ATLAS Top + Boson Measurements

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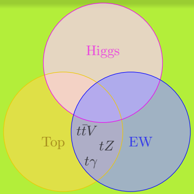
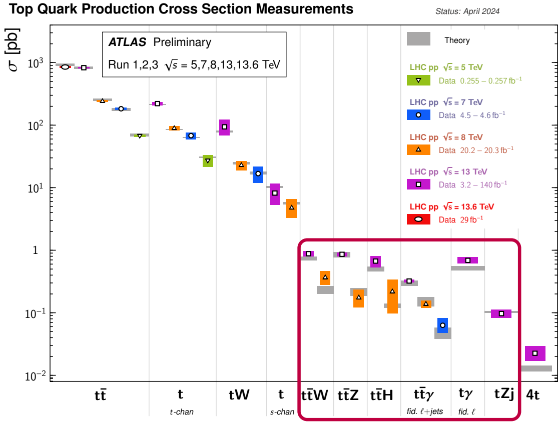
on behalf of the **ATLAS** collaboration

Top + boson (W, Z & γ) measurements

1. probe **electroweak couplings** of the top quarks to bosons
   - ↪ indirect searches for the BSM physics
   - ↪ sensitive to new physics → EFT interpretations
2. are important for several BSM searches & SM measurements ($t\bar{t}H$)
   - ↪ top + boson production as irreducible **background**
3. can improve **MC modelling** → differential measurements





⇒ rare processes

BUT: full Run 2 dataset available

⇒ precise measurements possible

Newer ATLAS results:

1. $tq\gamma$ & $A_C(t\bar{t}X)$
2. $t\bar{t}Z$
3. $t\bar{t}W$
4. $t\bar{t}\gamma$

Common characteristics:

- ↪ focused on leptonic final states
- ↪ ML techniques
- ↪ profile-likelihood approach

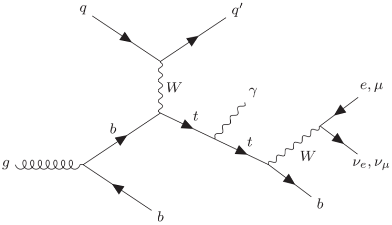
$tq\gamma$ & $A_C(t\bar{t}X)$

$tq\gamma$ observation

▸ Phys.Rev.Lett. 131 (2023) 181901

Main characteristics

- ↪ t-channel with γ emitted **before** or **after** top decay
- ↪ $tq\gamma$ observed with significance of 9.3σ ⇒ **first observation** of $tq\gamma$
- ↪ CMS: evidence with 35 fb^{-1}
  ▸ Phys. Rev. Lett. 121 (2018) 221802



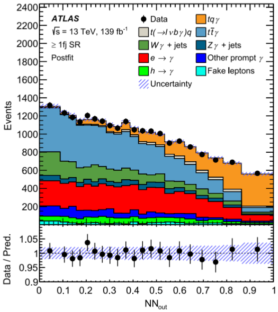
Parton-level fiducial cross section:

($t(\to \ell\nu b\gamma)q$ as background)

$$\sigma_{tq\gamma} \times \mathcal{B}(t \to \ell\nu b) = 688 \pm 23\,(\text{stat.})\,^{+75}_{-71}\,(\text{syst.})\,\text{fb}$$

MadGraph5 aMc@NLO:

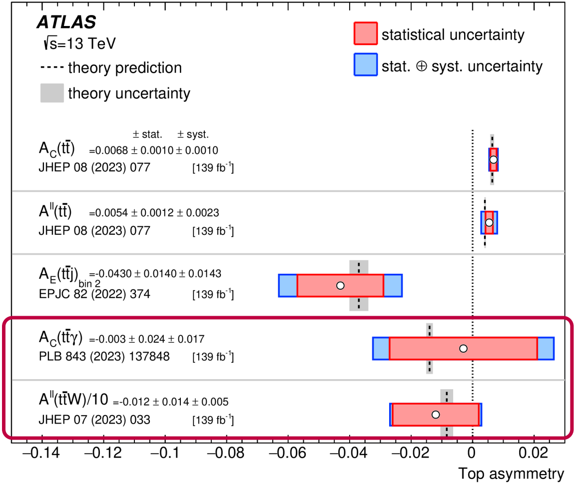
$$\sigma_{tq\gamma}^{\text{QCD+EW NLO}} = 515^{+36}_{-42}\,\text{fb}$$



