Differential cross-section measurements of $t\bar{t}Z$ with the ATLAS detector

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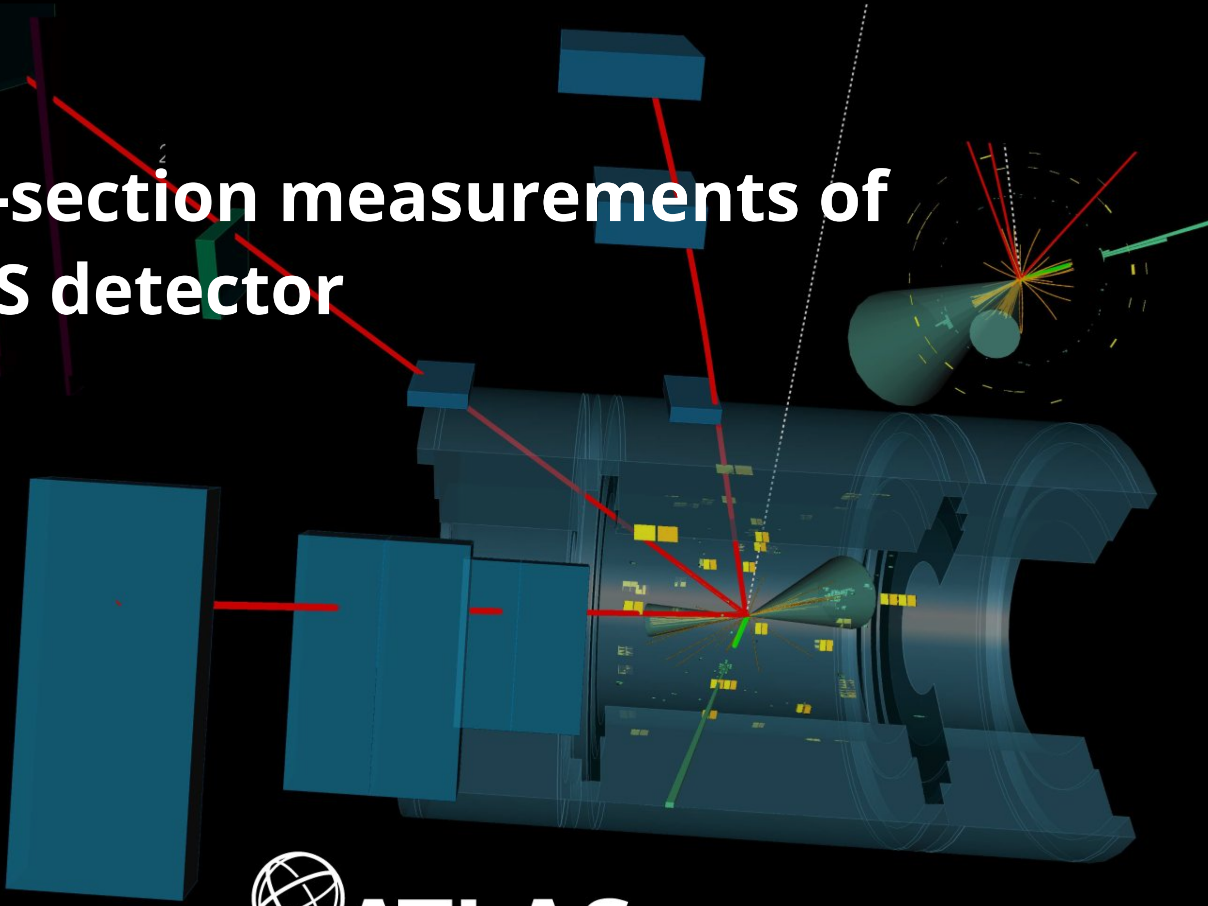

