Using associated production of top quarks to neutral bosons to probe standard model couplings

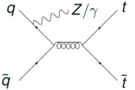
Michal Dubovsky[1], on behalf of ATLAS collaboration

[1]Comenius University, Bratislava

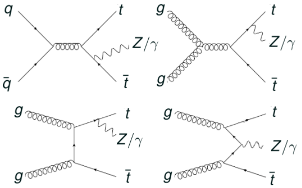
September 4, 2020

Introduction to $t\bar{t}Z$ and $t\bar{t}\gamma$ processes:

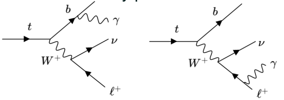
Initial state radiation (ISR)



Final state radiation (FSR)

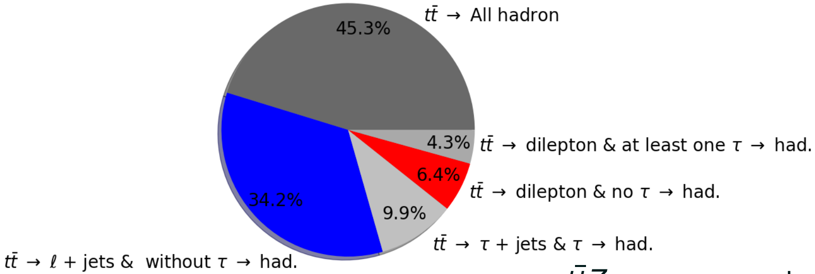


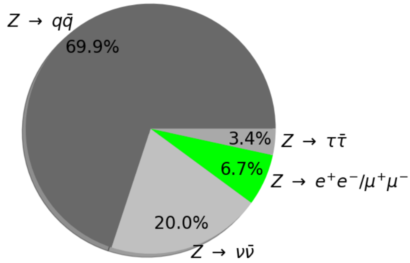
Photon can be also radiated by top-quark decay products:



- $t\bar{t}$ + Z/γ is similar to top-quark pair production.
- The neutral boson (Z or γ) can be radiated either by initial state quark, or by final state particles (such as top quarks).
- Compared to the top-quark pair production, the $t\bar{t}\gamma$ and $t\bar{t}Z$ production cross-sections are by far smaller.
- $\sigma_{t\bar{t}}$ = 832^{+40}_{-46} pb [arXiv:1303.6254]
- $\sigma_{t\bar{t}Z}$ = 863^{+70}_{-90}(scale)$\pm$30(PDF+α_S) fb [arXiv:1812.08622]
- $\sigma^{\mathrm{fiducial}}_{t\bar{t}\gamma}$ = $38.50^{+0.56}_{-2.18}$(scale)$^{+1.04}_{-1.18}$(PDF+α_S) fb [arXiv:1809.08562]

$t\bar{t}Z$ decay channels:



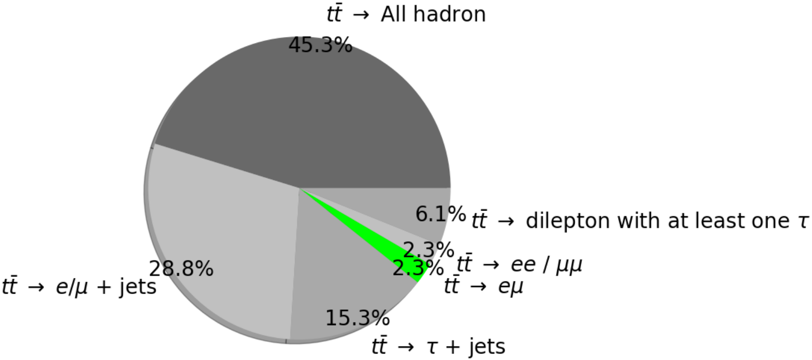


$t\bar{t}Z$ measurement targets 3ℓ and 4ℓ channels.