Charge asymmetries in $t\bar{t}X$

- ↪ **enhanced** compared to $t\bar{t}$
  (larger fraction of $q\bar{q}$ initiated processes)
- ↪ first $A_C(t\bar{t}X)$ measurements:

1. **$t\bar{t}\gamma$ charge asymmetry**
   ▸ Phys. Lett. B 843 (2023) 137848
   - ↪ $A_C^{t\bar{t}}$ extracted from unfolded $|y_t| - |y_{\bar{t}}|$ distribution
2. **$t\bar{t}W$ charge asymmetry**
   ▸ JHEP 07 (2023) 033
   - ↪ A_C^{ℓ} extracted from $|\eta_\ell| - |\eta_{\bar{\ell}}|$ distribution at detector level



▸ arXiv:2404.10674

$t\bar{t}Z$

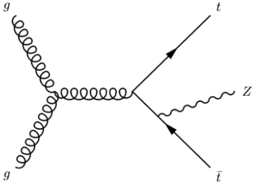
Refined $t\bar{t}Z$ measurement

▸ arXiv:2312.04450

↪ refines the previous ATLAS $t\bar{t}Z$ analysis
▸ Eur. Phys. J. C 81 (2021) 737

↪ the same dataset, but multiple **improvements**:

- 2ℓ channel included
- improved methodology
- precision recommendations



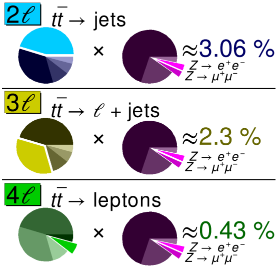
Analysis strategy

↪ signal-background separation with **NN**

- 2ℓ & 4ℓ: binary
- 3ℓ: multi-class
- NN output used for definition of regions

↪ main backgrounds:

1. 2ℓ: data-driven $t\bar{t}$, $Z + \mathrm{c/b}$ from the fit
2. 3ℓ & 4ℓ: WZ & ZZ control regions
3. fakes: **Fake Factor method**



Refined $t\bar{t}Z$ measurement ▸ arXiv:2312.04450 - **Inclusive xSec**

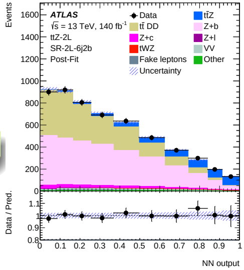
- ↪ 2ℓ, 3ℓ and 4ℓ decay channels
- ↪ simultaneous **profile-likelihood fit** to NN outputs in all regions

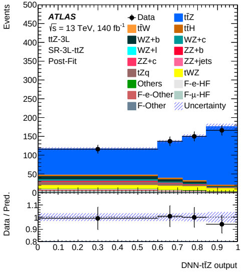
$$\sigma_{t\bar{t}Z} = 0.86 \pm 0.05\,\mathrm{pb} = 0.86 \pm 0.04\,(\mathrm{stat.}) \pm 0.04\,(\mathrm{syst.})\,\mathrm{pb}$$

- ↪ relative precision of **6.5%**
- ↪ **35%** improvement with NN, 2ℓ & latest systematic recommendations
- ↪ **systematic component reduced by 50%**
- ↪ leading systematics: background normalisations, jets + $E_{\mathrm{T}}^{\mathrm{miss}}$ and b-tagging
- ↪ in very good agreement with NLO+NNLL+EW SM prediction:

$$\sigma_{t\bar{t}Z} = 0.86^{+0.07}_{-0.08}(\mathrm{scale}) \pm 0.03(\mathrm{PDF} + \alpha_S)\,\mathrm{pb}$$

