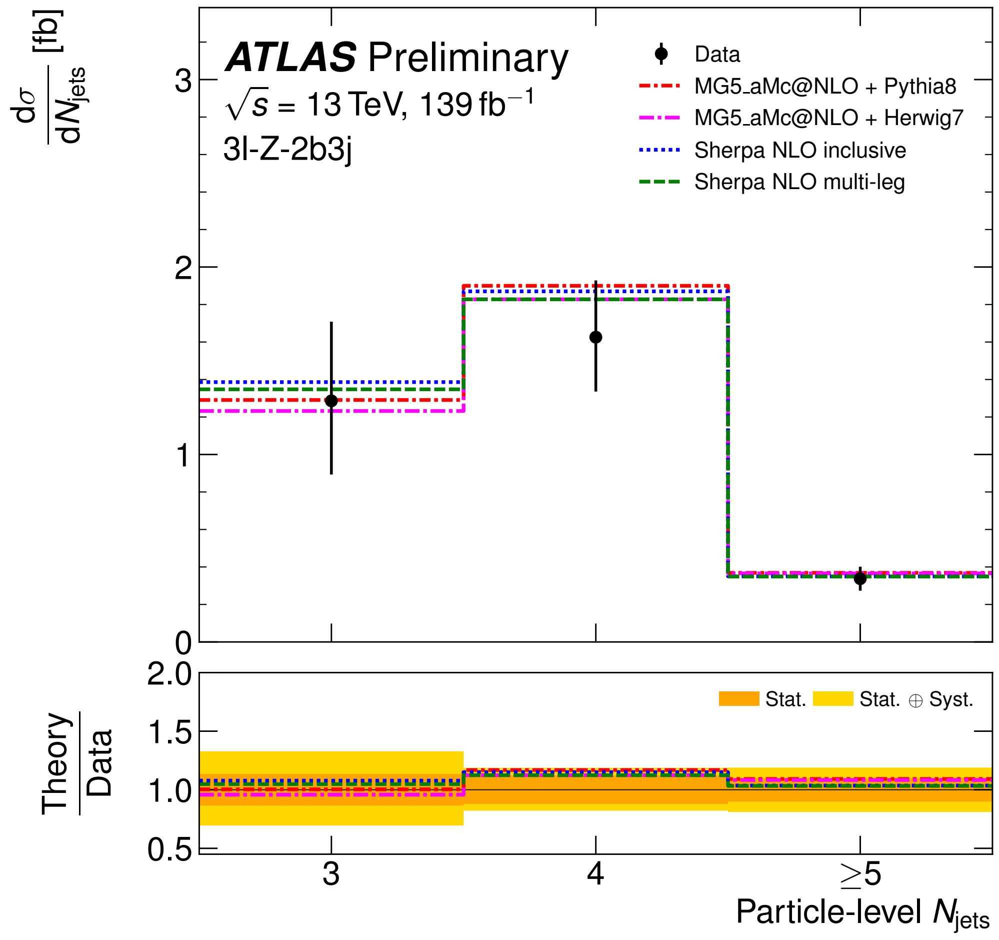
Uncertainty	$\Delta\sigma_{t\bar{t}Z}/\sigma_{t\bar{t}Z}$ [%]
$t\bar{t}Z$ parton shower	3.1
tWZ modelling	2.9
b-tagging	2.9
WZ/ZZ + jets modelling	2.8
tZq modelling	2.6
Lepton	2.3
Luminosity	2.2
Jets + $E_{\mathrm{T}}^{\mathrm{miss}}$	2.1
Non-prompt/fake leptons	2.1
$t\bar{t}Z$ A14 tune	1.6
$t\bar{t}Z$ μ_{f}, μ_{r} scales	0.9
Other backgrounds	0.7
Pile-up	0.7
$t\bar{t}Z$ PDF	0.2
Total systematics	8.4
Data statistics	5.2
Total	9.9