University of Glasgow

VIA VERITAS VITA

ATLAS EXPERIMENT

Introduction

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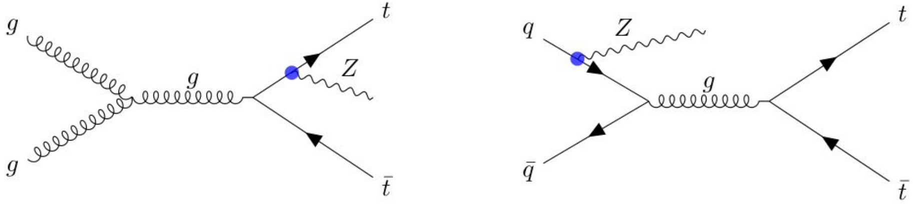
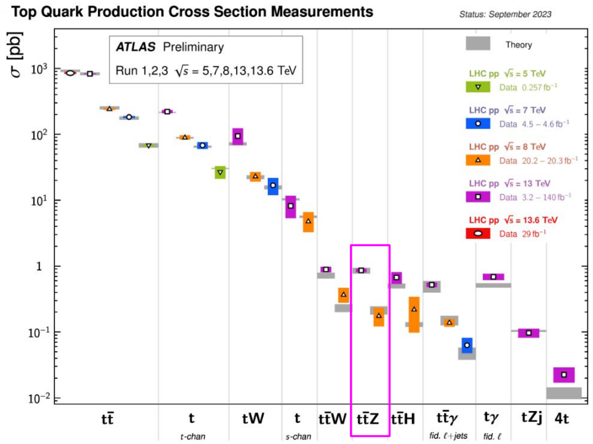
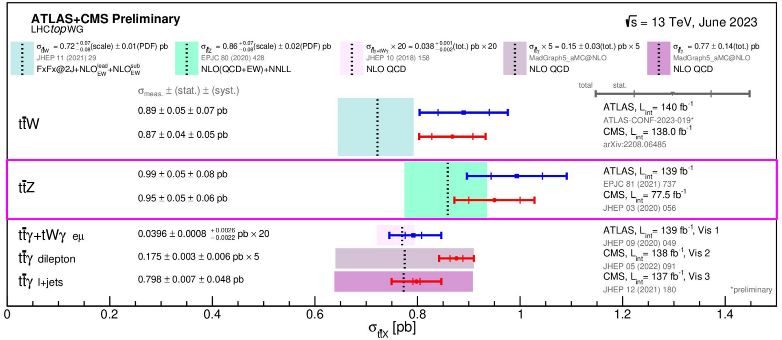
Production of a top and anti-top quark pair in association with a Z boson:



- Rare Standard Model process
- Direct probe of the neutral electroweak coupling of the top quark
- Important background for top processes (tZq, $t\bar{t}H$, $t\bar{t}W$) and BSM searches
- Sensitivity to new physics





NEW

This talk: differential cross-section measurements with 140 fb^{-1} (Run 2) dataset

Analysis channels

We measure $t\bar{t}Z$ in multilepton final states: $Z\to e^+e^-/\mu^+\mu^-$ and $t\bar{t}\to 1/2$ leptons.

3ℓ

- Best compromise between purity and statistics
- WZ+jets and tZq background
- Fake lepton background

4ℓ

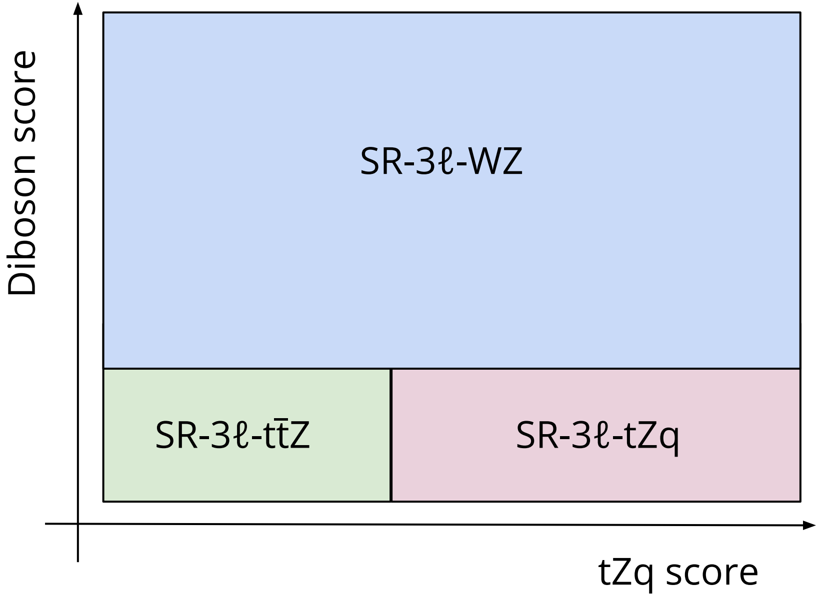
- High signal purity
- Different or same-flavour non-Z lepton pairs
- tWZ and ZZ+jets background