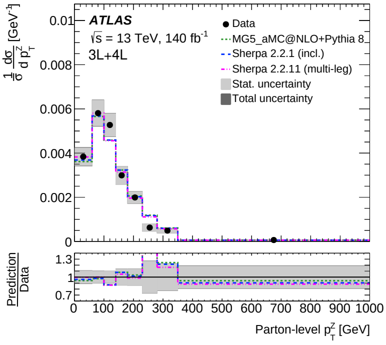
▸ Eur. Phys. J. C 79 (2019) 249

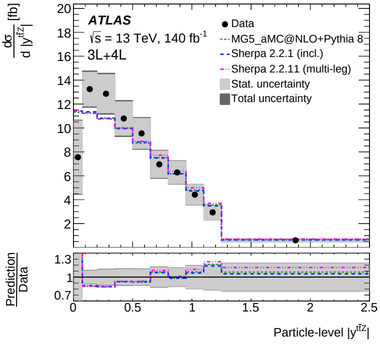




Refined $t\bar{t}Z$ measurement ▸ arXiv:2312.04450 - **Differential xSec**

- ↪ **profile-likelihood unfolding** in 3ℓ & 4ℓ channels
- ↪ 17 observables sensitive to EFT operators & MC modelling
- ↪ **regularisation** used for variables which require reconstruction of hadronic top
- ↪ both particle & parton-level and absolute & normalised measurements
- ↪ all measurements **statistically** limited
- ↪ full likelihoods available ▸ 10.17182/hepdata.146693.v1





Refined $t\bar{t}Z$ measurement ▸ arXiv:2312.04450 - **Spin correlations**

↪ **for the 1st time $t\bar{t}Z$ events** used for extraction of $t\bar{t}$ spin correlations from angular distributions

↪ angular distributions averages in $3\ell + 4\ell \rightarrow$ the coefficients of **spin density matrix**

↪ low stats in $4\ell \rightarrow$ non-zero coefficients obtained from **detector-level template fit**

↪ each observable $\mathcal{O}$ fitted to linear combination of spin-on and spin-off hypotheses:

$$\mathcal{O} = f_{\rm SM} \cdot \mathcal{O}_{\rm spin-on} + (1 - f_{\rm SM}) \cdot \mathcal{O}_{\rm spin-off}$$

POI
= 1 for SM-like correlations
= 0 for no correlations

SM-like template

∄ spin correlations

↪ $f_{\rm SM}$ values combined with **profiled χ^2-fit**:

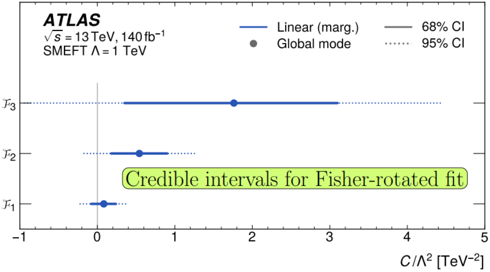
$$f_{\rm SM}^{\rm obs.} = 1.20 \pm 0.63\ ({\rm stat.}) \pm 0.25\ ({\rm syst.}) = 1.20 \pm 0.68\ ({\rm tot.})$$

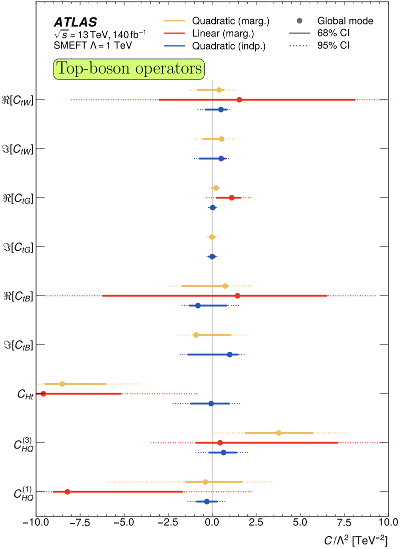
↪ spin-off hypothesis rejected with significance of 1.8σ

↪ statistically limited

Refined $t\bar{t}Z$ measurement ▸ arXiv:2312.04450 – EFT interpretation

- ↪ 20 dimension-6 SMEFT operators considered (**top-boson** & **four-quark**)
- ↪ input: **normalised particle-level differential distributions**
- ↪ linear and quadratic fits
- ↪ inverse covariance matrix rotated into the space of the Wilson coefficients → Fisher information matrix → sensitivity to directions in the space of Wilson coefficients





$t\bar{t}W$

Inclusive & differential $t\bar{t}W$ measurement

JHEP 05 (2024) 131

↪ demanding process for modelling:
- polarisation of initial-state quark if W as ISR
- charge-asymmetric production
- complex higher-order QCD and EWK corrections

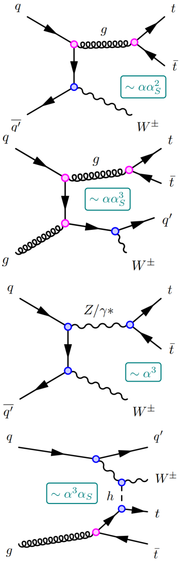
↪ previous $t\bar{t}W$ measurements: **higher cross section than SM prediction**!

