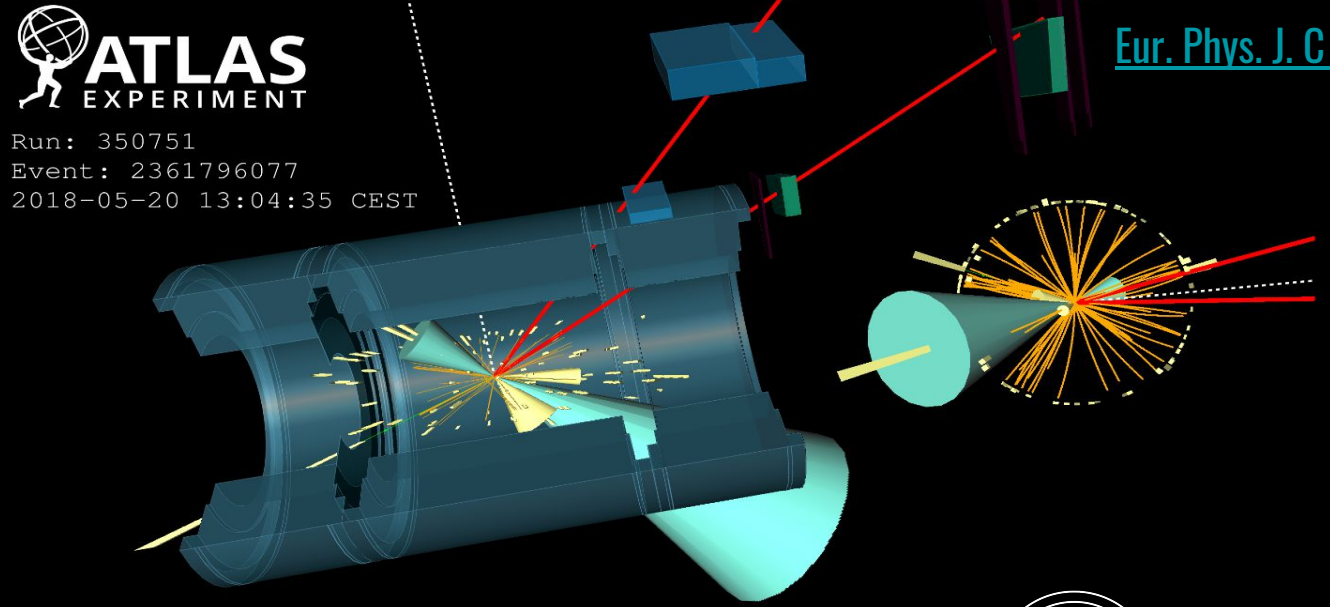
Measurements of the differential production cross sections of a top-quark-antiquark pair in association with a Z boson at √s = 13 TeV with the ATLAS detector



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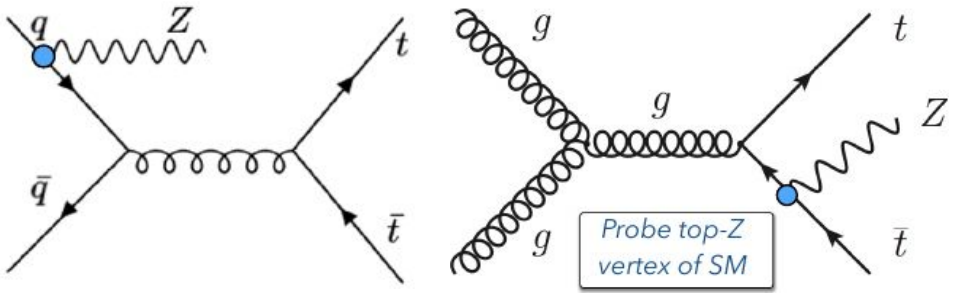
Dominik Babál on behalf of the ATLAS Collaboration
TOP 2021, 15.09.2021

