Measurements of the inclusive and differential production cross sections of a top-quark–antiquark pair in association with a Z boson at $\sqrt{s} = 13$ TeV with the ATLAS detector

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Introduction

Motivation:

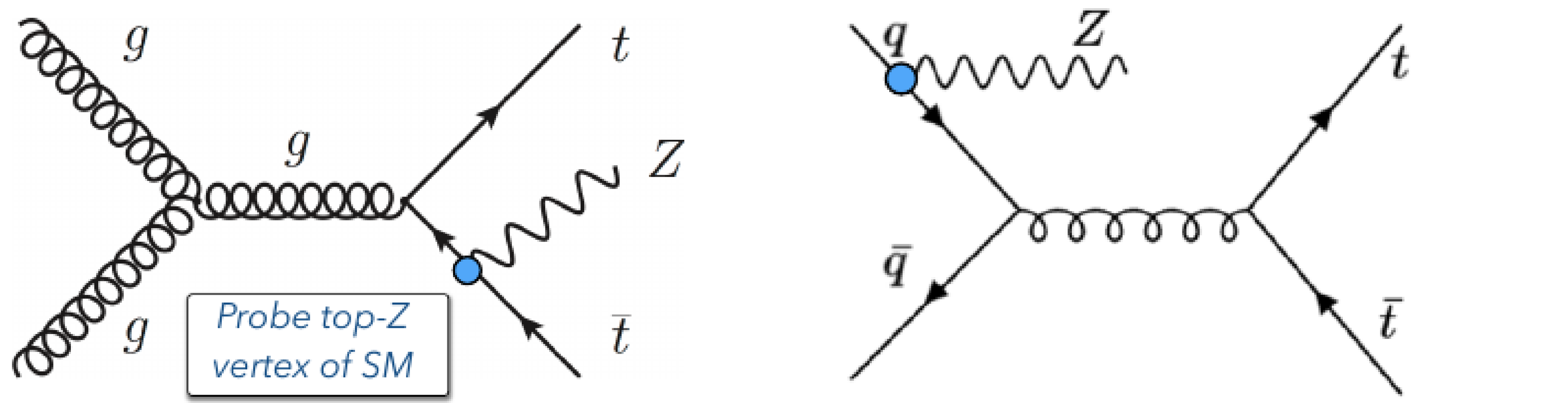
- First measurement of $t\bar{t}Z$ cross section using full Run 2 data with $\mathcal{L} = 139$ fb^{-1} [1]
- $t\bar{t}Z$ production directly probes the $t - Z$ coupling – internal consistency of the Standard Model (SM) + possible hints of a new physics beyond SM (BSM)
- Differential cross sections can offer sensitivity to differences among the various Monte Carlo (MC) predictions
- $t\bar{t}Z$ is an irreducible background in several searches for BSM phenomena and important SM processes

Production mechanism:

- $t\bar{t}$ pair production associated by Z boson from either initial or final state radiation
- Very rare SM process; most precise theoretical prediction at NLO+NNLL in QCD and EW [2]

$$\sigma^{\text{theo.}}_{\mathbf{ttZ}} = \mathbf{0.86^{+0.07}_{-0.08}(scale) \pm 0.03(pdf{+}\alpha_S)\ pb} \qquad (1)$$

- Representative LO feynman diagrams:



Definition of the signal regions

- Measurements focused on two most sensitive **multi-lepton** channels:
  - **3ℓ** $[Z \to \ell^-\ell^+,\ t\bar{t} \to \ell\nu_\ell jjjj]$
  - **4ℓ** $[Z \to \ell^-\ell^+,\ t\bar{t} \to \ell^-\bar{\nu}_\ell\ell^+\nu_\ell jj]$

3ℓ signal regions:

Variable	3ℓ-Z-1b4j-PCBT inclusive	3ℓ-Z-2b3j-PCBT inclusive	3ℓ-Z-2b3j differential
N_ℓ ($\ell = e, \mu$)	= 3		
	≥1 opposite-sign-same-flavour (OSSF) lepton pair with $\lvert m^Z_{\ell\ell} - m_Z\rvert < 10$ GeV		
	for all OSSF combinations: $m_{\text{OSSF}} > 10$ GeV		
$p_T(\ell_1, \ell_2, \ell_3)$	> 27, 20, 20 GeV		
N_{jets}	≥ 4	≥ 3	≥ 3
$N_{b-\text{jets}}$	= 1@60%	≥ 2@70%	≥ 2@85%
	veto add. b-jets@70%		

4ℓ signal regions:

Variable	4ℓ-SF-1b	4ℓ-SF-2b	4ℓ-DF-1b	4ℓ-DF-2b
$N_\ell(\ell = e, \mu)$	= 4			
	≥1 OSSF lepton pair with $\lvert m^Z_{\ell\ell} - m_Z\rvert < 10$ GeV			
	for all OSSF combinations: $m_{\text{OSSF}} > 10$ GeV			
$p_T(\ell_1, \ell_2, \ell_3, \ell_4)$	> 27, 20, 10, 7 GeV			
$\ell\ell^{\text{non}-Z}$	e^+e^- or $\mu^+\mu^-$	e^+e^- or $\mu^+\mu^-$	$e^\pm\mu^\mp$	$e^\pm\mu^\mp$
N_{jets}	≥ 2	≥ 2	≥ 2	≥ 2
$N_{b-\text{jets}}$@85%	= 1	≥ 2	= 1	≥ 2

+ E_T^{miss} cuts for SF regions to reduce ZZ+jets background

Inclusive cross section measurement

- Combined single-bin profile likelihood fit [3] in inclusive signal regions
- Fit configurations:

3ℓ	$\mu_{t\bar{t}Z}$, N_{WZ+l}	floating
4ℓ	$\mu_{t\bar{t}Z}$, N_{ZZ+l}	floating
3ℓ + 4ℓ	$\mu_{t\bar{t}Z}$, N_{WZ+l}, N_{ZZ+l}	floating

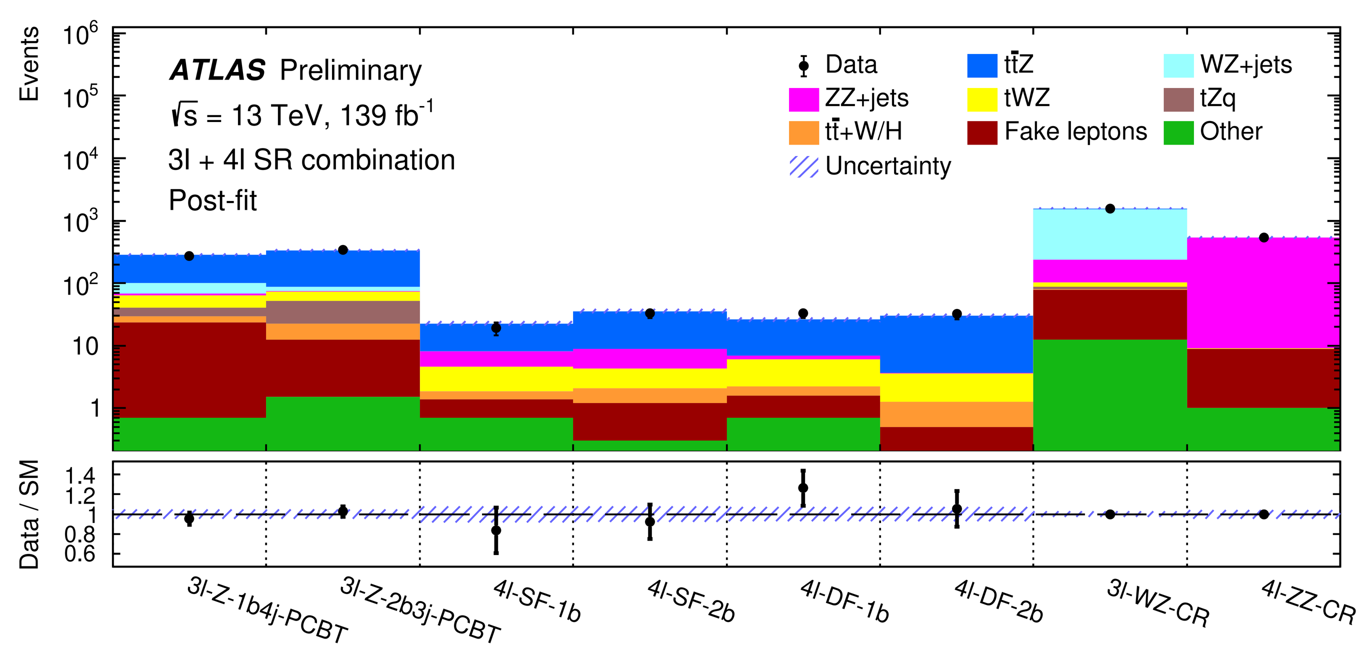
Channel	$\mu_{t\bar{t}Z}$
3ℓ	1.17 ± 0.07 (stat.) $^{+0.12}_{-0.11}$ (syst.)
4ℓ	1.21 ± 0.15 (stat.) $^{+0.11}_{-0.10}$ (syst.)
3ℓ + 4ℓ	1.19 ± 0.06 (stat.) ± 0.10 (syst.)