Analysis strategy

↪ final states with **2 same-sign (SS)** or **3** leptons

↪ channels split into signal regions based on lepton charge, lepton flavour, N_{jets} & $N_{b-\text{jets}}$

↪ main backgrounds:
1. fakes suppressed with BDTs
2. $t\bar{t}Z$: Z mass criterion in SRs
3. $t\bar{t}Z$, diboson & fakes: dedicated control regions

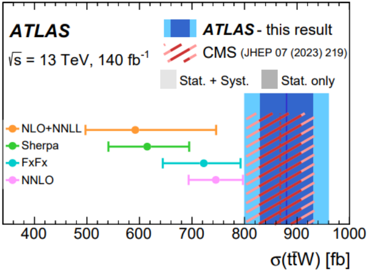


$t\bar{t}W$ measurement ▸ JHEP 05 (2024) 131 - Inclusive xSec

$$\sigma_{t\bar{t}W} = 880 \pm 50\,(\mathrm{stat.}) \pm 70\,(\mathrm{syst.})\,\mathrm{fb} = 880 \pm 80\,\mathrm{fb}$$

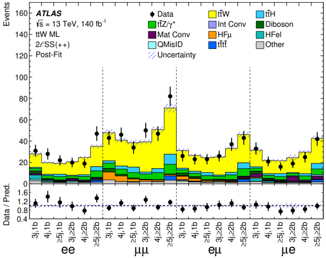
↪ 1.4σ deviation from NNLO QCD + NLO EW prediction

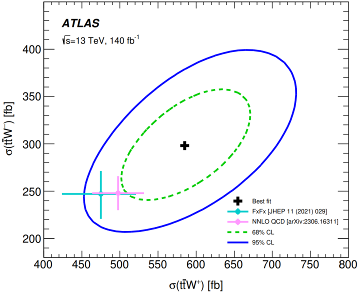
▸ Phys. Rev. Lett. 131 (2023) 231901



↪ strong charge asymmetry due to the asymmetry in the valence quark PDF → $\sigma_{t\bar{t}W^+}$ & $\sigma_{t\bar{t}W^-}$ measured as well

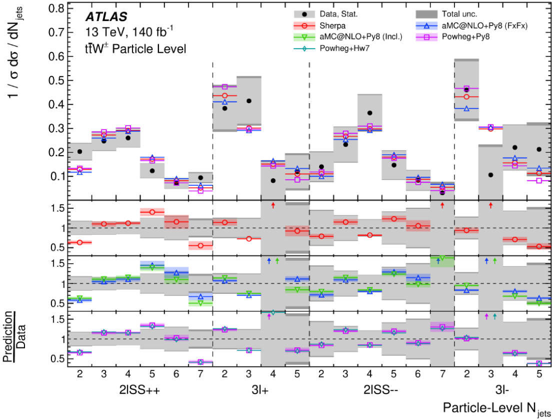
$$R(t\bar{t}W) = \frac{\sigma_{t\bar{t}W^+}}{\sigma_{t\bar{t}W^-}} = 1.96 \pm 0.21\,(\mathrm{stat.}) \pm 0.09\,(\mathrm{syst.})$$





$t\bar{t}W$ measurement ▸ JHEP 05 (2024) 131 - **Differential xSec**

- ↪ six observables sensitive to **MC modelling** or **NLO corrections** at particle level
- ↪ unfolding to fiducial regions split by lepton multiplicity & charge
- ↪ also **normalised** differential cross sections & differential **charge asymmetry** measurements
- ↪ dominated by **statistical** uncertainty