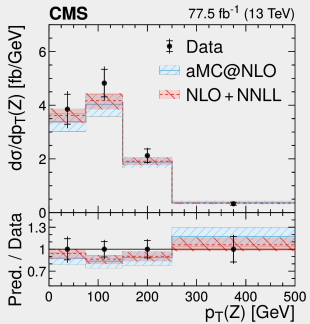
COMENIUS UNIVERSITY BRATISLAVA

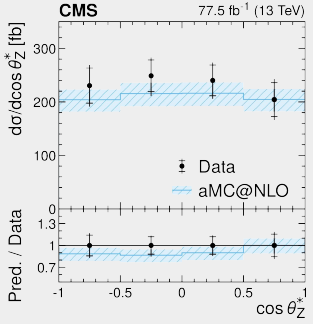
Introduction



- $t\bar{t}Z$ is **rare process** in the SM (≈1000 times lower cross section than $t\bar{t}$)
- differential measurements probe **top-Z coupling** of the SM → sensitivity to BSM physics (ability to constrain Wilson coef. c_{tG}, c_{tZ}, $c_{\phi t}$ ...)
- **important background** for LHC searches ($t\bar{t}H$, $t\bar{t}t\bar{t}$, tZ, BSM searches, ...)

- first differential measurement by CMS using 77.5 fb^{-1} (*JHEP 03 (2020) 056*)
  - Same technique: Iterative Bayesian Unfolding (IBU)
  - Two variables: p_T^Z, $\cos(\theta_Z^\star)$ → angular distribution of the negatively charged lepton from the Z
  - Unfolding to parton level (see also Joscha's talk)





- this is **first differential** $t\bar{t}Z$ measurement using full Run-2 dataset (139 fb^{-1})
- this differential analysis is part of a larger $t\bar{t}Z$ paper (for inclusive cross section measurement see Laurynas's talk)

Definition of the regions

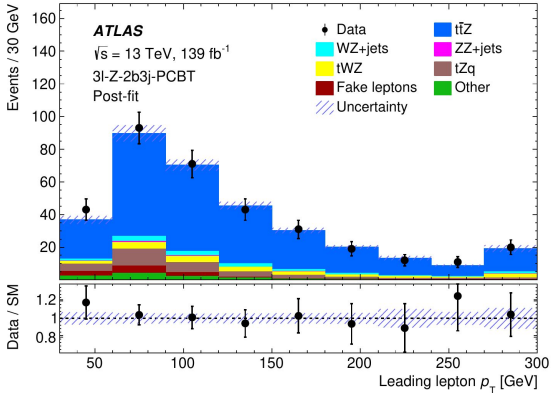
- Most sensitive signatures with **3l** and **4l** in final states: $Z \to l^+l^-$, $t\bar{t} \to$ dilepton (**4l** channel) or $t\bar{t} \to$ lepton+jets (**3l** channel)

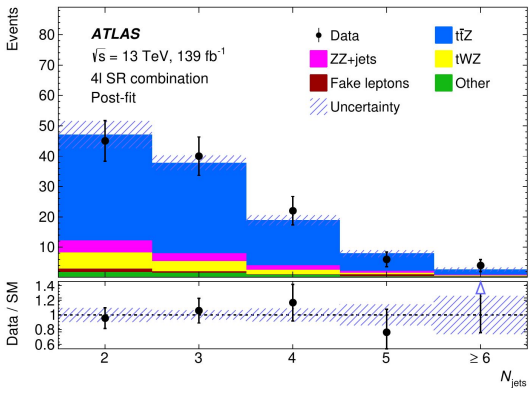
3l signal region

- Exactly **3 leptons**
- **≥ 1 OSSF** (opposite-sign-same-flavour) **lepton pair** with $\left|m_{ll}^{Z} - m_{Z}\right| < 10\,\text{GeV}$ and $m_{\text{OSSF}} > 10\,\text{GeV}$
- $p_T^{l1,l2,l3} > 27, 20, 20\,\text{GeV}$
- **≥ 3 jets** and at **≥ 2 *b*-tagged jets** (85% eff.)

4l signal region

- Exactly **4 leptons**
- **≥ 1 OSSF lepton pair** with $\left|m_{ll}^{Z} - m_{Z}\right| < 10\,\text{GeV}$ and $m_{\text{OSSF}} > 10\,\text{GeV}$
- $p_T^{l1,l2,l3,l4} > 27, 20, 10, 7\,\text{GeV}$
- **≥ 2 jets** and **≥ 1 *b*-tagged jet** (85% eff.)
- E_T^{miss} cuts to reduce **ZZ+jets background**





- Measured diff. cross sections corrected for detector effects to **particle** (after $t\bar{t}Z$ decay, including hadronization) and **parton** (after $t\bar{t}Z$ decay including QCD radiation, but before hadronization) level