3ℓ channel:
$0.342 \times 0.067 = 2.3\ \%$
Full Run 2 $\approx$ 2800 events

4ℓ channel:
$0.064 \times 0.067 = 0.4\ \%$
Full Run 2 $\approx$ 480 events

$t\bar{t}\gamma$ decay channels:



- $t\bar{t}\gamma$ measurement targets dilepton $e\mu$ channel, without $\tau \to e/\mu$ decays
- Number of expected fiducial events in full Run 2 dataset (without any detector-level requirements): 38.5 fb $\times$ 139 fb^{-1} $\approx$ 5350

Motivation:

- Standard Model testing.
- The cross sections depend on the top-quark to boson coupling constant.
- $t\bar{t}Z$ depends on the Z to top-quark coupling (**top-quark weak isospin**).
- $t\bar{t}\gamma$ depends on the photon to top-quark coupling (**top-quark electric charge**).
- A deviation from SM prediction could point us to new physic.
- Both processes produce multilepton final states, which are important backgrounds for other measurements/searches.

Aims of the measurements:

$t\bar{t}Z$: [ATLAS-CONF-2020-028]

- Targeting 3ℓ and 4ℓ channels.
- Total inclusive cross-section.
- Differential cross section in 9 variables (unfolded to parton and particle level):

Variable	Channel
p_{T}^{Z}	$3\ell + 4\ell$
$\lvert y^{Z}\rvert$	$3\ell + 4\ell$
N_{jets}	3ℓ, 4ℓ
$p_{\mathrm{T}}^{t\bar{t}}$	4ℓ
$\Delta\phi(\ell_{t}^{+}, \ell_{\bar{t}}^{-})$	4ℓ
$\Delta\phi(t\bar{t}, Z)$	4ℓ
$p_{\mathrm{T}}^{\ell_{non-Z}}$	3ℓ
$\Delta\phi(Z, t_{\mathrm{lep}})$	3ℓ
$\Delta y(Z, t_{\mathrm{lep}})$	3ℓ

$t\bar{t}\gamma$: [arXiv:2007.06946]

- Accepted in JHEP.
- Targeting $e\mu$ channel.
- Fiducial inclusive cross-section.
- Differential cross section in 5 variables (unfolded to parton level):

Variable
$p_{\mathrm{T}}(\gamma)$
$\lvert\eta(\gamma)\rvert$
$\Delta R(\gamma, \ell)_{\mathrm{min}}$
$\Delta\phi(\ell, \ell)$
$\Delta\eta(\ell, \ell)$

Analysis methods:

Inclusive cross-section:

- Nuisance parameter fit is used for inclusive measurement
- Signal cross-section is free parameter of the fit.
- Systematic uncertainties are introduced through nuisance parameters with Gaussian constrains.

Differential cross-section:

- Iterative Bayesian Unfolding is employed [arXiv:1010.0632].
- The prior distribution is being iteratively corrected to better fit observed data.
- Number of iterations together with choice of prior distribution serve as regularization.

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

$t\bar{t}Z$ 3ℓ signal regions ($t\bar{t} \to \ell$+jets, $Z \to e^+e^-$ / $\mu^+\mu^-$):

Expected final state:

- 2 b-jets
- 2 light jets
- 3 leptons (two from Z, one from $t\bar{t}$)
- neutrino (E_T^{miss})

Main backgrounds:

- WZ+jets
- tZ
- tWZ
- fakes

Variable	3ℓ-Z-1b4j-PCBT	3ℓ-Z-2b3j-PCBT	3ℓ-Z-2b3j-diff
N_ℓ ($\ell = e, \mu$)	$= 3$	$= 3$	$= 3$
	OSSF pair	OSSF pair	OSSF pair
m_{OSSF}^{min}	> 10 GeV	> 10 GeV	> 10 GeV
$p_T(\ell_1)$	≥ 27 GeV	≥ 27 GeV	≥ 27 GeV
$p_T(\ell_{2,3})$	≥ 20 GeV	≥ 20 GeV	≥ 20 GeV
$\|m_{OSSF} - m_Z\|$	≤ 10 GeV	≤ 10 GeV	≤ 10 GeV
N_{jets}	≥ 4	≥ 3	≥ 3
$N_{\text{b-jets}}$	$= 1$(@60%) veto add. b-jets @70%	≥ 2@70%	≥ 2@85%

PCBT = pseudo-continuous b-tagging (regions used for inclusive measurement)
3ℓ-Z-2b3j-diff = region used for differential measurement
m_{OSSF}^{min} = minimal invariant mass of any OSSF lepton pair (suppresion of non-promt leptons)
$|m_{OSSF} - m_Z|$ = on-shell Z requirement

$t\bar{t}Z$ 4ℓ signal regions ($t\bar{t} \rightarrow$ dilep. $Z \rightarrow e^+e^-$ / $\mu^+\mu^-$):