$t\bar{t}\gamma$

Inclusive & differential $t\bar{t}\gamma$ measurement

arXiv:2403.09452

↪ focused on $t\bar{t}\gamma$ with γ **from production**

- $=$ **$t\bar{t}\gamma$ production**
- γ radiated from initial-state parton or off-shell top
- sensitive to $t\gamma$ coupling
- measured separately from $t\bar{t}\gamma$ decay **(not measured before)**

Analysis strategy

↪ **single-lepton** and **dilepton** channels

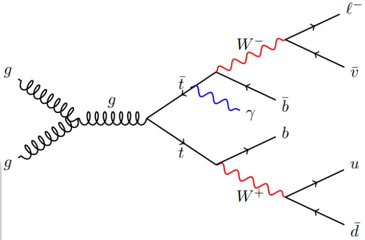
↪ **NNs** used for background suppression

- multi-class in single-lepton
- binary in dilepton

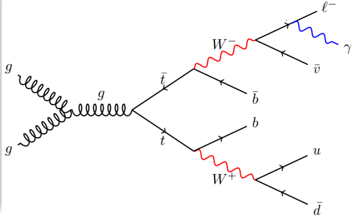
↪ main backgrounds:

1. $t\bar{t}\gamma$ decay dominates, separated with NN
2. misidentified photons ($e \to \gamma$, hadron $\to \gamma$) $\to$ data-driven estimates
3. lepton fakes $\to$ matrix method

$t\bar{t}\gamma$ production



$t\bar{t}\gamma$ decay



$t\bar{t}\gamma$ measurement ▸ arXiv:2403.09452 - Inclusive xSec

↪ extracted from signal and control regions defined by NN outputs

↪ particle-level fiducial phase space

$$\sigma_{t\bar{t}\gamma\,\text{production}} = 322^{+16}_{-15}\,\text{fb} = 322 \pm 5\,(\text{stat}) \pm 15\,(\text{syst})\,\text{fb}$$

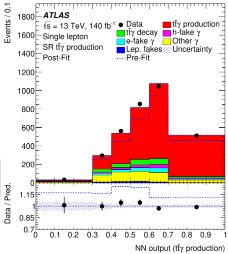
↪ $t\bar{t}\gamma$ production measured **separately** for the **first** time

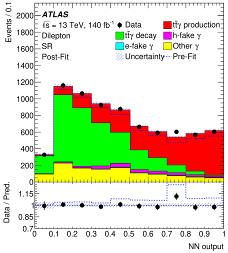
↪ relative uncertainty of **5.2%**

↪ **systematically** limited: $t\bar{t}\gamma$ modelling, $t\bar{t}\gamma$ decay normalisation, jets & b-tagging

↪ **slightly higher** than the MadGraph5 aMC@NLO prediction

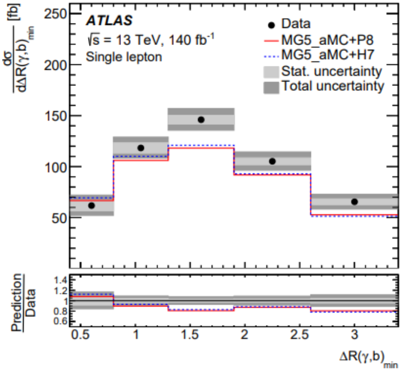
$$\sigma^{\text{production}}_{t\bar{t}\gamma} = 299^{+29}_{-30}\,(\text{scale})\,^{+7}_{-4}\,(\text{PDF})\,\text{fb}$$