★ Apply basic object preselection
★ Separate signal and background with binary/multi-class neural networks
★ Measure differential cross-sections with a profile likelihood unfolding (PLU)

3ℓ channel

- Multi-class deep neural network (DNN) separates $t\bar{t}Z$ signal from WZ+jets and tZq backgrounds.
- Input: reconstructed kinematic observables and b-tagging information.
- 3-prong output produces a 2D distribution.

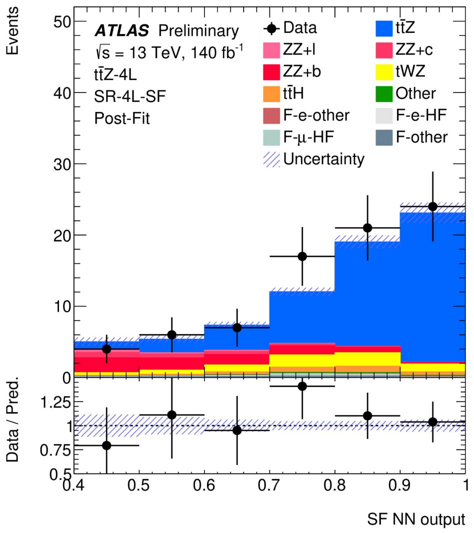
	SR-3ℓ-$t\bar{t}$Z	SR-3ℓ-tZq	SR-3ℓ-WZ
DNN-tZq output	< 0.40	≥ 0.40	—
DNN-WZ output	< 0.22	< 0.22	≥ 0.22
$N_{b\text{-tagged jets}}$	—	—	$\geq 1@60\%$



Cut on 2D output to give best S/B

4ℓ channel

- Use multi-variate (MVA) approach to suppress ZZ+jets background.
- Two ttZ-4ℓ categories based on non-Z lepton flavour:
  - $\ell\ell^{\text{non-Z}} = e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp} \rightarrow$ **same flavour (SF)**
  - $\ell\ell^{\text{non-Z}} = e^{\pm}\mu^{\mp} \rightarrow$ **different flavour (DF)**



Binary classifier DNN separates ttZ-4ℓ-SF signal and ZZ+jets background.

Cut on DNN output and define 3 regions:

	SR-4ℓ-SF	SR-4ℓ-DF	CR-4ℓ-ZZ
$\ell\ell^{\text{non-Z}}$	e^+e^- or $\mu^+\mu^-$	$e^{\pm}\mu^{\mp}$	e^+e^- or $\mu^+\mu^-$
DNN output	≥ 0.4	—	< 0.4

Unfolding procedure

Profile likelihood unfolding (PLU) with likelihood constructed as:

$$L\left(\vec{n}|\vec{\mu},\vec{\theta},\vec{k}\right) = \prod_{r\in\text{regions}}\prod_{i\in\text{bins}}\text{Pois}\left(n_{i,r}|\nu_{i,r}(\vec{\mu},\vec{\theta},\vec{k})\right)\times\prod_{j\in\text{NPs}}\text{Gaus}\left(\theta_j\right)\times R(\vec{\mu})$$