Unfolding and variables

➢ **Iterative Bayesian Unfolding** (IBU) technique - based on Bayes theorem, stable procedure (does not require matrix inversion)

data - $\sum$ backgrounds

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

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

ΔX^i = bin width

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

M = migration matrix

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

3l variables:

- N_{jets}, $p_T^{l,non-Z}$ ⟩ generator modelling (QCD radiation, hadronisation)
- $|\Delta\phi(Z,t_{lep})|$, $|\Delta y(Z,t_{lep})|$ ⟩ BSM effects (probes $t\bar{t}Z$ vertex)

4l variables:

- N_{jets}, $p_T^{t\bar{t}}$ ⟩ generator modelling (hard-scatter, parton shower)
- $\left|\Delta\phi\left(l_t^+, l_{\bar{t}}^-\right)\right|$, $\left|\Delta\phi\left(t\bar{t}, Z\right)\right|$ ⟩ BSM effects (spin correlations)

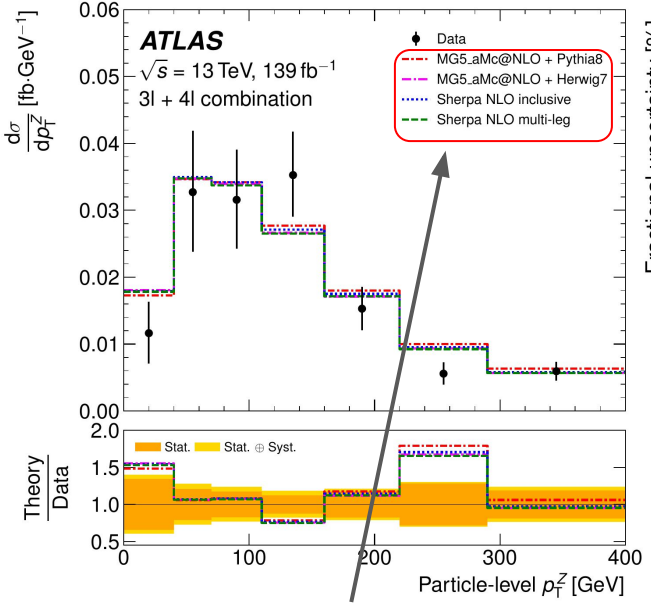
3l +4l variables:

- p_T^Z, $|y^Z|$ ⟩ generator modelling + BSM effects, increased sensitivity in combined channel

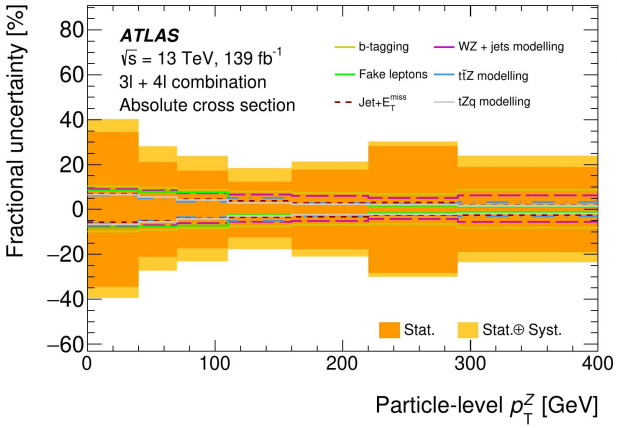
* Partial $t\bar{t}$ reconstruction (only leptonic top decays in 3l and ϕ plane in 4l), focus on most sensitive variables

Results

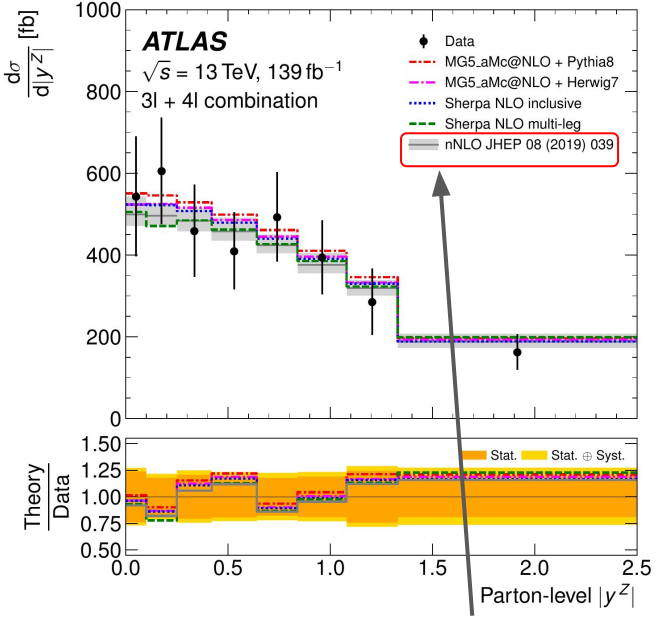
- **Absolute** and **normalised** differential cross sections unfolded to **particle** and **parton** level