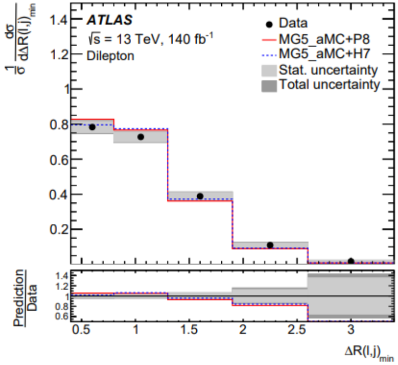




$t\bar{t}\gamma$ measurement arXiv:2403.09452 - **Differential xSec**

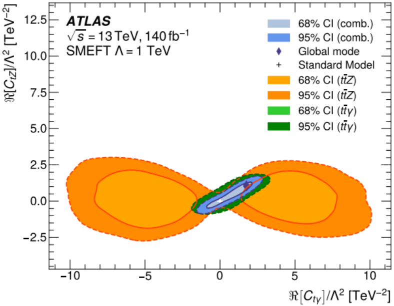
- ↪ observables sensitive to $t\gamma$ coupling unfolded to **particle**-level
- ↪ both **absolute** & **normalised** measurements
- ↪ performed separately for $t\bar{t}\gamma$ production and combination of $t\bar{t}\gamma$ production + decay
- ↪ total uncertainty varies from 8% to 20% in combination & single-lepton
- ↪ dilepton channel is statistically limited

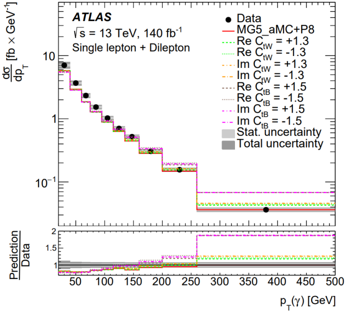


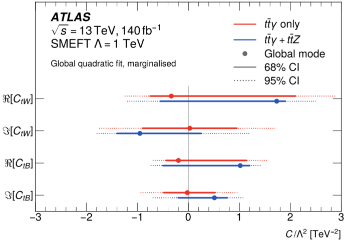


$t\bar{t}\gamma$ measurement ▸ arXiv:2403.09452 - **EFT interpretation**

- ↪ $t\bar{t}\gamma$ is most sensitive to C_{tB} & C_{tW} EFT operators (linear combinations of $C_{t\gamma}$ & C_{tZ})
- ↪ limits set from p_{T}^{γ} distribution
- ↪ $t\bar{t}Z$ is sensitive to C_{tB} and C_{tW} as well ⇒ also combined EFT interpretation with the refined $t\bar{t}Z$ measurement ▸ arXiv:2312.04450 (simultaneous unfolding of p_{T}^{γ} & p_{T}^{Z})



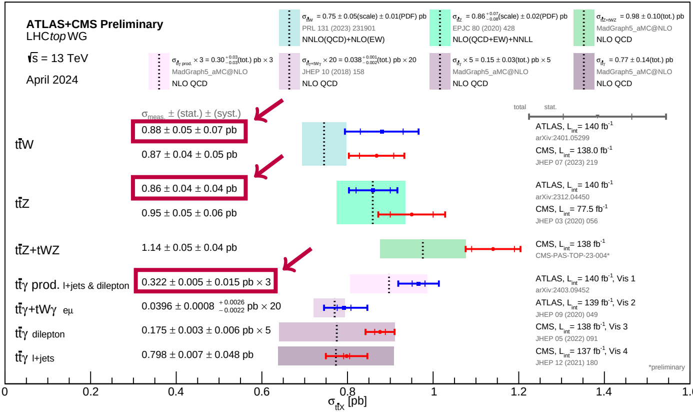




Summary

↪ top + boson **inclusive xSec** measurements reached precision regime:

1. $t\bar{t}Z$: 35% improvement with the same dataset
2. $t\bar{t}W$: theory moving closer to experimental results
3. $t\bar{t}\gamma$: production measured separately for first time



↪ top + boson **differential xSec** measurements are mostly statistically limited

↪ first EFT interpretations in $t\bar{t}Z$ and $t\bar{t}\gamma$ measurements

BACKUP

$t\bar{t}Z$

arXiv:2312.04450

Refined $t\bar{t}Z$ measurement arXiv:2312.04450 – **Inclusive and differential**