$$\nu_{i,r} = S_{i,r}(\vec{\mu},\vec{\theta}) + B_{i,r}(\vec{\theta},\vec{k})$$

$$n_{i,folded} = \frac{1}{\alpha_i}\sum_j \epsilon_j M_{ij} n_{j,truth}$$

$$\alpha_i = \frac{n_{i,reco}\ \&\ n_{i,truth}}{n_{i,reco}}$$

$$\epsilon_j = \frac{n_{j,reco}\ \&\ n_{j,truth}}{n_{j,truth}}$$

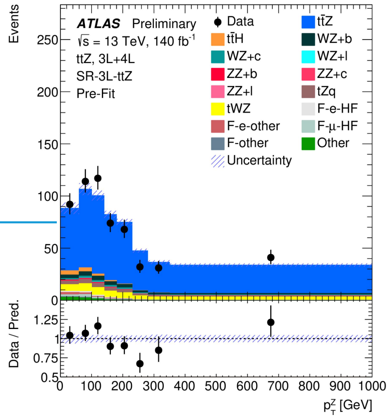
- Differential cross-section: extract signal parameter μ_{ttZ} in each bin.
- Easy combination between **orthogonal channels and regions**.
- Free-floating normalisation of backgrounds:

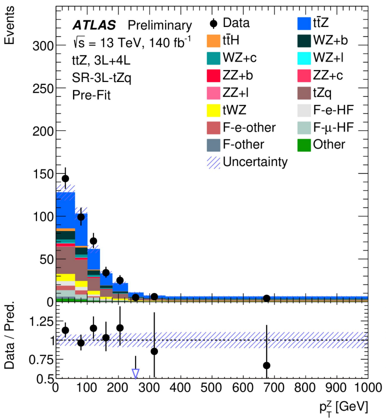
$$N_{WZ+b}(3\ell),\ N_{ZZ+b}\ (4\ell),\ N_{\mu,HF},\ N_{e,HF},\ N_{e,other}$$

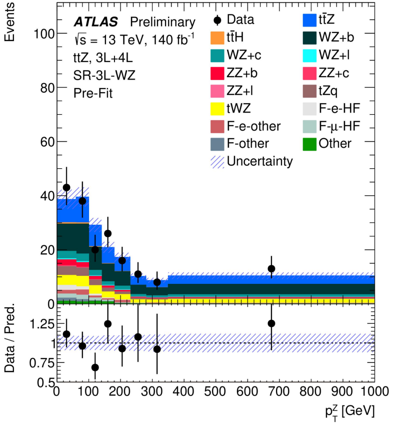
- Inclusion of systematic uncertainties in the fit via θ.
- 5/3/9 observables in 3ℓ/4ℓ/3ℓ+4ℓ unfolded to **particle and parton level**.
- Tikhonov regularisation used for hadronic top observables.

$$R(\vec{\mu}) = \exp\left[-\frac{\tau^2}{2}\sum_{i=2}^{i+1<N_{bins}}\left((\mu_i-\mu_{i-1})-(\mu_{i+1}-\mu_i)\right)^2\right]$$

3ℓ unfolding - p_T^Z







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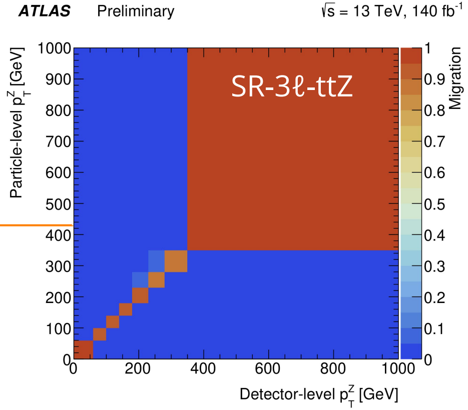

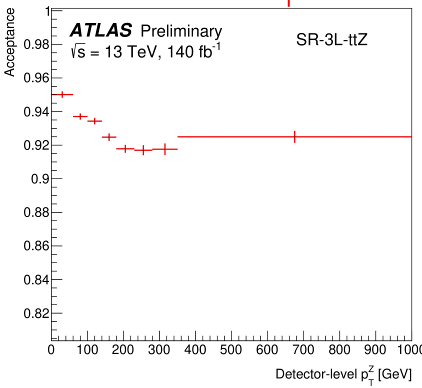

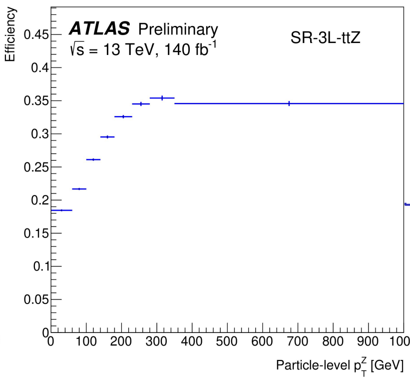

Differential cross-section measurements

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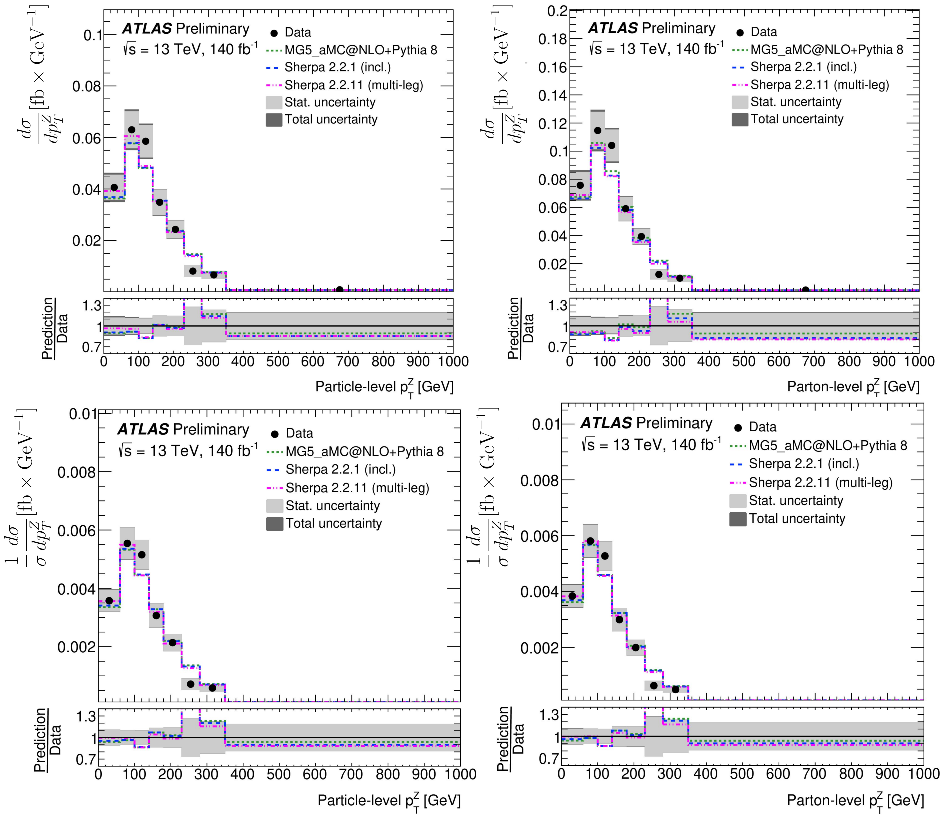
Combination of the 3ℓ + 4ℓ signal and control regions:

Data, N_{WZ+b} and N_{ZZ+b} are found to be **consistent with the Standard Model.**

Particle level | Parton level

Absolute x-sec

Normalised x-sec



Differential cross-section measurements

Combination of the 3ℓ + 4ℓ signal and control regions:

Data, N_{WZ+b} and N_{ZZ+b} are found to be **consistent with the Standard Model.**

≈ 30% improvement with respect to the previous ATLAS analysis (EPJC 81 (2021) 737)

➔ precision of ~20% at 500 GeV

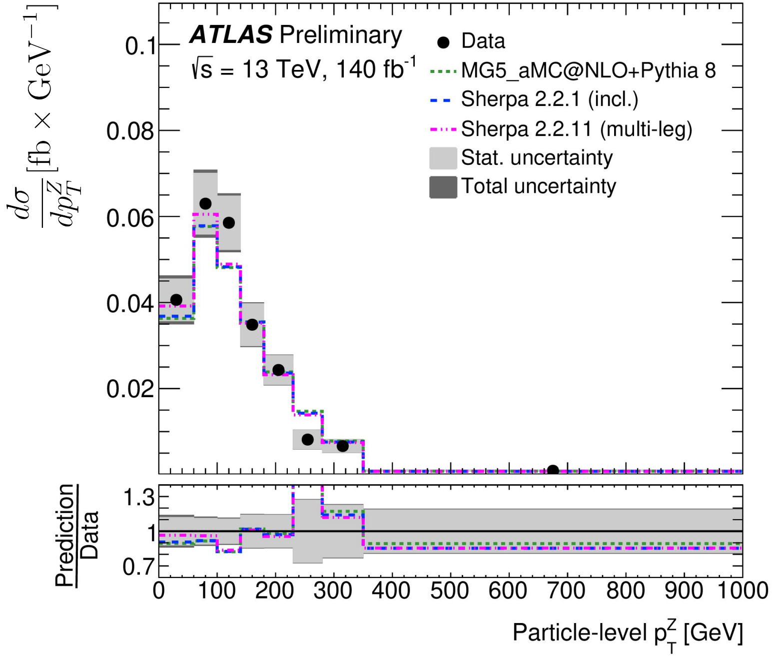
➔ total uncertainty is **stat-dominated**.

Gain in precision comes from

- MVA technique to separate signal and background.
- Simultaneous fit to multiple regions via PLU.

Particle level

Absolute x-sec



Transverse momentum of the Z boson

Differential cross-section measurements

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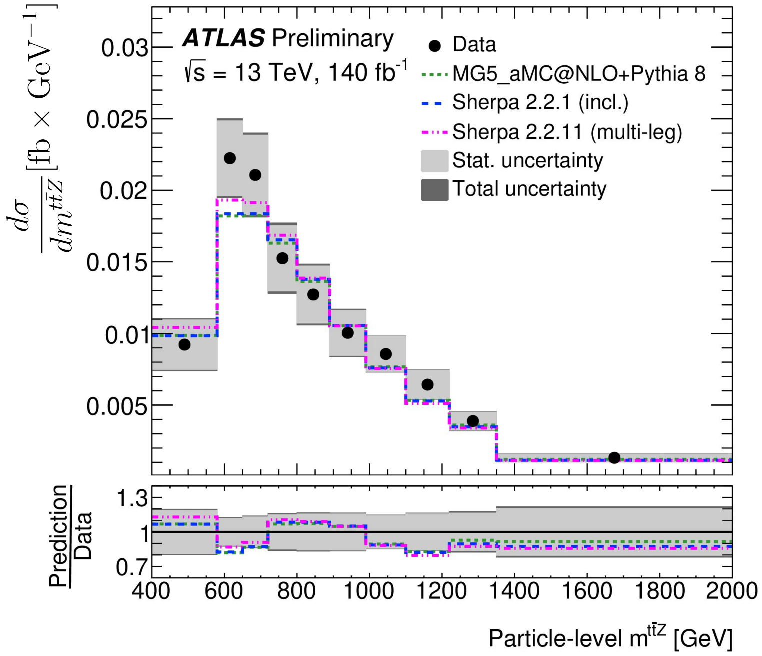

Invariant mass of tt̄Z system

Summary

Differential measurements of the $t\bar{t}Z$ cross-section in multi-lepton final states (3ℓ & 4ℓ) using 140 fb^{-1} of Run 2 data have been performed with ATLAS.

- ★ Analysis builds and improves upon the previous ATLAS result: MC modelling, MVA-based strategy, fake lepton estimation, systematics model.
- ★ Approximately **30% improvement** on the differential cross-section precision using the same dataset.
- ★ Differential measurements are performed for 17 observables in the 3ℓ, 4ℓ or 3ℓ+4ℓ channels with a precision of ~20% at 500 GeV.
- ★ Full likelihoods will be available via HEPData.