Comparison with various MC generators, nominal is MG5_aMC@NLO+Pythia 8



- All channels are dominated by **statistical uncertainty**
- Leading systematics: ***b*-tagging** and **MC modelling**



Dedicated theory predictions for most variables at parton level (NLO,NLO+NNLL, nNLO)

Compatibility with predictions

- χ^2/ndf and *p*-value used to quantify overall agreement between unfolded data and various predictions
- Elements of covariance matrix determined with **bootstrap technique**
- Overall good agreement observed

Particle level — Absolute — Normalised

	Variable	χ^2/ndf	*p*-value	χ^2/ndf	*p*-value
3ℓ	N_{jets}	0.8/3	0.85	0.3/2	0.88
	$p_{\text{T}}^{\ell,\text{non-}Z}$	7.5/4	0.11	6.4/3	0.09
	$\lvert\Delta\phi(Z,t_{\text{lep}})\rvert$	5.4/3	0.14	4.0/2	0.14
	$\lvert\Delta y(Z,t_{\text{lep}})\rvert$	0.9/3	0.83	0.4/2	0.81
4ℓ	N_{jets}	1.4/4	0.84	0.4/3	0.94
	$\lvert\Delta\phi(\ell_t^+,\ell_{\bar{t}}^-)\rvert$	2.0/4	0.73	1.3/3	0.74
	$\lvert\Delta\phi(t\bar{t},Z)\rvert$	5.2/3	0.16	5.3/2	0.07
	$p_{\text{T}}^{t\bar{t}}$	3.5/4	0.47	3.9/3	0.28
$3\ell+4\ell$	p_{T}^{Z}	12.8/7	0.08	11.0/6	0.09
	$\lvert y^Z\rvert$	2.8/8	0.94	2.4/7	0.94

Parton level — Absolute — Normalised

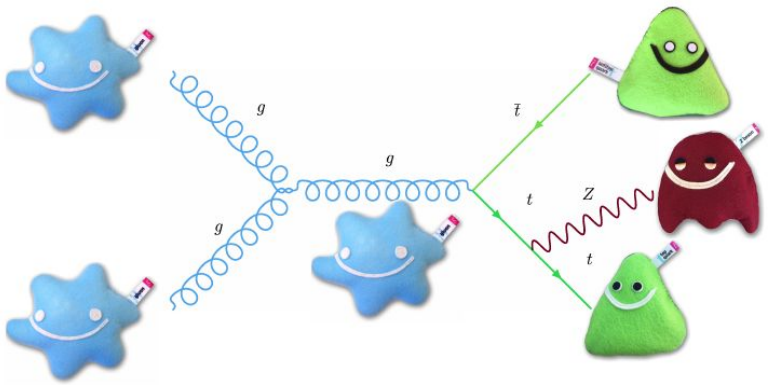
	Variable	χ^2/ndf	*p*-value	χ^2/ndf	*p*-value
3ℓ	$p_{\text{T}}^{\ell,\text{non-}Z}$	7.6/4	0.11	6.6/3	0.09
	$\lvert\Delta\phi(Z,t_{\text{lep}})\rvert$	5.5/3	0.14	3.9/2	0.14
	$\lvert\Delta y(Z,t_{\text{lep}})\rvert$	0.9/3	0.82	0.4/2	0.80
4ℓ	$\lvert\Delta\phi(\ell_t^+,\ell_{\bar{t}}^-)\rvert$	2.1/4	0.72	1.2/3	0.75
	$\lvert\Delta\phi(t\bar{t},Z)\rvert$	5.2/3	0.16	5.4/2	0.07
	$p_{\text{T}}^{t\bar{t}}$	3.5/4	0.47	4.0/3	0.26
$3\ell+4\ell$	p_{T}^{Z}	12.8/7	0.08	11.0/6	0.09
	$\lvert y^Z\rvert$	2.8/8	0.94	2.3/7	0.94