	$\sigma_{t\bar{t}Z}$ [pb]	Relative uncertainty [%]
Theory Eur. Phys. J. C 79 (2019) 249	$0.86^{+0.07}_{-0.08}(\text{scale}) \pm 0.03(\text{PDF} + \alpha_S)$	≈ 10
Previous analysis	$0.99 \pm 0.05(\text{stat.}) \pm 0.08(\text{syst.})$	≈ 10
Combination $(2\ell + 3\ell + 4\ell)$	$0.86 \pm 0.05\,\text{pb} = 0.86 \pm 0.04\,(\text{stat.}) \pm 0.04\,(\text{syst.})$	≈ 6.5
$\hookrightarrow$ Dilepton	$0.84 \pm 0.11\,\text{pb} = 0.84 \pm 0.06\,(\text{stat.}) \pm 0.09\,(\text{syst.})$	≈ 13
$\hookrightarrow$ Trilepton	$0.84 \pm 0.07\,\text{pb} = 0.84 \pm 0.05\,(\text{stat.}) \pm 0.05\,(\text{syst.})$	≈ 8.4
$\hookrightarrow$ Tetralepton	$0.97\,^{+0.13}_{-0.12}\,\text{pb} = 0.97 \pm 0.11\,(\text{stat.}) \pm 0.05\,(\text{syst.})$	≈ 13

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

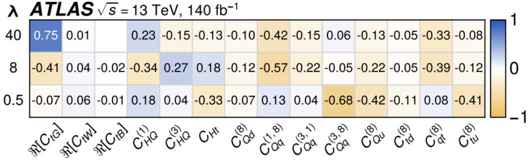
Uncertainty Category	$\Delta\sigma_{t\bar{t}Z}/\sigma_{t\bar{t}Z}$ [%]
Background normalisations	2.0
Jets and E_T^{miss}	1.9
b-tagging	1.7
$t\bar{t}Z$ μ_F and μ_R scales	1.6
Leptons	1.6
Z+jets modelling	1.5
tWZ modelling	1.1
$t\bar{t}Z$ showering	1.0
$t\bar{t}Z$ A14	1.0
Luminosity	1.0
Diboson modelling	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

Refined $t\bar{t}Z$ measurement ▸ arXiv:2312.04450 – Interpretations

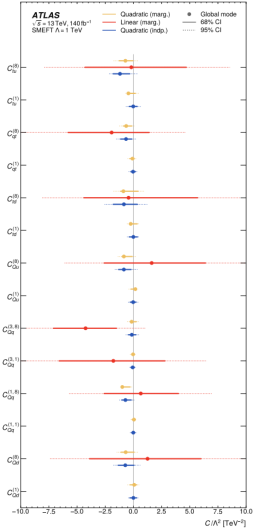
- $\hookrightarrow$ θ: **the polar angle** of the charged lepton or down-type quark from $t/\bar{t}$ with respect to one of the three axes (k, n, r) in $t\bar{t}$ rest frame
- $\hookrightarrow$ φ: **the opening angle** between $\ell^{\pm}\ell^{\mp}/\ell s$

Distribution	Channel	Expected values	Observed values
$\cos\varphi$	$3\ell + 4\ell$	$1^{+1.39}_{-1.38}$	$-0.09^{+1.34}_{-1.28}$
$\cos\theta_r^+ \cdot \cos\theta_r^-$	$3\ell + 4\ell$	$1^{+1.83}_{-1.82}$	$1.17^{+1.80}_{-1.76}$
$\cos\theta_k^+ \cdot \cos\theta_k^-$	$3\ell + 4\ell$	$1^{+1.78}_{-1.78}$	$1.39^{+1.72}_{-1.73}$
$\cos\theta_n^+ \cdot \cos\theta_n^-$	$3\ell + 4\ell$	$1^{+1.87}_{-1.86}$	$-1.05^{+2.06}_{-1.96}$
$\cos\theta_r^+ \cdot \cos\theta_k^- + \cos\theta_r^- \cdot \cos\theta_k^+$	$3\ell + 4\ell$	$1^{+1.93}_{-1.93}$	$0.36^{+1.99}_{-1.93}$
$\cos\theta_r^+$	$3\ell + 4\ell$	$1^{+1.81}_{-1.80}$	$1.56^{+1.86}_{-1.98}$
$\cos\theta_r^-$	$3\ell + 4\ell$	$1^{+1.82}_{-1.78}$	$1.81^{+1.63}_{-1.68}$
$\cos\theta_k^+$	$3\ell + 4\ell$	$1^{+1.69}_{-1.67}$	$2.00^{+1.65}_{-1.70}$
$\cos\theta_k^-$	$3\ell + 4\ell$	$1^{+1.68}_{-1.68}$	$2.31^{+1.68}_{-1.68}$