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Backup

DNN input - 3ℓ

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Table 23

Variable	Definition
PCBT_{b1}	highest discretised b-tagging efficiency (100-85-77-70-60%) of all jets in the event.
PCBT_{b2}	second highest discretised b-tagging efficiency of all jets in the event.
Jet $p_{\text{T},i}$	transverse momentum of the i'th jet in the event where $i \in [1,4]$
$E_{\text{T}}^{\text{miss}}$	missing transverse energy of the event
Lepton $p_{\text{T},i}$	transverse momentum of the i'th lepton in the event where $i \in [1,3]$
m_t^{lep}	reconstructed mass of the leptonically decaying top quark
m_t^{had}	reconstructed mass of the hadronically decaying top quark
N_{jets}	jet multiplicity in event
Leading b-tagged jet p_{T}	transverse momentum of the jet with the highest discretised b-tagging efficiency. If two have the same bin the leading p_{T} jet of the two is used.
H_{T}	sum of the transverse momentum of all jets in the event
$\Delta R(l_i, b_1)$	distance in ΔR between the i'th lepton and the b-tagged jet tagged with the highest working point in the event where $i \in [1,3]$
$p_{\text{T},i}^{Z}$	transverse momentum of the first and second lepton ($i \in [1,2]$) assigned to the Z boson based on their invariant mass being closest to the Z mass
η_i^{Z}	pseudo-rapidity of the first and second lepton ($i \in [1,2]$) assigned to the Z boson based on their invariant mass being closest to the Z mass
Lepton $p_{\text{T}}^{\text{non}-Z}$	transverse momentum of the remaining lepton not assigned to the Z boson

DNN input - 4ℓ

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Table 24

Variable	Definition	SF	DF
E_T^{miss}	the missing transverse energy in the event	✓	—
$m^{\ell\ell,non-Z}$	the invariant mass of two leptons which were not reconstructed as originating from Z	✓	✓
2νSM weight	the output of the *Two neutrino scanning method* for event	✓	✓
p_T^Z	the transverse momentum of OSSF lepton pair identified as Z pair (invariant mass of lepton pair closest to Z mass)	✓	✓
$m_t^{\ell b}$	the invariant mass of lepton and b-tagged jet reconstructed as originating from top by *Two neutrino scanning method*	✓	✓
$m_{\bar{t}}^{\ell b}$	the invariant mass of lepton and b-tagged jet reconstructed as originating from antitop by *Two neutrino scanning method*	✓	✓
PCBT_{b1}	highest discretised b-tagging efficiency (100-85-77-70-60%) of all jets in the event.	✓	—
$p_T^{\mathrm{lep}_1}$	the transverse momentum of the leading lepton	✓	✓
$p_T^{\mathrm{jet}_2}$	the transverse momentum of the sub-leading jet	✓	✓
PCBT_{b2}	second highest discretised b-tagging efficiency of all jets in the event.		
N_{jets}	jet multiplicity in event	—	✓
$N_{b-\mathrm{tagged\ jets}}$	b-tagged jet multiplicity in event	—	✓