Expected final state:

- 2 b-jets
- 4 leptons (two from Z, two from $t\bar{t}$)
- 2 neutrinos

Main backgrounds:

- ZZ
- tWZ

Event Selection:

- At least one Z-like pair (OSSF, $|M_{\ell\ell} - M_Z| < 10$ GeV)
- The other lepton pair has to be opposite sign
- $p_T^{1lep} > 27$ GeV, $p_T^{2lep} > 20$ GeV, $p_T^{3lep} > 10$ GeV
- $M_{\ell\ell} > 10$ GeV for all OSSF lepton pairs (fakes suppression)
- At least two jets, at least one of them b-tagged (@85%)

Region	$\ell\ell^{non-Z}$ leptons	$\|m_Z - m_{\ell\ell,non-Z}\|$	E_T^{miss}	$N_{b\text{-jets}}$ (@85%)
4ℓ-DF-1b	$e^\pm\mu^\mp$	-	-	== 1
4ℓ-DF-2b	$e^\pm\mu^\mp$	-	-	≥ 2
4ℓ-SF-1b	$e^\pm e^\mp, \mu^\pm\mu^\mp$	{ > 10 GeV < 10 GeV	> 50 GeV > 100 GeV }	== 1
4ℓ-SF-2b	$e^\pm e^\mp, \mu^\pm\mu^\mp$	{ > 10 GeV < 10 GeV	- > 50 GeV }	≥ 2

$t\bar{t}Z$ fiducial volume definitions:

3ℓ channel:

Parton level:

- Z decaying into ee or $\mu\mu$ pair.
- $|M_{\ell\ell Z} - M_Z| < 15$ GeV.
- $t\bar{t} \rightarrow e/\mu$ + jets.

Particle level:

- Exactly 3 leptons, at least one Z-like lepton pair.
- $p_T^{1lep} > 27$ GeV, $p_T^{2lep} > 20$ GeV, $p_T^{3lep} > 20$ GeV.
- At least 3 jets, at least two of them are b-jets

4ℓ channel:

Parton level:

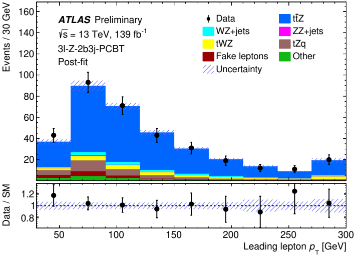
- Z decaying into ee or $\mu\mu$ pair.
- $|M_{\ell\ell Z} - M_Z| < 15$ GeV.
- $t\bar{t} \rightarrow$ dilepton, without taus.

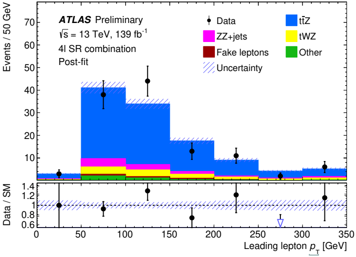
Particle level:

- Exactly 4 leptons, sum of their charges equal to zero, at least one Z-like lepton pair.
- $p_T^{1lep} > 27$ GeV, $p_T^{2lep} > 20$ GeV, $p_T^{3lep} > 10$ GeV.
- At least 2 jets, at least one of them are b-jets

$t\bar{t}Z$ events after selection:

Region	3ℓ-Z-$1b4j$ -PCBT	3ℓ-Z-$2b3j$ -PCBT	4ℓ-SF-$1b$	4ℓ-SF-$2b$	4ℓ-DF-$1b$	4ℓ-DF-$2b$	3ℓ-WZ-CR	4ℓ-ZZ-CR
$t\bar{t}Z$	**164 $\pm$ 14**	**210.0 $\pm$ 8.9**	**13.0 $\pm$ 1.6**	**23.3 $\pm$ 1.8**	**16.8 $\pm$ 1.4**	**22.5$\pm$ 1.0**	**44 $\pm$ 11**	**0.67 $\pm$ 0.11**
$WZ + l$	3.1 $\pm$ 2.3	0.34 $\pm$ 0.32	–	–	–	–	1160 $\pm$ 370	–
$WZ + b$	30 $\pm$ 18	16.0 $\pm$ 9.4	–	–	–	–	17 $\pm$ 10	–
$WZ + c$	12.5 $\pm$ 5.9	2.1 $\pm$ 1.0	–	–	–	–	230 $\pm$ 100	–
ZZ+jets	4.6 $\pm$ 1.8	2.4 $\pm$ 1.1	3.9 $\pm$ 1.4	5.0 $\pm$ 2.0	0.86 $\pm$ 0.23	0.121 $\pm$ 0.054	132 $\pm$ 22	496 $\pm$ 39
tWZ	23.7 $\pm$ 4.2	19.3 $\pm$ 7.1	2.65 $\pm$ 0.48	2.03 $\pm$ 0.78	3.6 $\pm$ 1.1	2.12 $\pm$ 0.88	13.3 $\pm$ 1.2	0.155 $\pm$ 0.058
tZq	11.7 $\pm$ 5.0	29.3 $\pm$ 9.3	–	–	–	–	9.1 $\pm$ 3.5	–
ttW/H	5.80 $\pm$ 0.85	10.1 $\pm$ 2.2	0.461 $\pm$ 0.056	0.862 $\pm$ 0.097	0.641 $\pm$ 0.069	0.754 $\pm$ 0.082	1.80 $\pm$ 0.38	0.012 $\pm$ 0.004
Fake leptons	30 $\pm$ 15	14.6 $\pm$ 7.4	0.68 $\pm$ 0.55	0.89 $\pm$ 0.75	0.85 $\pm$ 0.75	0.26 $\pm$ 0.26	86 $\pm$ 43	7.7 $\pm$ 3.6
Other	0.71 $\pm$ 0.36	1.46 $\pm$ 0.74	0.66 $\pm$ 0.34	0.25 $\pm$ 0.13	0.71 $\pm$ 0.36	0.22 $\pm$ 0.11	12.4 $\pm$ 6.4	0.93 $\pm$ 0.61
SM total	**286 $\pm$ 31**	**306 $\pm$ 21**	**21.3 $\pm$ 2.3**	**32.4 $\pm$ 3.0**	**23.4 $\pm$ 2.0**	**26.0 $\pm$ 1.5**	**1710 $\pm$ 390**	**505 $\pm$ 39**
Data	**272**	**343**	**19**	**33**	**33**	**32**	**1569**	**539**





$t\bar{t}Z$ inclusive cross section:

- Event yields in 6 signal regions and 2 control regions (table from the previous slide) are fitted.
- Three free parameters of the fit: Signal strength, normalizations of WZ+light and ZZ+light.

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	$1.19 \pm 0.06\,(\text{stat.})\,\pm 0.10\,(\text{syst.})$

$$\sigma(pp \to t\bar{t}Z) = 1.05 \pm 0.05\,(\text{stat.}) \pm 0.09\,(\text{syst.})\,\text{pb} = 1.05 \pm 0.10\,\text{pb}$$

- Result in a good agreement with theory prediction:

$$\sigma^{\text{NLO+NNLL}}_{t\bar{t}Z} = 0.863^{+0.07}_{-0.09}\,(\text{scale}) \pm 0.03\,(\text{PDF} + \alpha_{\text{s}})\text{ pb}$$

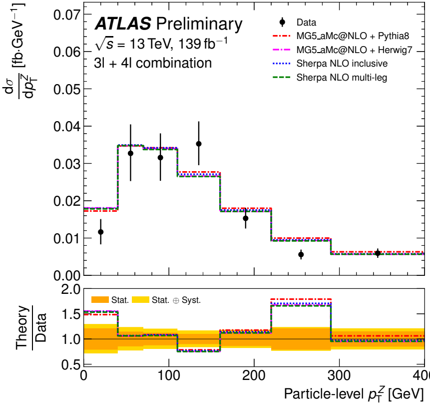
Leading systematic uncertainties:

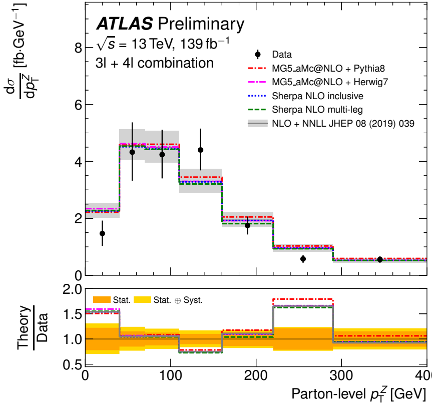
- $t\bar{t}Z$ parton shower = Pythia8 (nominal) vs. Herwig7
- tWZ modelling = Diagram removal schemes DR1 (nominal) vs. DR2