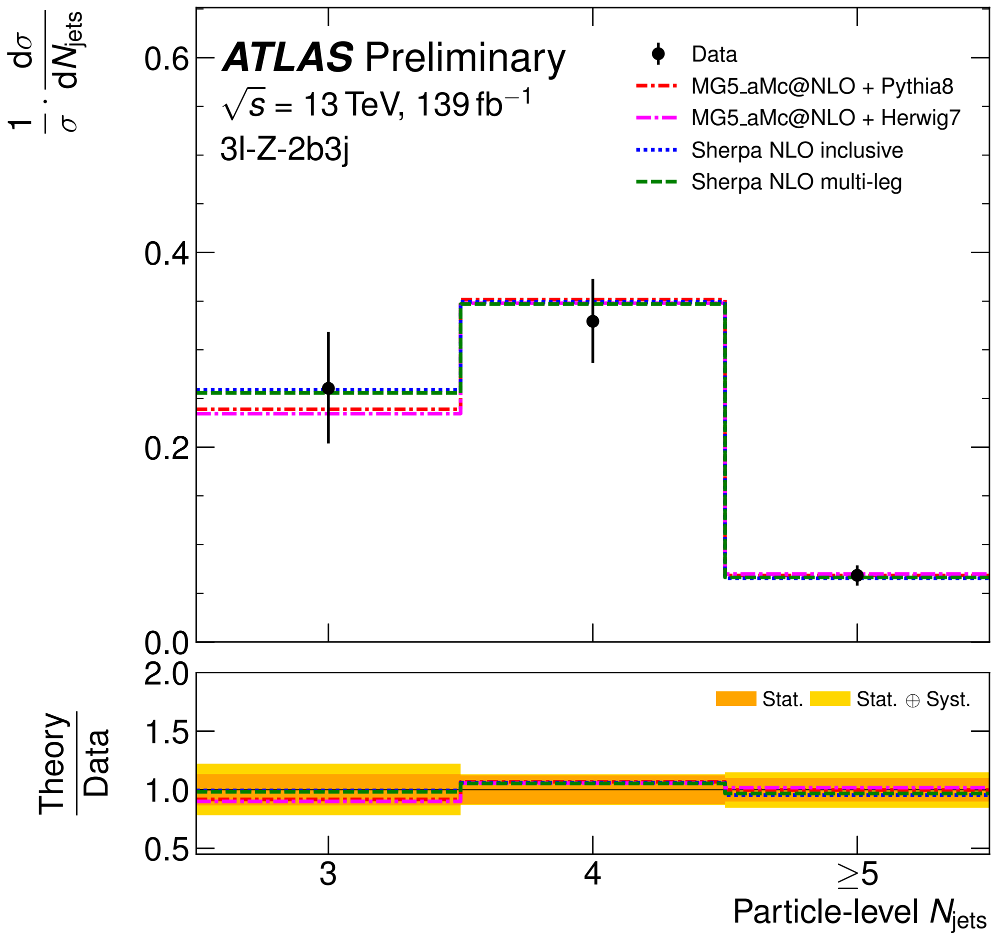
ATLAS EXPERIMENT

ttZ – unfolding variables

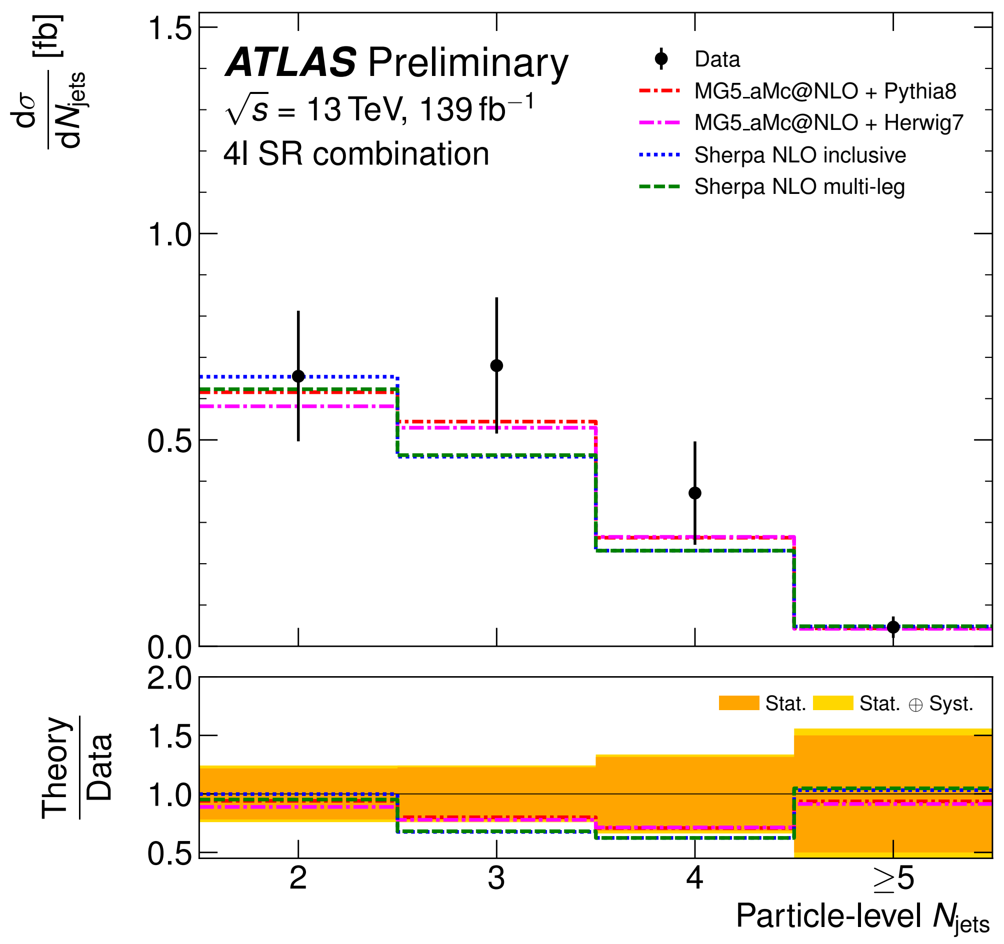
	Variable	Definition
$3\ell + 4\ell$	p_{T}^{Z}	Transverse momentum of the Z boson
	$\|y^{Z}\|$	Absolute value of the rapidity of the Z boson
3ℓ	N_{jets}	Number of selected jets with $p_{\mathrm{T}} > 25$ GeV and $\|\eta\| < 2.5$
	$p_{\mathrm{T}}^{\ell,\mathrm{non}-Z}$	Transverse momentum of the lepton which is not associated with the Z boson
	$\|\Delta\phi(Z, t_{\mathrm{lep}})\|$	Azimuthal separation between the Z boson and the top quark (antiquark) featuring the $W \to \ell\nu$ decay
	$\|\Delta y(Z, t_{\mathrm{lep}})\|$	Absolute rapidity difference between the Z boson and the top quark (antiquark) featuring the $W \to \ell\nu$ decay
4ℓ	N_{jets}	Number of selected jets with $p_{\mathrm{T}} > 25$ GeV and $\|\eta\| < 2.5$
	$\|\Delta\phi(\ell_t^+, \ell_{\bar{t}}^-)\|$	Azimuthal separation between the two leptons from the $t\bar{t}$ system
	$\|\Delta\phi(t\bar{t}, Z)\|$	Azimuthal separation between the Z boson and the $t\bar{t}$ system
	$p_{\mathrm{T}}^{t\bar{t}}$	Transverse momentum of the $t\bar{t}$ system

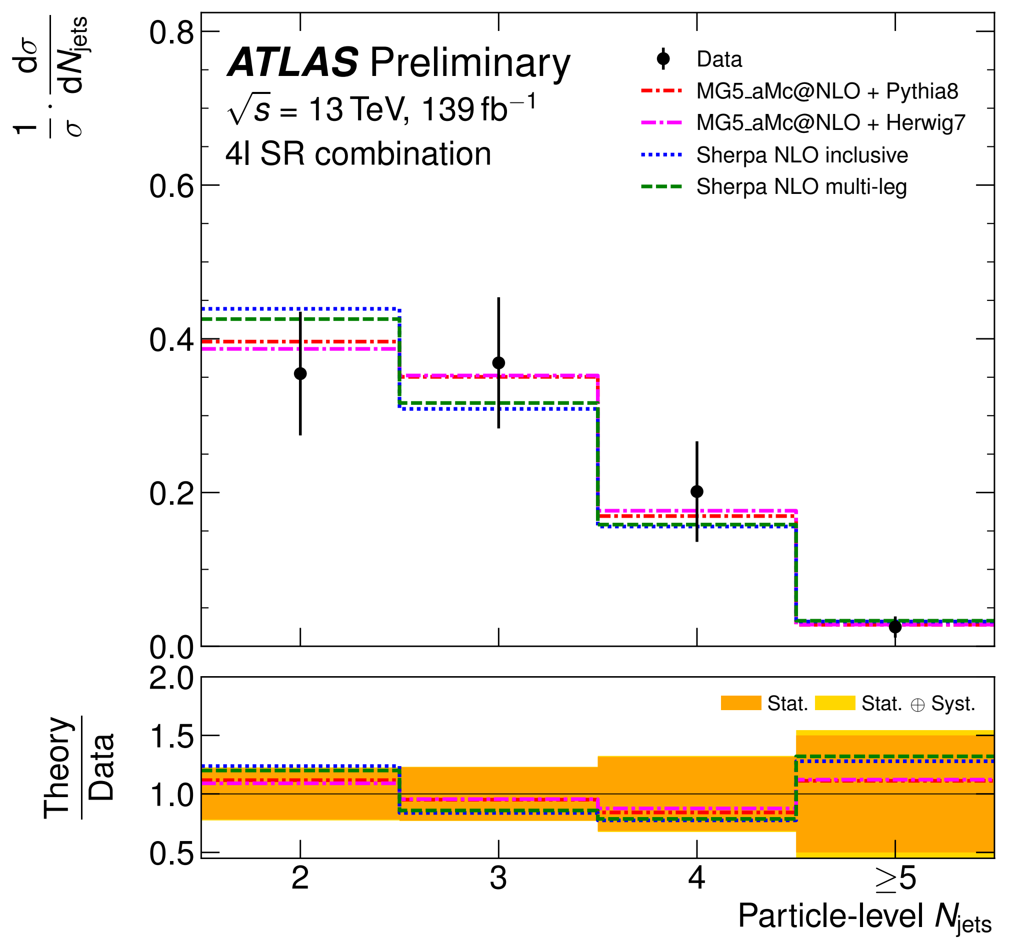
ttZ – unfolded number of jets (3l)



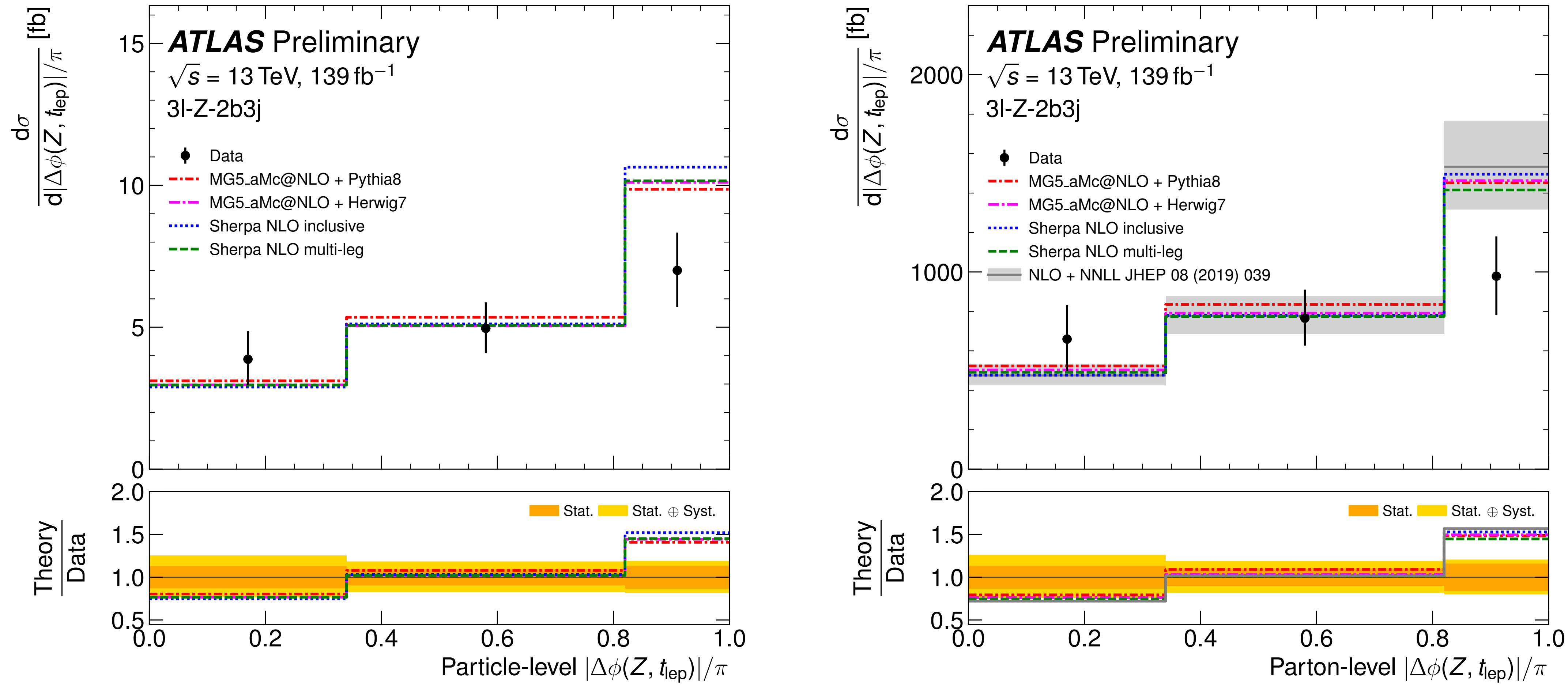


ttZ – unfolded number of jets (4l)

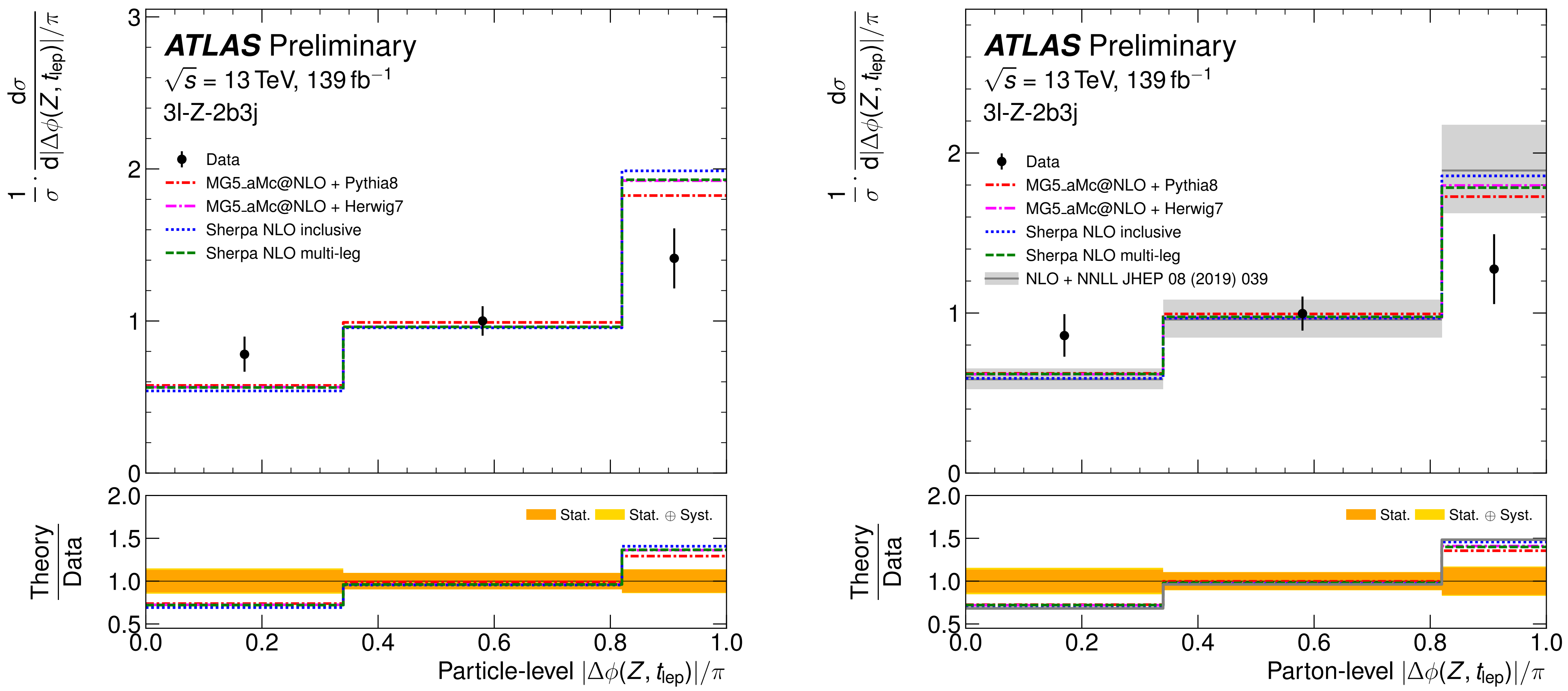




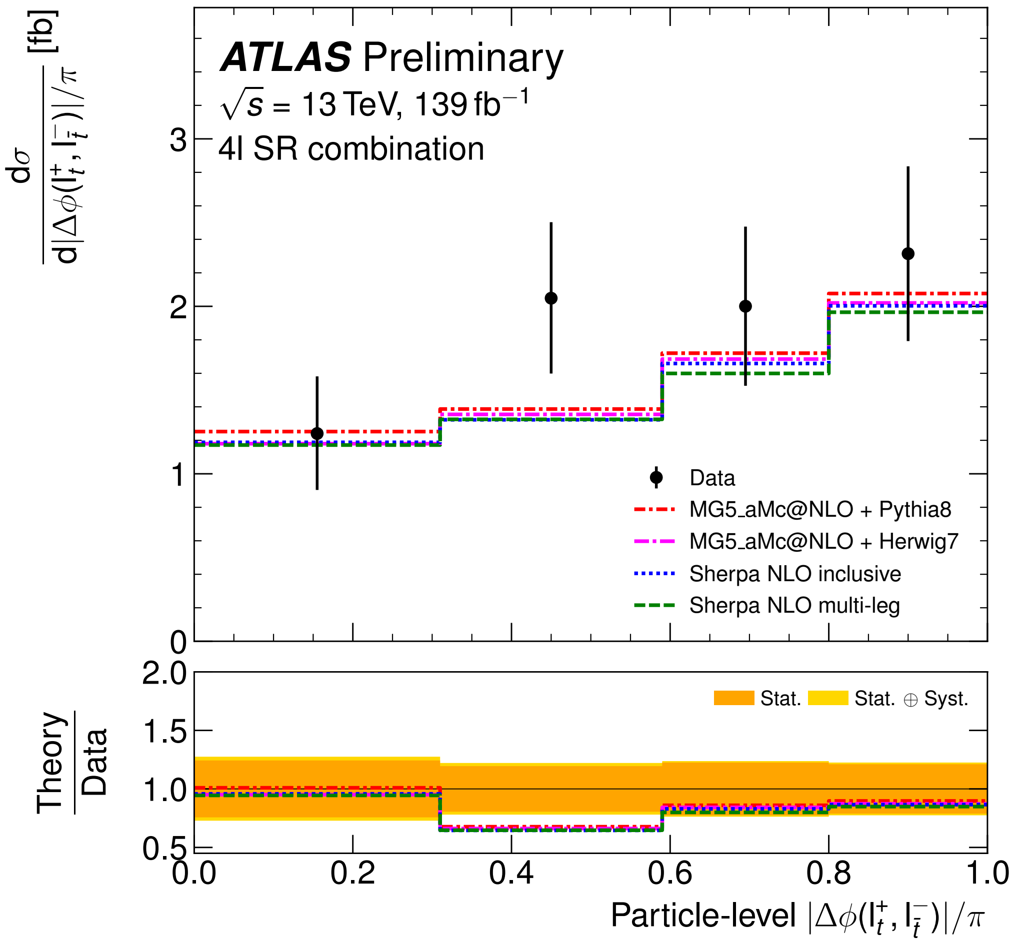
ttZ – unfolded absolute distributions (3l)

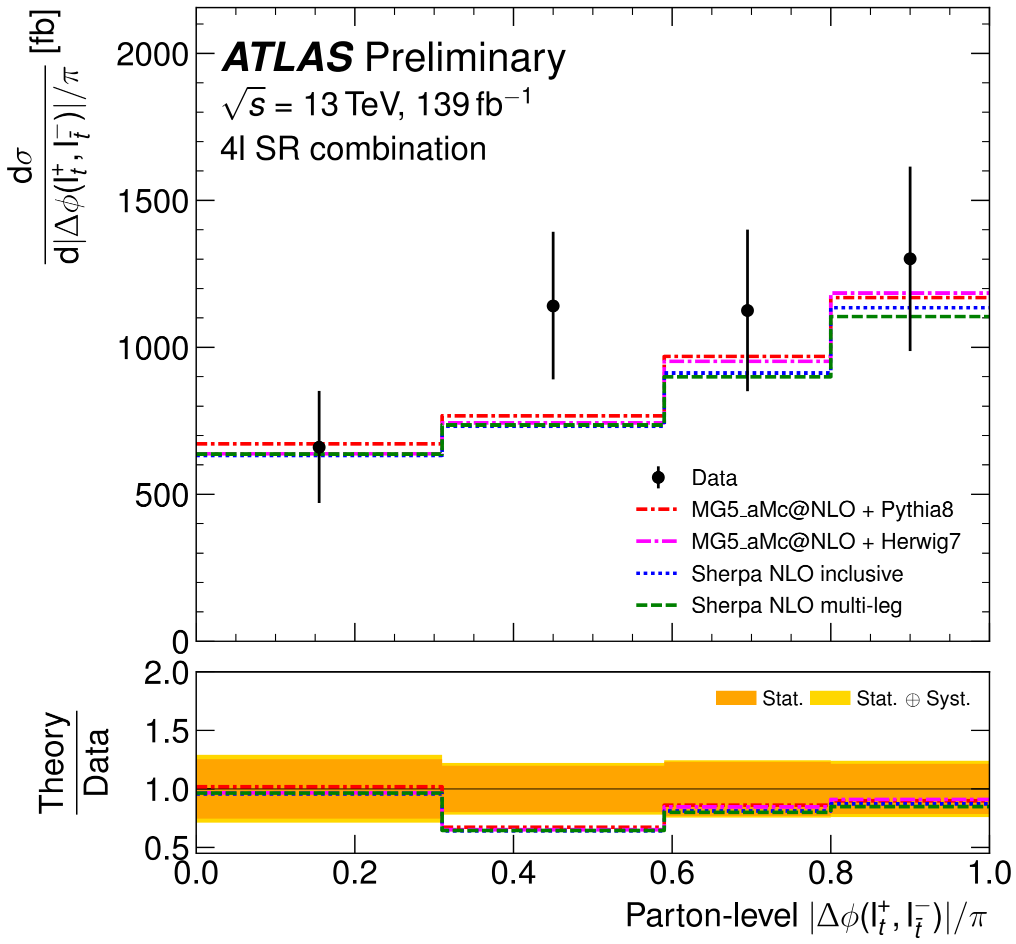


ttZ – unfolded normalised distributions (3l)

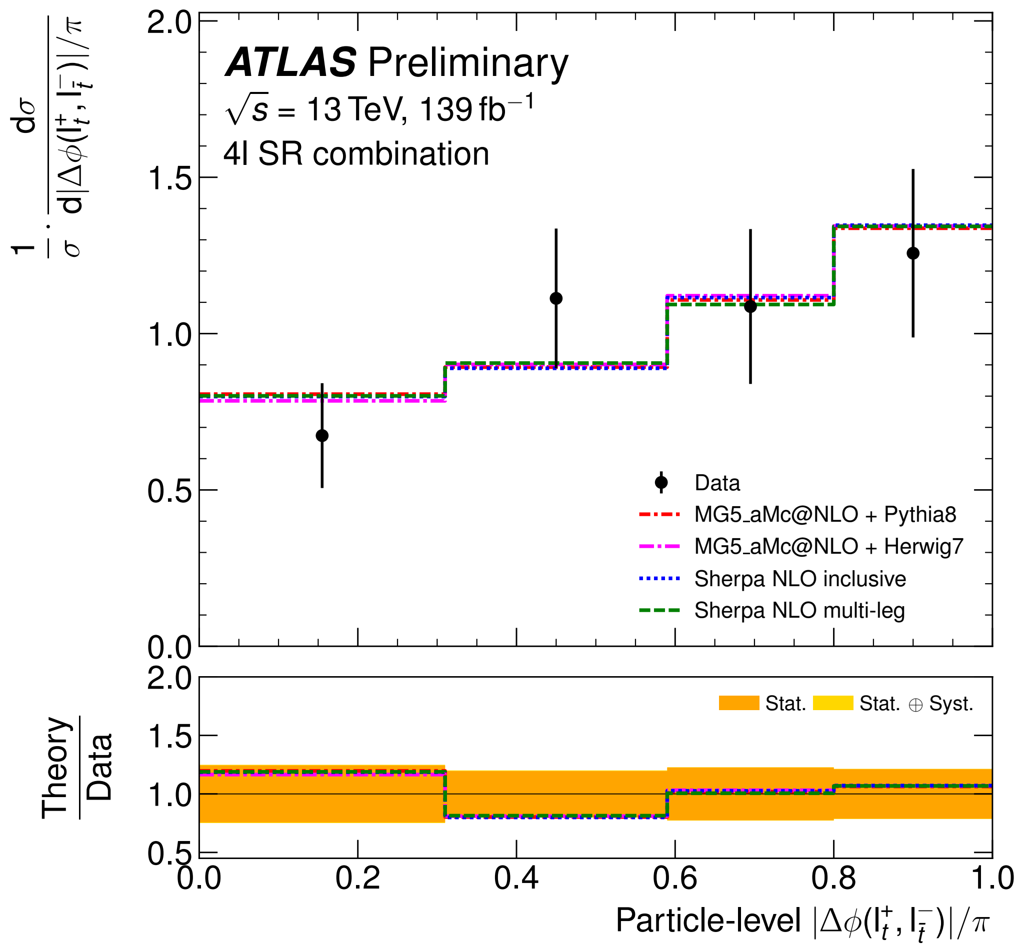


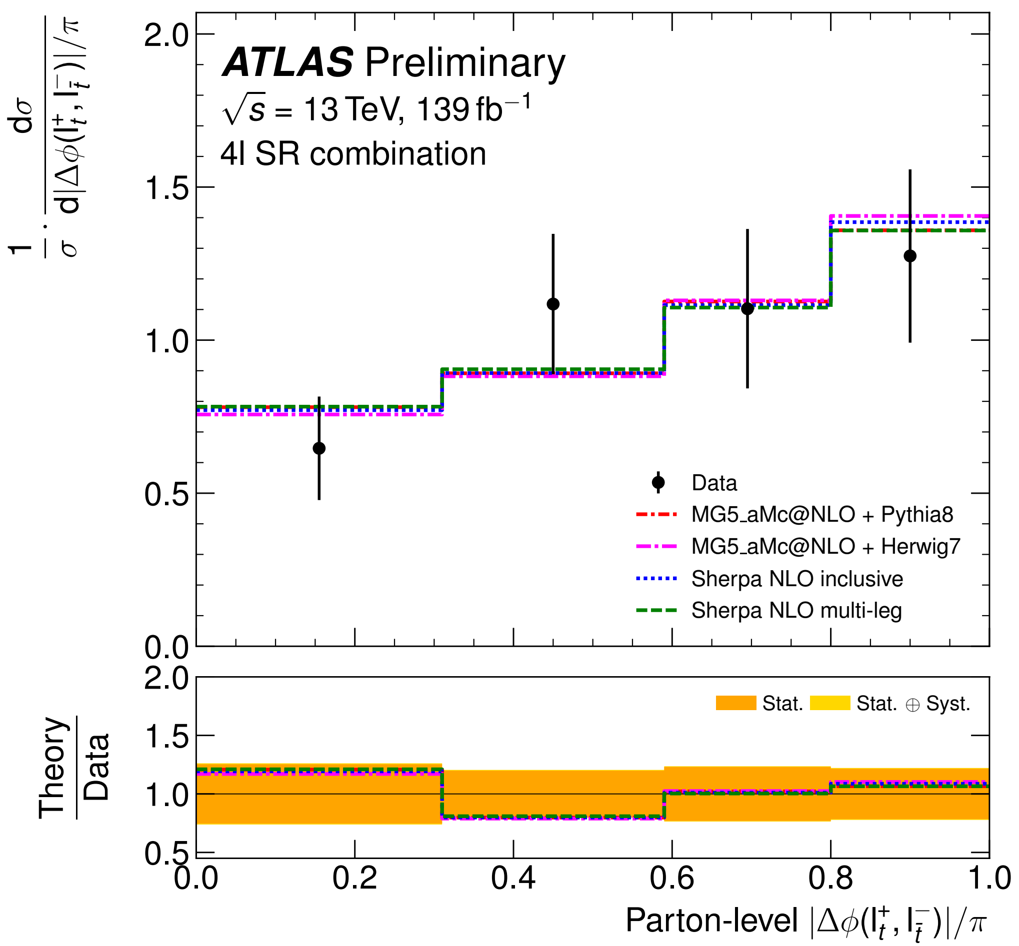
ttZ – unfolded absolute distributions (4l)



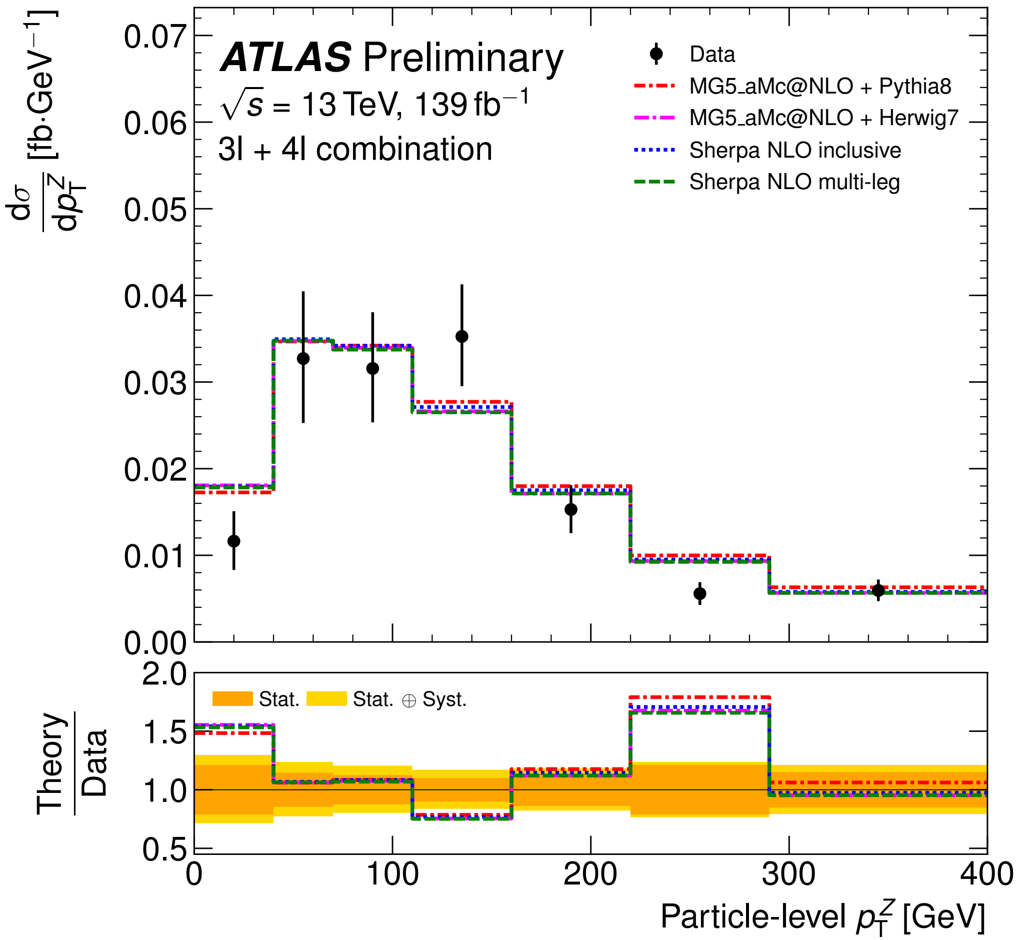


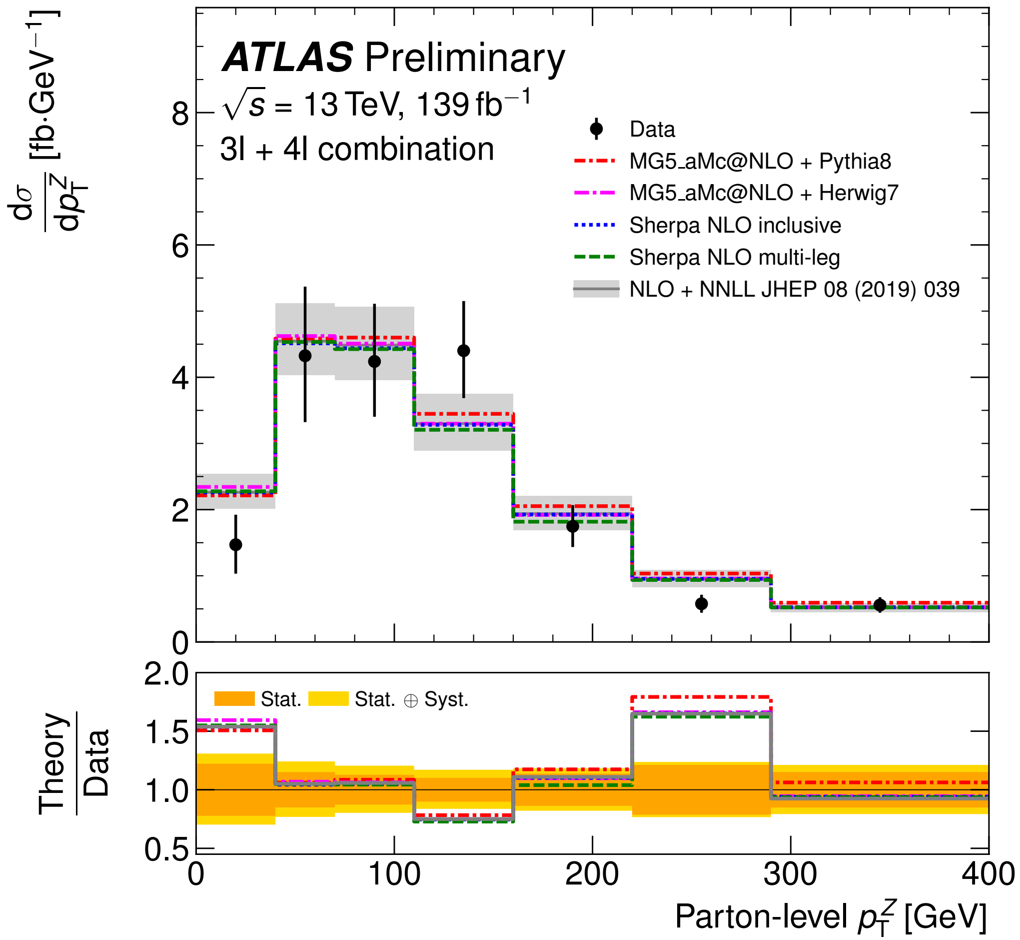
ttZ – unfolded normalised distributions (4l)



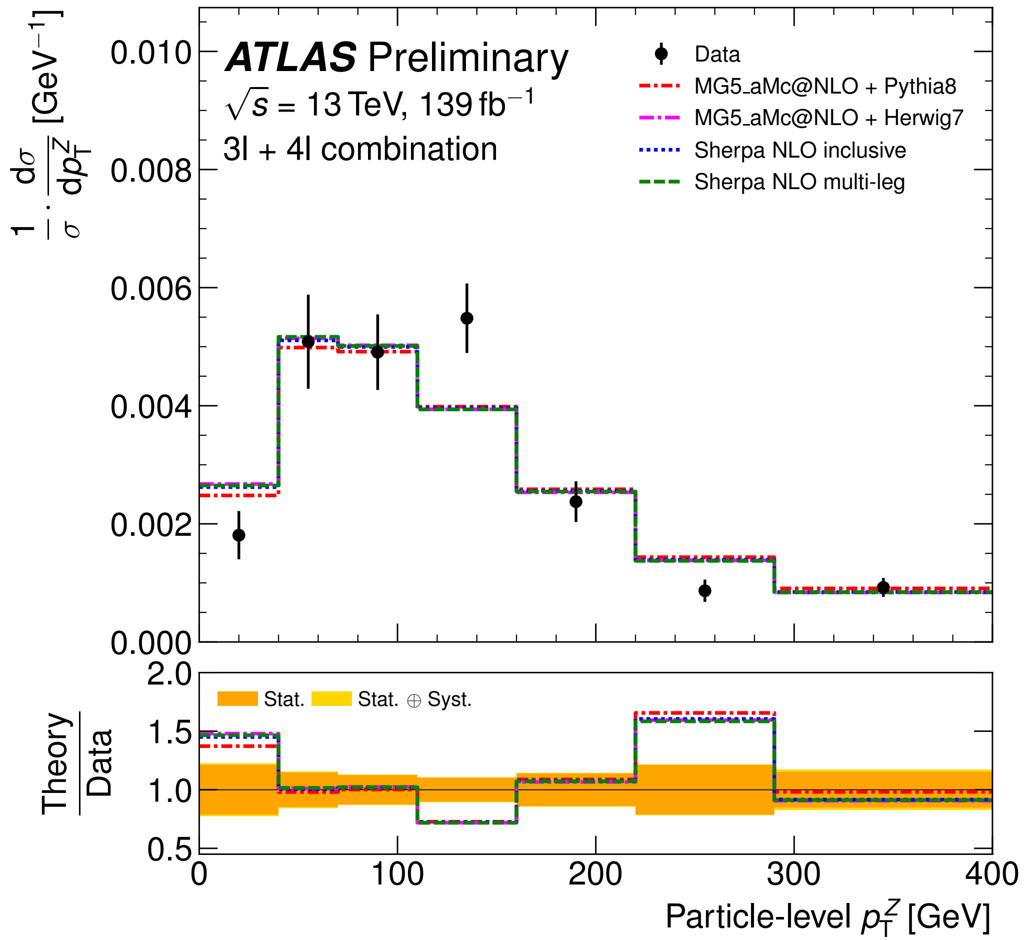


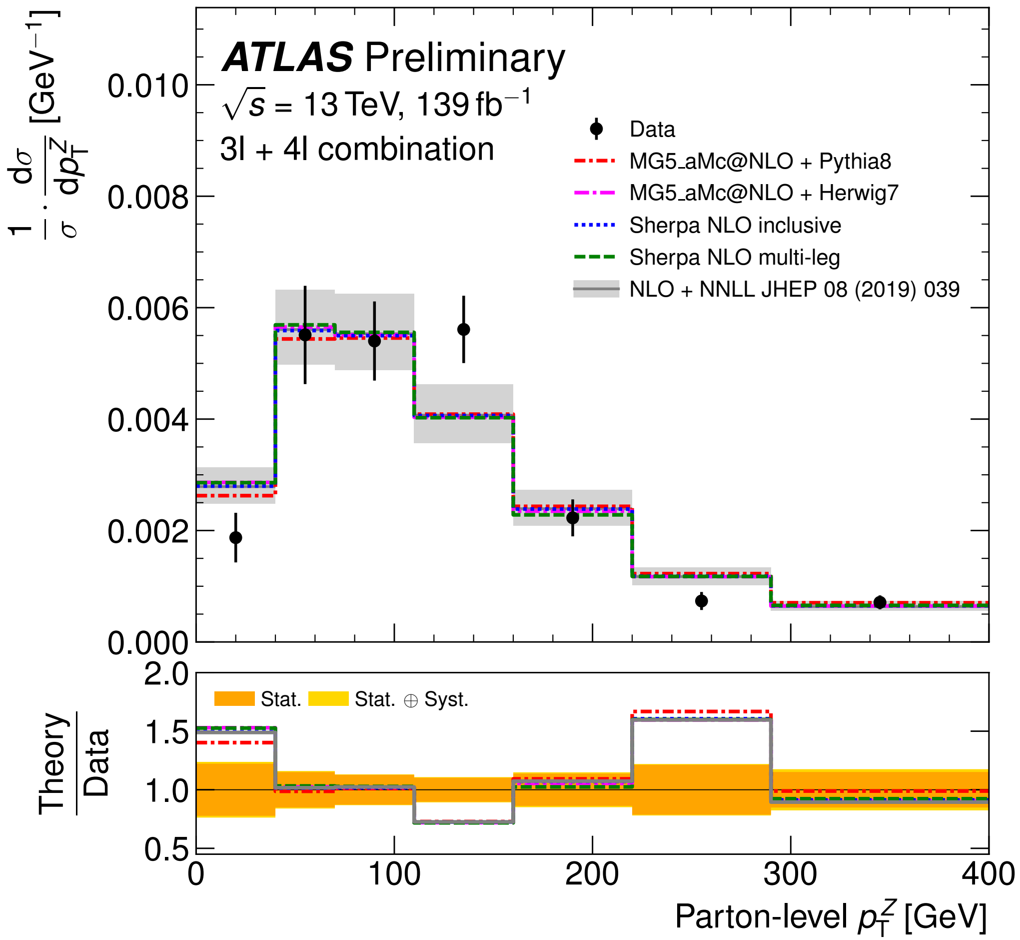
$t\bar{t}Z$ – channel combination (absolute)





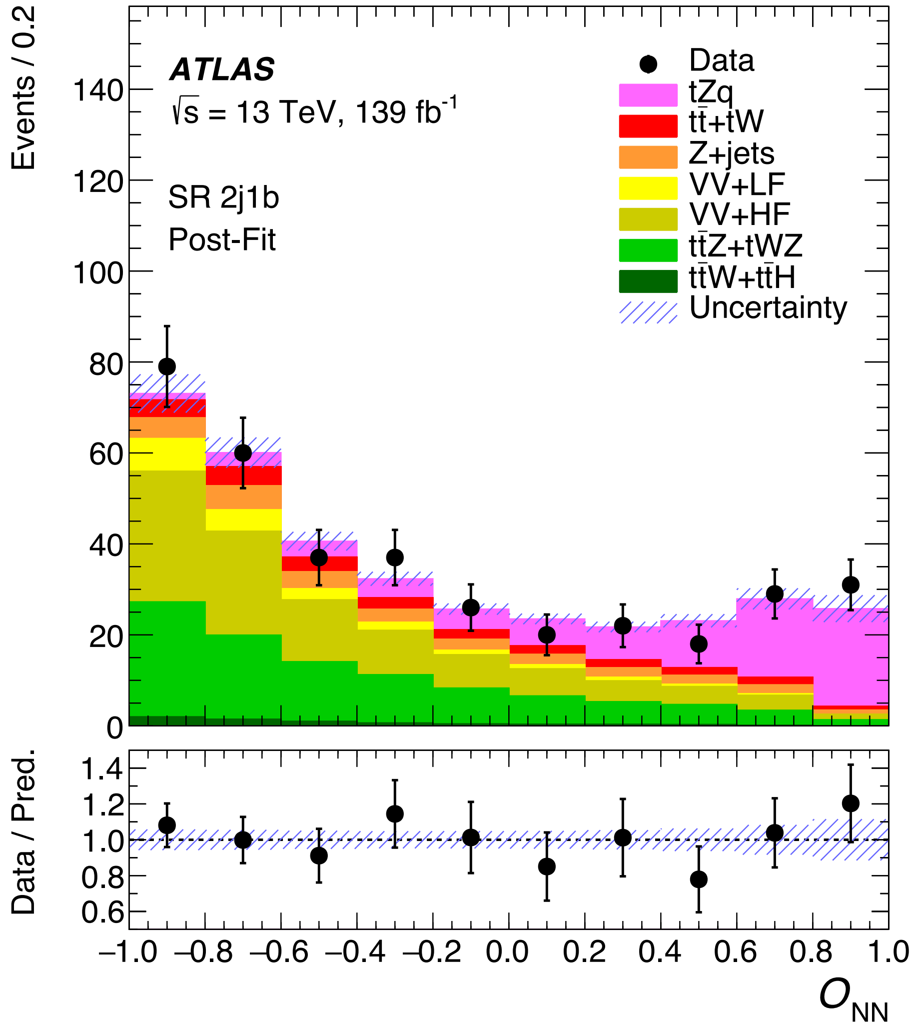
ttZ – channel combination (normalised)

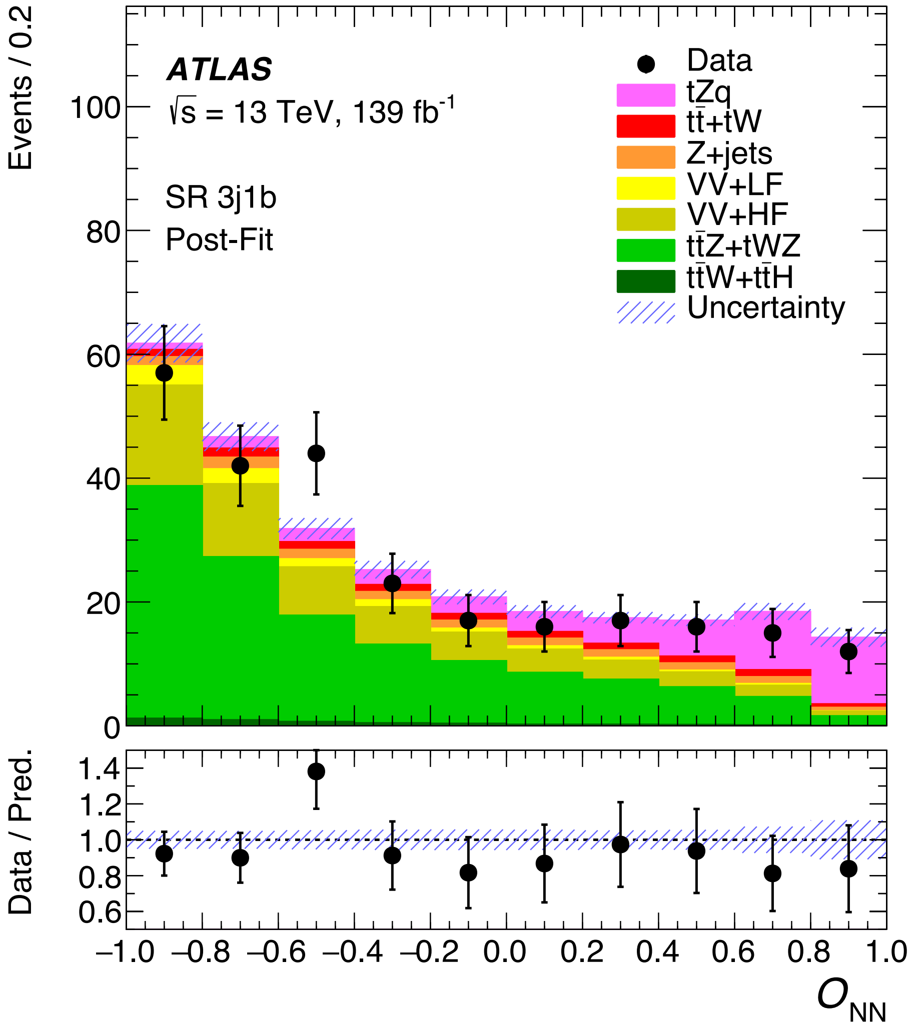




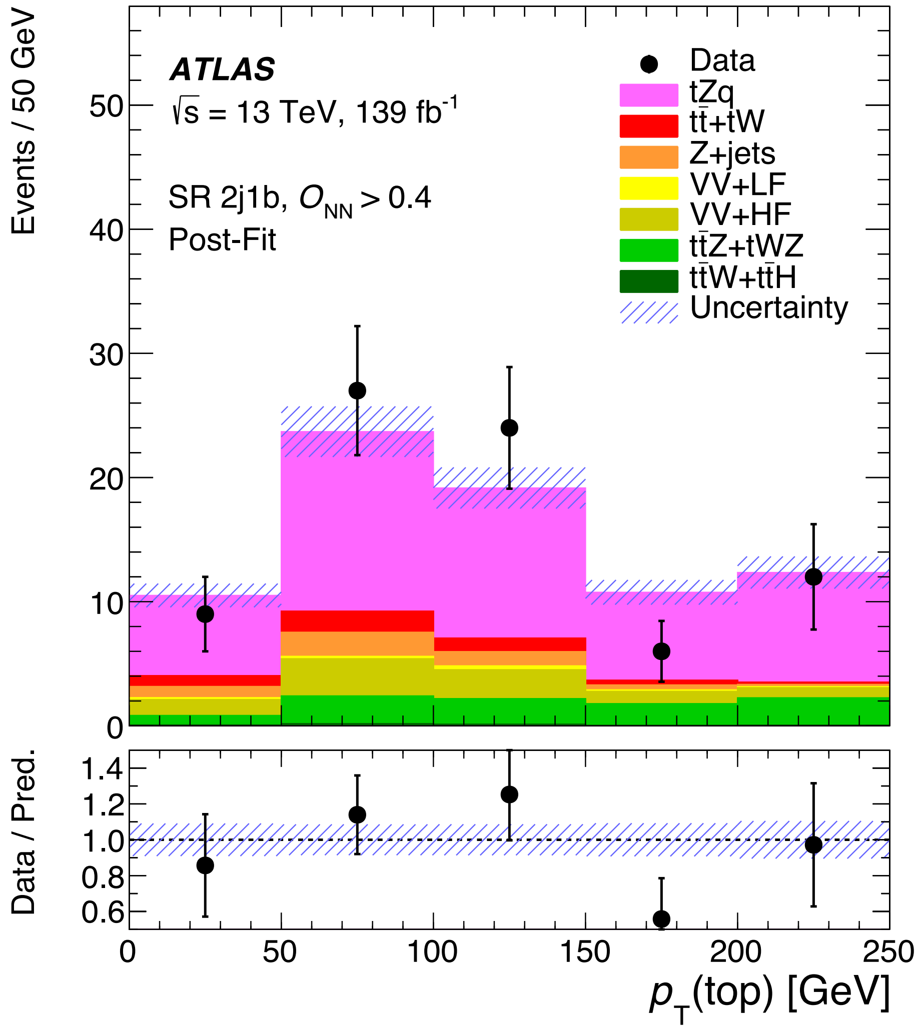
Observation of tZq production

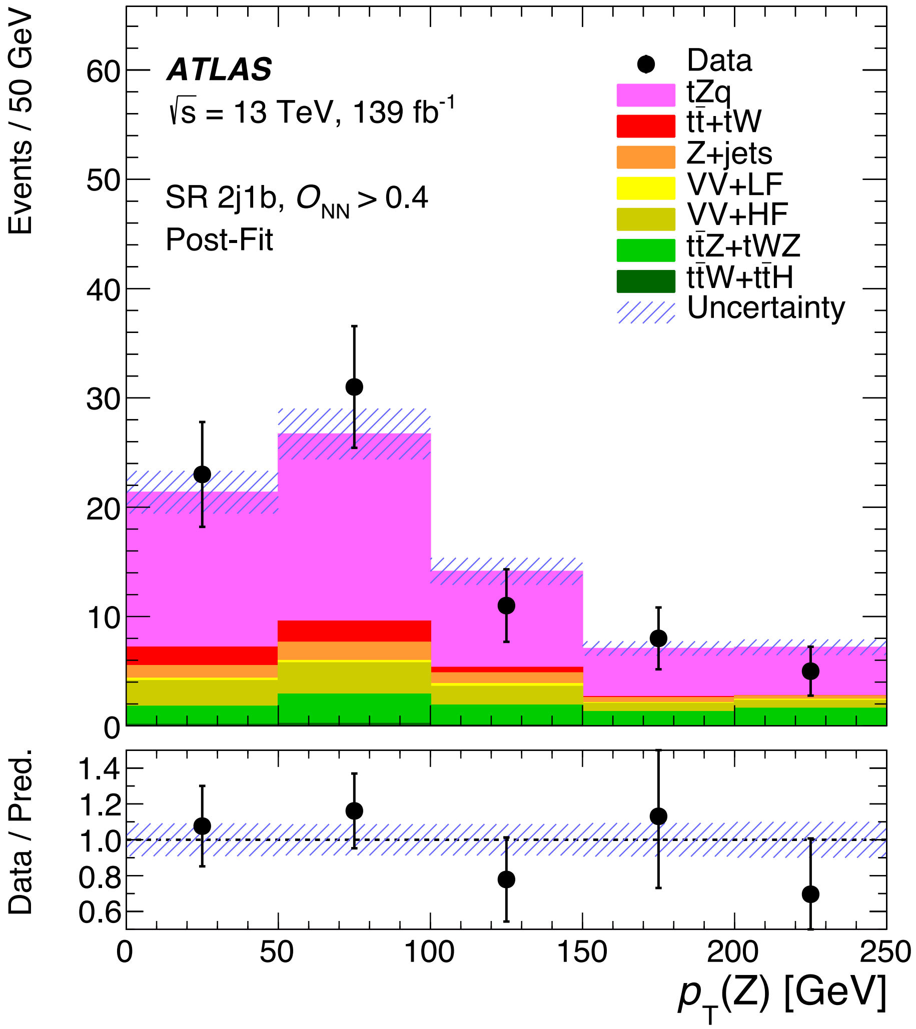
tZq – NN output distribution in SRs



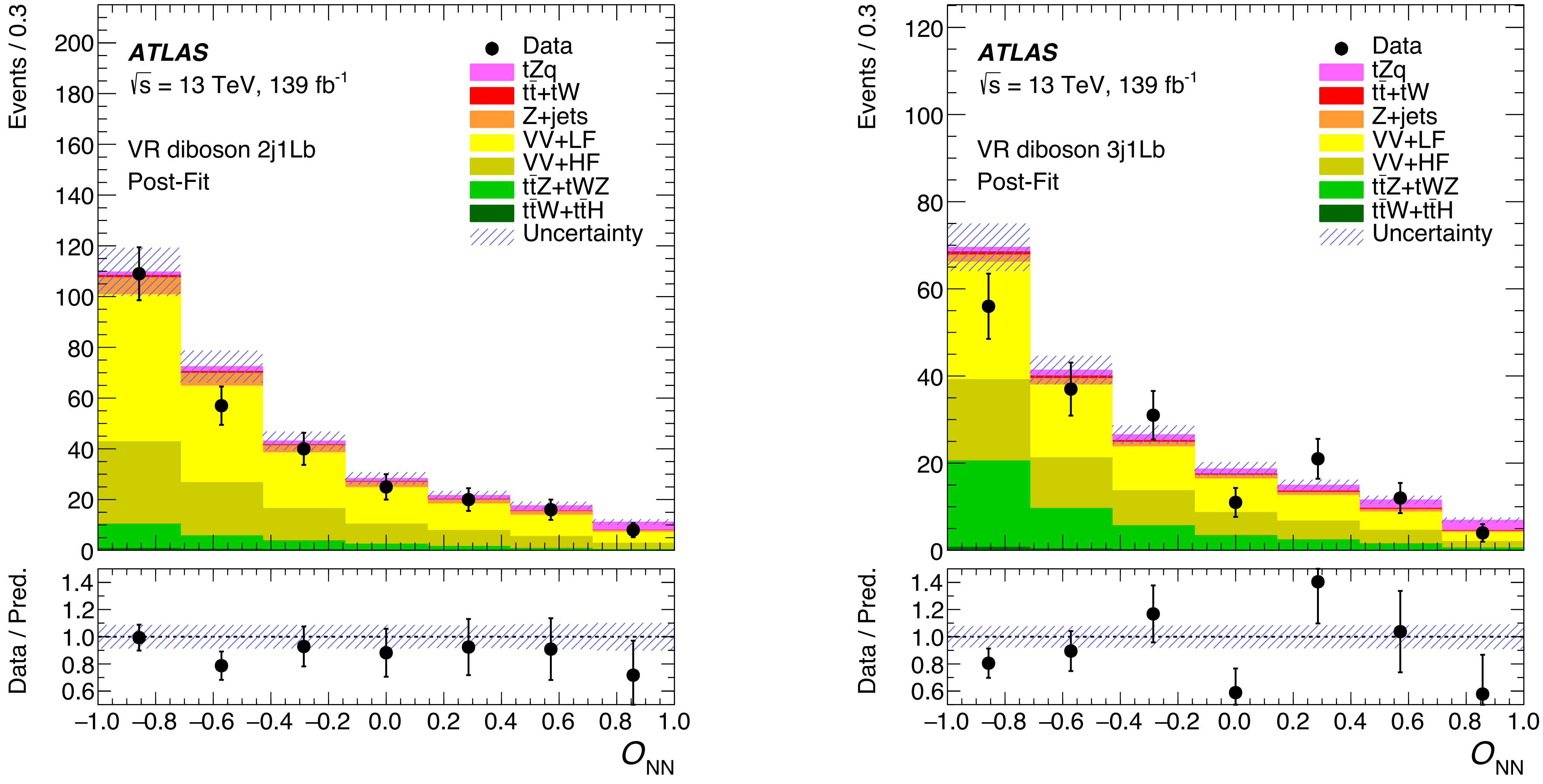


tZq – post-fit control plots with cut on NN

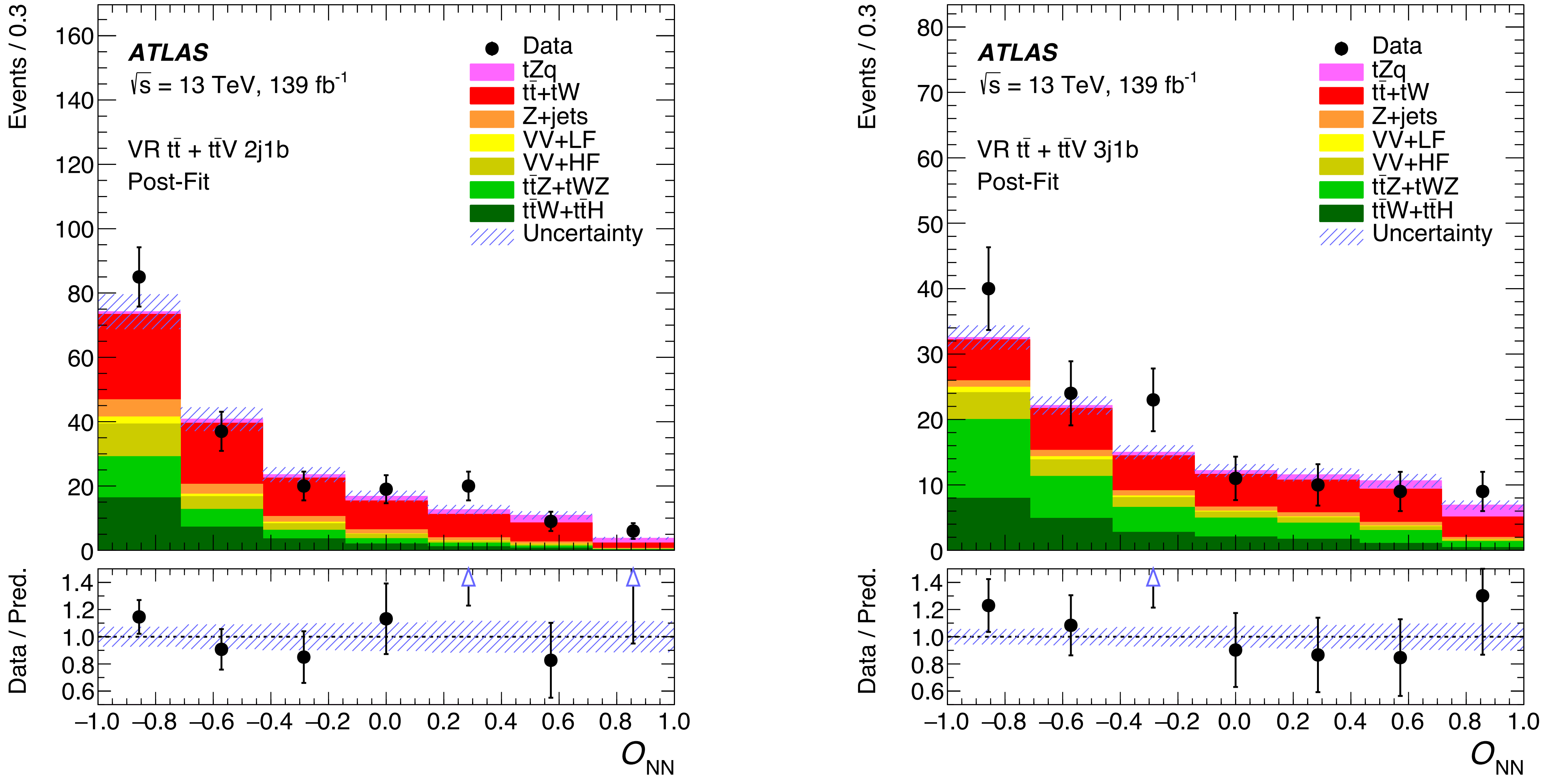




tZq – NN output distribution in CRs (1)



tZq – NN output distribution in CRs (2)



tZq – definition of signal and control regions

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

tZq – ranking of variables in NNs

Variable	Rank SR 2j1b	Rank SR 3j1b	Definition
$m_{b\mathrm{j_f}}$	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 yields in signal and control regions

	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 – impact of systematic uncertainties

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 statistical	12.6
$t\bar{t}$ and $Z+$jets normalisation	2.1
Total statistical uncertainty	12.9