Better agreement with NLO+NNLL prediction (***p* = 0.17**)

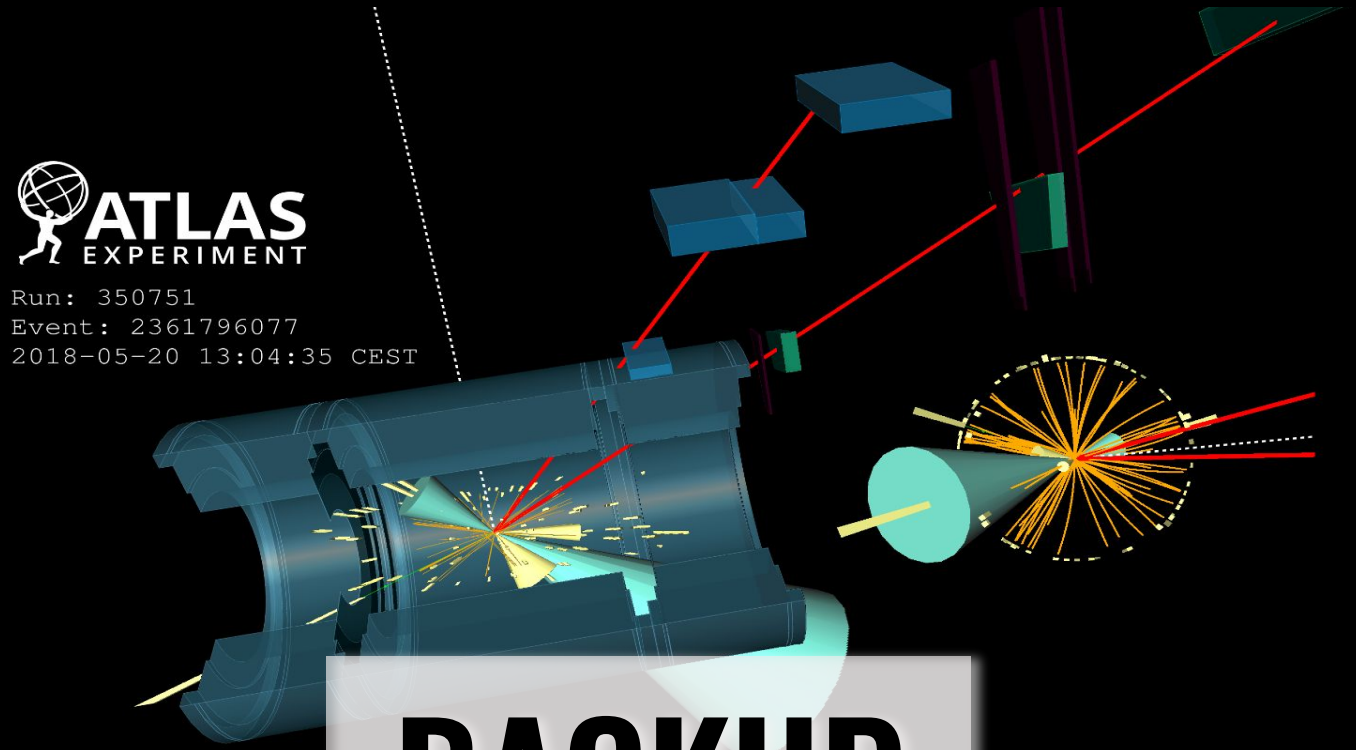
Better agreement with SHERPA (***p* = 0.33**)

Summary

- Measurements of **differential** cross section of $t\bar{t}Z$ production in **3 signal regions** (3l, 4l, and combined 3l+4l)
- Distributions of 9 variables unfolded to particle and parton level using **Iterative Bayesian Unfolding** technique
- Absolute and normalised differential cross sections compared to various $t\bar{t}Z$ generators and dedicated theory predictions
- Dominant source of uncertainty is **limited data statistics** (will benefit from Run 3)
- **Overall good compatibility** of unfolded data with predicted differential cross sections



Thank you for your attention!