- The cross section is measured to be

$$\sigma(\mathbf{pp \to ttZ}) = \mathbf{0.99 \pm 0.05\ (stat.)\ \pm 0.08\ (syst.)\ pb}$$

- The result agrees with theory prediction (1)

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_T^{miss}	2.1
Fake leptons	2.1
$t\bar{t}Z$ ISR	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	10



⇑ **Post-fit event yields in signal and control regions; combined measurement dominated by 3ℓ-channel events (only slight difference between data and SM prediction)**

⇐ **List of the relative uncertainties of the measured inclusive $t\bar{t}Z$ cross section.**

Differential cross section measurement

- **Iterative Bayesian Unfolding** (IBU) technique [4]
- Measuring **absolute** and **normalised** differential cross sections
- Fiducial volumes are defined at **parton** (after $t\bar{t}Z$ decay including QCD radiation, but before hadronization) and **particle** (after $t\bar{t}Z$ decay, including hadronisation) level

$$\frac{d\sigma_{t\bar{t}Z}}{dX^i} = \frac{1}{\mathcal{L}\cdot\mathcal{B}\cdot\Delta X^i\cdot f^i_{\text{acc}}}\cdot\sum_j\left[M^{-1}\right]_{ij}\cdot\epsilon^j_{\text{eff}}\cdot\left(N^j_{\text{obs}} - N^j_{\text{bkg}}\right)$$

data - $\sum$ backgrounds

M = migration matrix

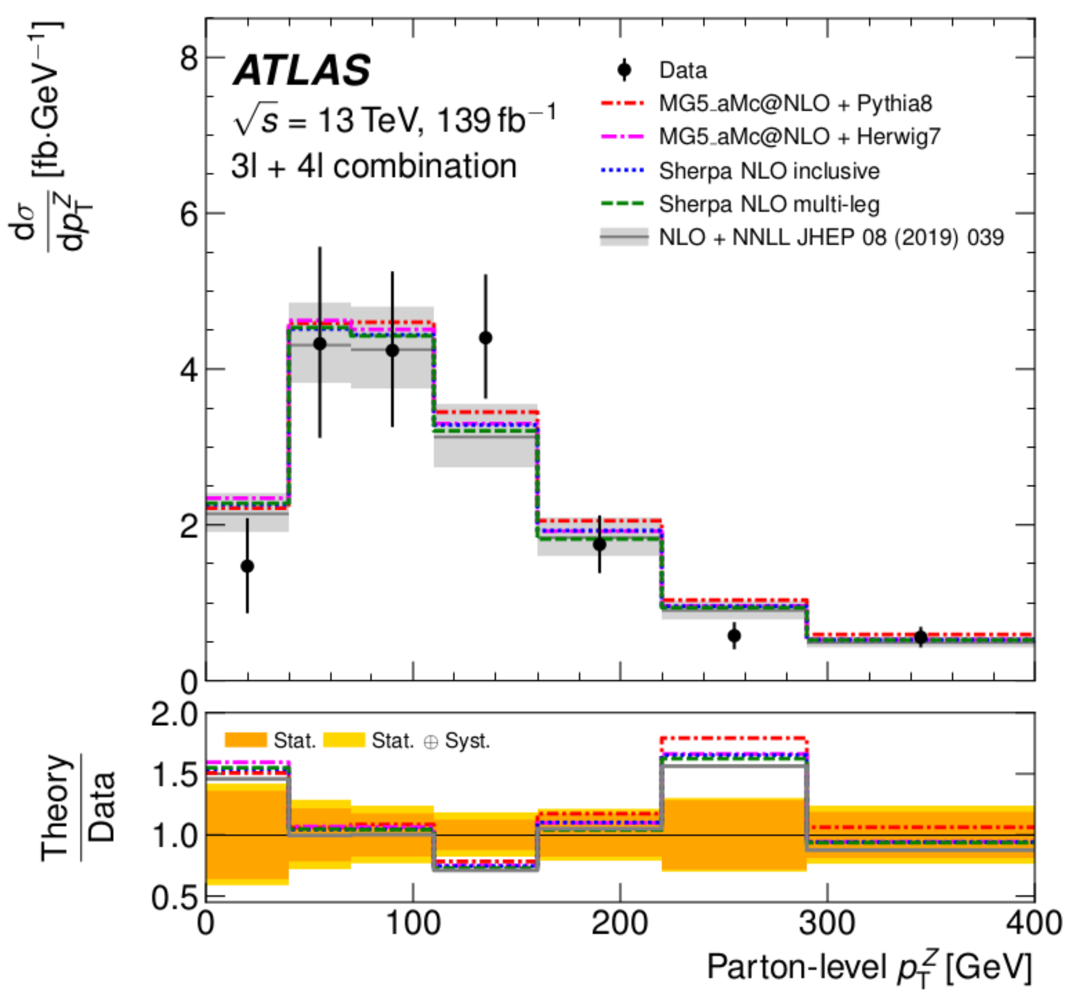
$\epsilon^j_{\text{eff}} = \frac{\text{pass(detector)} \wedge \text{pass(parton)}}{\text{pass(detector)}}$