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
VV+jets modelling	2.8
tZq modelling	2.6
Lepton	2.3
Luminosity	2.2
Jets + $E_{\text{T}}^{\text{miss}}$	2.1
Non-prompt/fake leptons	2.1
$t\bar{t}Z$ A14 tune	1.6
$t\bar{t}Z$ μ_F, μ_F scales	0.9
Other backgrounds	0.7
Pile-up	0.7
$t\bar{t}Z$ PDF	0.2
Total systematic unc.	8.4
Statistical unc.	5.2
Total uncertainty	9.9

$t\bar{t}Z$ differential cross section:

- 9 variables are unfolded to particle and parton level.
- Unfolded data are compared to 4 MC generators and to NLO + NNLL theory prediction.
- Reasonable agreement between unfolded data and predictions.
- Migration matrix and corrections can be found in back-up.





$t\bar{t}\gamma$ + $tW\gamma$ signal region definition:

Detector-level:

- One muon, $p_{\mathrm{T}}^{\mu} > 25$ GeV
- One electron, $p_{\mathrm{T}}^{e} > 25$ GeV
- Additional 25-28 GeV (depends on data-taking year) requirement for p_T of the lepton that fired the trigger
- Opposite charge
- $M_{\ell\ell} > 15$ GeV
- At least 2 jets, at least one of them *b*-tagged at 85% efficiency
- One photon, $p_{\mathrm{T}}^{\gamma} > 20$ GeV

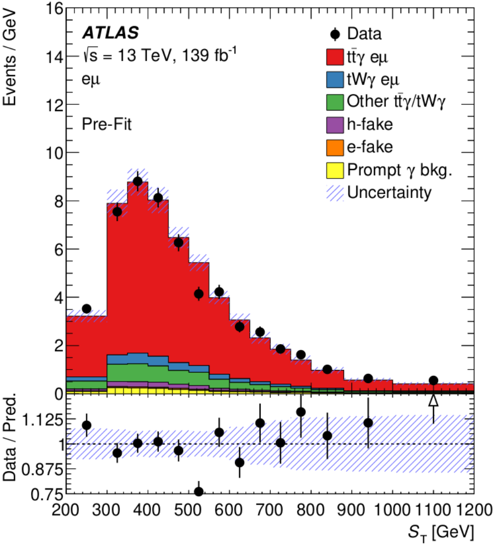
Parton-level (fiducial volume):

- $t\bar{t}/tW \to e\mu$, without intermediate taus
- Exactly one isolated photon, $p_{\mathrm{T}}^{\gamma} > 20$ GeV
- η, p_{T} cuts and overlap removal are applied in the same way as for detector-level objects

Events in $t\bar{t}\gamma$ + $tW\gamma$ signal region:

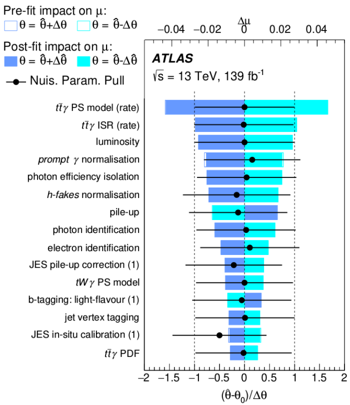
- MC in the table and plots is rescaled to match event yield in data, for display purposes.

Process	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



$t\bar{t}\gamma + tW\gamma$ inclusive fiducial cross section:

- S_{T} distribution is fitted.
- One free parameter of the fit: signal inclusive fiducial cross section.
- Good agreement between theory and measurement.



Leading systematic uncertainties:

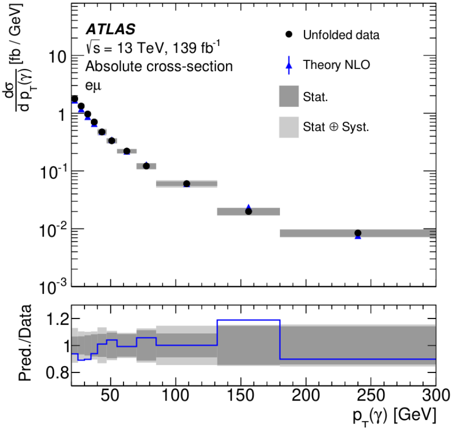
- $t\bar{t}\gamma$ PS model (rate) = Pythia8 (nominal) vs. Herwig7. Only normalization effect.
- $t\bar{t}\gamma$ ISR (rate) = Initial state radiation (*var3c* tune variations). Only normalization effect.