ATLAS
EXPERIMENT
Run: 350751
Event: 2361796077
2018-05-20 13:04:35 CEST

BACKUP

Signal region definitions

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 $\lvert m^Z_{\ell\ell} - m_Z \rvert < 10$ 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%		

➢ Note differences in *b*-tagging requirements (pseudo-continuous *b*-tagging (**PCBT**) used in inclusive regions to suppress **WZ+jets** background, while **fixed 85%** *b*-tagging WP is used in differential region to increase the data statistics)

➢ Additional E_T^{miss} cuts for same flavour regions to suppress **ZZ+jets** background

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} (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 $\lvert m^{\text{non-}Z}_{\ell\ell} - m_Z \rvert \le 10$ GeV	> 50 GeV, if $\lvert m^{\text{non-}Z}_{\ell\ell} - m_Z \rvert \le 10$ GeV	–	–
	> 50 GeV, if $\lvert m^{\text{non-}Z}_{\ell\ell} - m_Z \rvert > 10$ GeV	–		
N_{jets}	≥ 2	≥ 2	≥ 2	≥ 2
$N_{b\text{-jets}}$@85%	= 1	≥ 2	= 1	≥ 2

Compatibility with predictions (complete tables)

ATLAS EXPERIMENT

Particle level Absolute cross section		MG5_aMC@NLO 2.3.3 + Pythia 8		MG5_aMC@NLO 2.3.3 + Herwig 7		Sherpa 2.2.1 NLO multi-leg		Sherpa 2.2.1 NLO inclusive	
	Variable	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value
3ℓ	N_{jets}	0.8/3	0.85	0.6/3	0.90	0.3/3	0.95	0.5/3	0.92
	$p_{\text{T}}^{\ell,\text{non-}Z}$	7.5/4	0.11	7.2/4	0.13	7.7/4	0.11	7.7/4	0.10
	$\lvert\Delta\phi(Z,t_{\text{lep}})\rvert$	5.4/3	0.14	6.5/3	0.09	6.7/3	0.08	8.6/3	0.04
	$\lvert\Delta y(Z,t_{\text{lep}})\rvert$	0.9/3	0.83	0.7/3	0.87	0.5/3	0.93	0.9/3	0.81
4ℓ	N_{jets}	1.4/4	0.84	1.7/4	0.79	2.8/4	0.59	2.8/4	0.59
	$\lvert\Delta\phi(\ell_t^+,\ell_{\bar{t}}^-)\rvert$	2.0/4	0.73	2.3/4	0.69	2.7/4	0.62	2.5/4	0.65
	$\lvert\Delta\phi(t\bar{t},Z)\rvert$	5.2/3	0.16	4.9/3	0.18	4.1/3	0.25	3.7/3	0.30
	$p_{\text{T}}^{t\bar{t}}$	3.5/4	0.47	3.6/4	0.46	3.8/4	0.44	3.7/4	0.45
$3\ell+4\ell$	p_{T}^{Z}	12.8/7	0.08	12.0/7	0.10	11.6/7	0.11	12.1/7	0.10
	$\lvert y^{Z}\rvert$	2.8/8	0.94	2.9/8	0.94	3.8/8	0.90	2.9/8	0.94

Particle level Normalised cross section		MG5_aMC@NLO 2.3.3 + Pythia 8		MG5_aMC@NLO 2.3.3 + Herwig 7		Sherpa 2.2.1 NLO multi-leg		Sherpa 2.2.1 NLO inclusive	
	Variable	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value
3ℓ	N_{jets}	0.3/2	0.88	0.2/2	0.92	0.1/2	0.94	0.2/2	0.89
	$p_{\text{T}}^{\ell,\text{non-}Z}$	6.4/3	0.09	6.4/3	0.09	6.8/3	0.08	6.7/3	0.08
	$\lvert\Delta\phi(Z,t_{\text{lep}})\rvert$	4.0/2	0.14	5.4/2	0.07	5.5/2	0.06	6.7/2	0.03
	$\lvert\Delta y(Z,t_{\text{lep}})\rvert$	0.4/2	0.81	0.5/2	0.79	0.2/2	0.89	0.5/2	0.77
4ℓ	N_{jets}	0.4/3	0.94	0.3/3	0.96	1.3/3	0.73	1.6/3	0.66
	$\lvert\Delta\phi(\ell_t^+,\ell_{\bar{t}}^-)\rvert$	1.3/3	0.74	1.1/3	0.78	1.1/3	0.77	1.3/3	0.74
	$\lvert\Delta\phi(t\bar{t},Z)\rvert$	5.3/2	0.07	4.8/2	0.09	3.3/2	0.19	3.0/2	0.22
	$p_{\text{T}}^{t\bar{t}}$	3.9/3	0.28	3.7/3	0.30	3.6/3	0.30	3.7/3	0.30
$3\ell+4\ell$	p_{T}^{Z}	11.0/6	0.09	10.8/6	0.09	10.6/6	0.10	10.7/6	0.10
	$\lvert y^{Z}\rvert$	2.4/7	0.94	2.6/7	0.92	3.1/7	0.87	2.5/7	0.92

Parton level Absolute cross section		MG5_aMC@NLO 2.3.3 + Pythia 8		MG5_aMC@NLO 2.3.3 + Herwig 7		Sherpa 2.2.1 NLO multi-leg		Sherpa 2.2.1 NLO inclusive		Additional Theory	
	Variable	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
3ℓ	$p_{\text{T}}^{\ell,\text{non-}Z}$	7.6/4	0.11	8.8/4	0.07	8.3/4	0.08	8.6/4	0.07	/	/
	$\lvert\Delta\phi(Z,t_{\text{lep}})\rvert$	5.5/3	0.14	5.8/3	0.12	5.2/3	0.16	6.9/3	0.07	6.6/3	0.09
	$\lvert\Delta y(Z,t_{\text{lep}})\rvert$	0.9/3	0.82	0.7/3	0.88	0.2/3	0.98	0.5/3	0.92	0.3/3	0.96
4ℓ	$\lvert\Delta\phi(\ell_t^+,\ell_{\bar{t}}^-)\rvert$	2.1/4	0.72	2.3/4	0.69	2.7/4	0.62	2.6/4	0.63	/	/
	$\lvert\Delta\phi(t\bar{t},Z)\rvert$	5.2/3	0.16	4.7/3	0.19	3.5/3	0.32	3.4/3	0.33	4.9/3	0.18
	$p_{\text{T}}^{t\bar{t}}$	3.5/4	0.47	3.6/4	0.47	3.5/4	0.48	3.5/4	0.47	4.6/4	0.33
$3\ell+4\ell$	p_{T}^{Z}	12.8/7	0.08	11.7/7	0.11	11.2/7	0.13	11.3/7	0.13	10.4/7	0.17
	$\lvert y^{Z}\rvert$	2.8/8	0.95	2.9/8	0.94	4.0/8	0.85	2.7/8	0.95	2.9/8	0.94

Parton level Normalised cross section		MG5_aMC@NLO 2.3.3 + Pythia 8		MG5_aMC@NLO 2.3.3 + Herwig 7		Sherpa 2.2.1 NLO multi-leg		Sherpa 2.2.1 NLO inclusive		Additional Theory	
	Variable	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
3ℓ	$p_{\text{T}}^{\ell,\text{non-}Z}$	6.6/3	0.09	7.8/3	0.05	7.6/3	0.06	7.7/3	0.05	/	/
	$\lvert\Delta\phi(Z,t_{\text{lep}})\rvert$	3.9/2	0.14	4.7/2	0.09	4.6/2	0.10	5.9/2	0.05	6.4/2	0.04
	$\lvert\Delta y(Z,t_{\text{lep}})\rvert$	0.4/2	0.80	0.4/2	0.80	0.1/2	0.93	0.4/2	0.83	0.3/2	0.86
4ℓ	$\lvert\Delta\phi(\ell_t^+,\ell_{\bar{t}}^-)\rvert$	1.2/3	0.75	1.3/3	0.74	1.1/3	0.77	1.2/3	0.75	/	/
	$\lvert\Delta\phi(t\bar{t},Z)\rvert$	5.4/2	0.07	4.7/2	0.10	2.3/2	0.31	2.6/2	0.28	2.5/2	0.29
	$p_{\text{T}}^{t\bar{t}}$	4.0/3	0.26	3.9/3	0.28	3.5/3	0.32	3.5/3	0.32	3.0/3	0.39
$3\ell+4\ell$	p_{T}^{Z}	11.0/6	0.09	10.8/6	0.10	10.7/6	0.10	10.6/6	0.10	10.5/6	0.11
	$\lvert y^{Z}\rvert$	2.3/7	0.94	2.5/7	0.93	3.5/7	0.84	2.4/7	0.94	2.6/7	0.92