Regularisation τ

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Table 15

	Variable	Regularisation	τ^{particle}	τ^{parton}	Definition
$3\ell + 4\ell$	p_T^Z	No	-	-	Transverse momentum of the Z boson
	$\lvert y^Z \rvert$	No	-	-	Absolute rapidity of the Z boson
	$\cos\theta_Z^*$	No	-	-	Angle between the direction of the Z boson in the detector reference frame and the direction of the negatively charged lepton in the rest frame of the Z boson
	p_T^t	Yes	1.5	1.4	Transverse momentum of the top quark
	$p_T^{t\bar{t}}$	Yes	1.6	1.5	Transverse momentum of the $t\bar{t}$ system
	$\lvert\Delta\phi(t\bar{t}, Z)\rvert$	Yes	2.4	2.1	Absolute azimuthal separation between the Z boson and the $t\bar{t}$ system
	$m^{t\bar{t}Z}$	Yes	1.5	1.6	Invariant mass of the $t\bar{t}Z$ system
	$m^{t\bar{t}}$	Yes	1.5	1.4	Invariant mass of the $t\bar{t}$ system
	$\lvert y^{t\bar{t}Z}\rvert$	Yes	1.5	1.5	Absolute rapidity of the $t\bar{t}Z$ system
3ℓ	H_T^ℓ	No	-	-	Sum of the transverse momenta of all the signal leptons
	$\lvert\Delta\phi(Z, t_{\text{lep}})\rvert$	No	-	-	Absolute azimuthal separation between the Z boson and the top (anti-top) quark featuring the $W \to \ell\nu$ decay
	$\lvert\Delta y(Z, t_{\text{lep}})\rvert$	No	-	-	Absolute rapidity difference between the Z boson and the top (anti-top) quark featuring the $W \to \ell\nu$ decay
	$p_T^{\ell,\text{non}-Z}$	No	-	-	Transverse momentum of the lepton which is not associated with the Z boson
	N_{jets}	No	-	-	Number of selected jets with $p_T > 25$ GeV and $\lvert\eta\rvert < 2.5$
4ℓ	H_T^ℓ	No	-	-	Sum of the transverse momenta of all the signal leptons
	$\lvert\Delta\phi(\ell_t^+, \ell_{\bar{t}}^-)\rvert$	No	-	-	Absolute azimuthal separation between the two leptons from the $t\bar{t}$ system
	N_{jets}	No	-	-	Number of selected jets with $p_T > 25$ GeV and $\lvert\eta\rvert < 2.5$

Parton and particle level

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Table 5

Particle-level selection	
3ℓ channel	4ℓ channel
Exactly 3 leptons, with $p_{\mathrm{T}}(\ell_1, \ell_2, \ell_3) > 27, 20, 15$ GeV	Exactly four leptons, with $p_{\mathrm{T}}(\ell_1, \ell_2, \ell_3, \ell_4) > 27, 7, 7, 7$ GeV
The sum of charges is ± 1	The sum of charges is $= 0$
At least 3 jets, with $p_{\mathrm{T}} > 25$ GeV	At least 2 jets, with $p_{\mathrm{T}} > 25$ GeV
At least 1 b-jet (jet ghost-matched to a b-hadron)	
At least one OSSF lepton pair, with $\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV	

Parton-level selection	
3ℓ channel	4ℓ channel
$t\bar{t} \rightarrow e^{\pm}/\mu^{\pm}$ + jets	$t\bar{t} \rightarrow e^{\pm}\mu^{\mp}/e^{\pm}e^{\mp}/\mu^{\pm}\mu^{\mp}$
$Z \rightarrow e^{\pm}e^{\mp}/\mu^{\pm}\mu^{\mp}$	
$\lvert m_{\ell\ell} - m_Z \rvert < 15$ GeV	

Systematic uncertainties

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Table 14
(inclusive measurement)

Uncertainty Category	$\Delta\sigma_{t\bar{t}Z}/\sigma_{t\bar{t}Z}$ [%]
Background normalisations	2.0
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	1.9
b-tagging	1.7
$t\bar{t}Z$ μ_F and μ_R scales	1.6
Leptons	1.6
~~Z +jets modelling~~	~~1.5~~
tWZ modelling	1.1
$t\bar{t}Z$ showering	1.0
$t\bar{t}Z$ A14	1.0
Luminosity	1.0
Diboson modelling	0.8
tZq modelling	0.7
PDF (signal & backgrounds)	0.6
MC statistical	0.5
Other backgrounds	0.5
Fake leptons	0.4
Pile-up	0.3
~~Data-driven $t\bar{t}$~~	~~0.1~~

Changes w.r.t previous analysis

	Previous analysis	Legacy analysis
	Eur. Phys. J. C 81 (2021) 737	ATLAS-CONF-2023-065
b-tagging	mv2c10	DL1r
Unfolding method	iterative Bayesian	profile likelihood
Neural network	✗	✓
Lepton isolation and p_T	Tight(er)	Loose(r)

b-tagging

Eur. Phys. J. C 83 (2023) 681