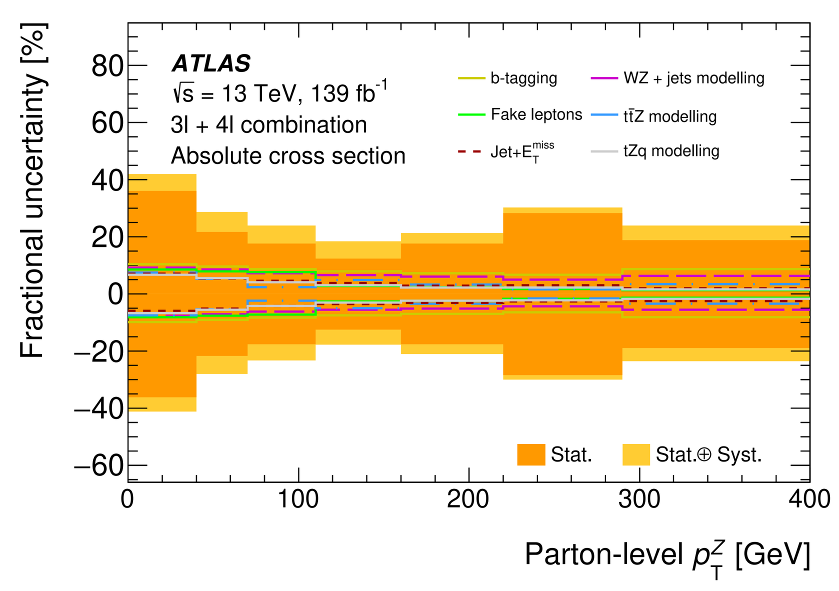
ΔX^i = bin width

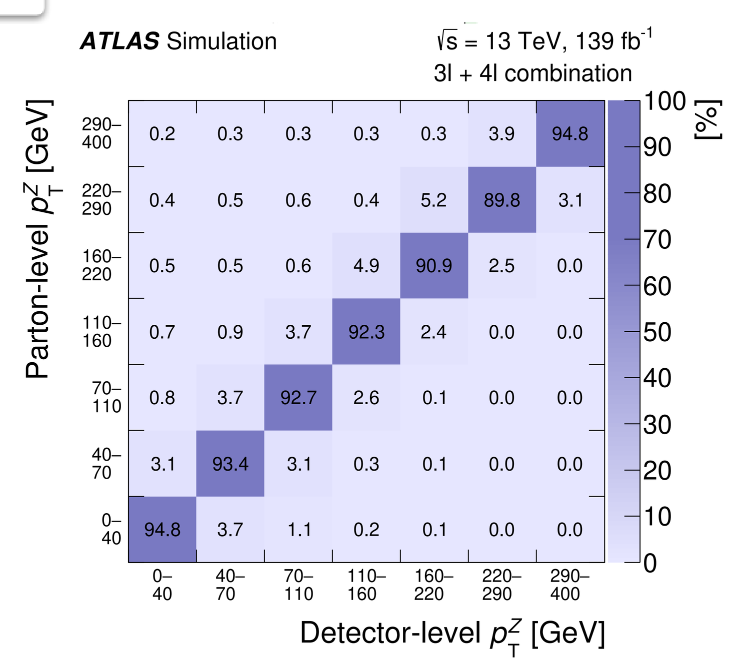
$\mathcal{B}(3\ell) \approx 1.928\,\%$
$\mathcal{B}(4\ell) \approx 0.3038\,\%$

$f^i_{\text{acc}} = \frac{\text{pass(detector)} \wedge \text{pass(parton)}}{\text{pass(parton)}}$

Absolute parton level differential $t\bar{t}Z$ cross section measured as a function of p_T^Z ⇓







⇑ **Decomposition of the total uncertainty (left) and migration matrix (right) for parton level differential cross section measured as a function of p_T^Z**

Compatibility (χ^2 and p values) between the unfolded measurements and nominal ⇒ **MC prediction**

Unfolded variables:

Channel	Variables
3ℓ + 4ℓ	p_T^Z, $\lvert y^Z\rvert$
3ℓ	N_{jets}*, $p_T^{\ell,\text{non}-Z}$, $\lvert\Delta\phi(Z, t_{\text{lep}})\rvert$, $\lvert\Delta y(Z, t_{\text{lep}})\rvert$
4ℓ	N_{jets}*, $p_T^{t\bar{t}}$, $\lvert\Delta\phi(\ell_t^+, \ell_{\bar{t}}^-)\rvert$, $\lvert\Delta\phi(t\bar{t}, Z)\rvert$

*unfolded only to particle level

- Kinematic variables related to $t\bar{t}Z$ provide sensitivity to either **BSM effects** (separation variables) or **generator modelling** (Z and $t/\bar{t}$ related variables)

Parton level Absolute cross section		MG5_aMC@NLO 2.3.3 + Pythia 8	
	Variable	χ^2/ndf	p-value
3ℓ	$p_T^{\ell,\text{non}-Z}$	7.6/4	0.11
3ℓ	$\lvert\Delta\phi(Z, t_{\text{lep}})\rvert/\pi$	5.5/3	0.14
3ℓ	$\lvert\Delta y(Z, t_{\text{lep}})\rvert$	0.9/3	0.82
4ℓ	$\lvert\Delta\phi(\ell_t^+, \ell_{\bar{t}}^-)\rvert/\pi$	2.1/4	0.72
4ℓ	$\lvert\Delta\phi(t\bar{t}, Z)\rvert/\pi$	5.2/3	0.16
4ℓ	$p_T^{t\bar{t}}$	3.5/4	0.47
3ℓ/4ℓ	p_T^Z	12.8/7	0.08
3ℓ/4ℓ	$\lvert y^Z\rvert$	2.8/8	0.95

References:

[1] Georges Aad et al. Measurements of the inclusive and differential production cross sections of a top-quark-antiquark pair in association with a Z boson at $\sqrt{s} = 13$ TeV with the ATLAS detector. 3 2021.

[2] Anna Kulesza, Leszek Motyka, Daniel Schwartländer, Tomasz Stebel, and Vincent Theeuwes. Associated production of a top quark pair with a heavy electroweak gauge boson at NLO+NNLL accuracy. *Eur. Phys. J. C*, 79(3):249, 2019.

[3] Glen Cowan, Kyle Cranmer, Eilam Gross, and Ofer Vitells. Asymptotic formulae for likelihood-based tests of new physics. *Eur. Phys. J. C*, 71:1554, 2011.

[4] G. D'Agostini. Improved iterative Bayesian unfolding. In *Alliance Workshop on Unfolding and Data Correction Hamburg, Germany, May 27-28, 2010*, 2010.