Fisher information matrix



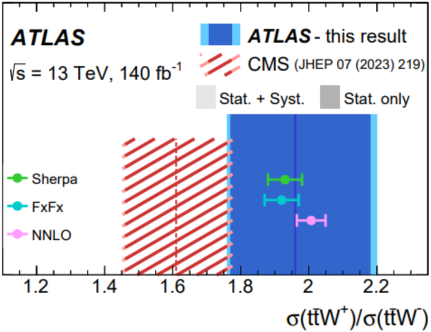
Four-quark operators



$t\bar{t}W$

JHEP 05 (2024) 131

$t\bar{t}W$ measurement ▸ JHEP 05 (2024) 131



$A_C^{\text{rel}} = 0.33 \pm 0.05(\text{stat.}) \pm 0.02(\text{syst.}) = 0.33 \pm 0.05$

	$\frac{\Delta\sigma(t\bar{t}W)}{\sigma(t\bar{t}W)}$ [%]
$t\bar{t}W$ ME modelling	6.0
Prompt-lepton bkg. norm.	3.1
Lepton isolation BDT	2.3
Fakes/VV/$t\bar{t}Z$ norm. (free to vary)	2.3
Non-prompt-lepton bkg. modelling	2.0
Trigger	1.9
MC statistics	1.5
$t\bar{t}W$ PDF	1.5
Jet energy scale	1.3
Prompt-lepton bkg. modelling	1.3
Luminosity	0.9
Charge Mis-ID	0.7
Jet energy resolution	0.5
Flavour tagging	0.4
$t\bar{t}W$ PS modelling	0.4
$t\bar{t}W$ scale	0.24
Electron/photon reconstruction	0.21
Muon	0.15
E_T^{miss}	<0.10
Pile-up	<0.10
Total systematic uncertainty	8
Statistical uncertainty	5
Total	9

Differential variables:

$\hookrightarrow$ N_{jets}, H_T^{jet}, H_T^{lep}, $\Delta R_{\ell b,\text{lead}}$, $|\Delta\phi_{\ell\ell,\text{SS}}|$ & $|\Delta\eta_{\ell\ell,\text{SS}}|$

$t\bar{t}\gamma$

▸ arXiv:2403.09452

$t\bar{t}\gamma$ measurement

▸ arXiv:2403.09452

Source	$\Delta\sigma_{t\bar{t}\gamma\text{ production}}/\sigma_{t\bar{t}\gamma\text{ production}}$ (%) Single lepton	Dilepton	Combination
Statistical uncertainty	1.8	3.3	1.5
MC statistical uncertainties	1.5	1.5	1.0
Modelling uncertainties			
$t\bar{t}\gamma$ production PS uncertainty	2.4	3.7	0.9
Other $t\bar{t}\gamma$ production modelling	5.1	1.6	3.0
$t\bar{t}\gamma$ decay modelling	0.3	1.3	0.8
$t\bar{t}\gamma$ decay normalisation	2.4	3.1	2.1
Prompt photon background normalisation	1.5	2.0	2.0
Fake photon background estimate	0.8	1.5	1.6
Fake lepton background estimate	0.4	–	0.1
Other Background modelling	0.7	0.2	0.5
Experimental uncertainties			
Jet uncertainties	3.5	3.0	1.7
B-tagging uncertainties	2.6	2.1	1.0
Photon	0.5	1.5	0.8
Lepton	1.3	1.4	1.3
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.3	0.4	0.4
Pile-up	0.3	0.7	0.5
Luminosity	0.8	1.0	0.8
Total systematic uncertainty	7.6	7.1	5.0
Total uncertainty	7.8	7.7	5.2

Both channels

$p_{\mathrm{T}}(\gamma)$

$|\eta(\gamma)|$

$\Delta R(\gamma,\ell)_{\mathrm{min}}$

$\Delta R(\gamma,b)_{\mathrm{min}}$

$\Delta R(\ell,j)_{\mathrm{min}}$

$p_{\mathrm{T}}(j_1)$

Dilepton channel

$\Delta R(\gamma,\ell_1)$

$\Delta R(\gamma,\ell_2)$

$|\Delta\eta(\ell,\ell)|$

$\Delta\phi(\ell,\ell)$

$p_{\mathrm{T}}(\ell,\ell)$