$$\sigma_{\mathrm{fid}}^{\mathrm{meas.}} = 39.6 \pm 0.8\,(\mathrm{stat.})^{+2.6}_{-2.2}\,(\mathrm{syst.})\,\mathrm{fb} = 39.6^{+2.7}_{-2.3}\,\mathrm{fb}$$

$$\sigma_{\mathrm{fid}}^{\mathrm{theo.}} = 38.50^{+0.56}_{-2.18}\,(\mathrm{scale})^{+1.04}_{-1.18}\,(\mathrm{PDF})\,\mathrm{fb}$$

$t\bar{t}\gamma + tW\gamma$ differential cross section:

- 5 variables are unfolded to parton-level: $p_{\mathrm{T}}(\gamma)$, $|\eta(\gamma)|$, $\Delta R(\gamma,\ell)_{\mathrm{min}}$, $\Delta\phi(\ell,\ell)$ and $\Delta\eta(\ell,\ell)$.
- The unfolded data are compared to 2 MC generators and NLO theory prediction.
- χ^2/ndf. and p-values are calculated. Good agreement between unfolded data and theory is observed (better for NLO).
- Migration matrix and corrections are in back-up.



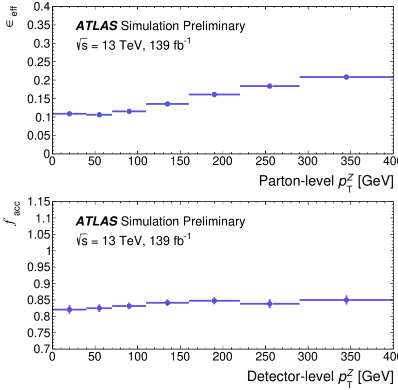
Predictions	$p_{\mathrm{T}}(\gamma)$ χ^2/ndf	$p_{\mathrm{T}}(\gamma)$ p-value	$\lvert\eta(\gamma)\rvert$ χ^2/ndf	$\lvert\eta(\gamma)\rvert$ p-value	$\Delta R(\gamma,\ell)_{\mathrm{min}}$ χ^2/ndf	$\Delta R(\gamma,\ell)_{\mathrm{min}}$ p-value	$\Delta\phi(\ell,\ell)$ χ^2/ndf	$\Delta\phi(\ell,\ell)$ p-value	$\lvert\Delta\eta(\ell,\ell)\rvert$ χ^2/ndf	$\lvert\Delta\eta(\ell,\ell)\rvert$ 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

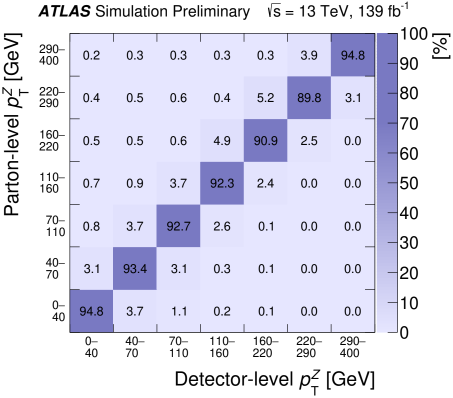
Conclusion:

- ATLAS Collaboration recently finalized $t\bar{t}Z$ and $t\bar{t}\gamma$+$tW\gamma$ differential and total cross-section measurements, using full Run 2 dataset corresponding to 139 fb^{-1}.
- Good agreement between theory and observation.
- **Total cross section uncertainty is dominated by systematics** and it approaches the precision of the best available theory calculation ($\approx$ 6% for $t\bar{t}\gamma$+$tW\gamma$ and $\approx$ 10% for $t\bar{t}Z$).
- **Differential cross-section** measurements are still **dominated by statistical uncertainty.**
- More details can be found in $t\bar{t}\gamma$ paper [arXiv:2007.06946] and $t\bar{t}Z$ conf note [ATLAS-CONF-2020-028]

Back-up slides

$t\bar{t}Z$, migration matrices and corrections for p_{TZ}:





$t\bar{t}\gamma$, migration matrices and corrections for $p_{T\gamma}$: