Inclusive and differential $t\bar{t}Z$ cross-section measurement, including interpretations, with the full ATLAS Run 2 dataset

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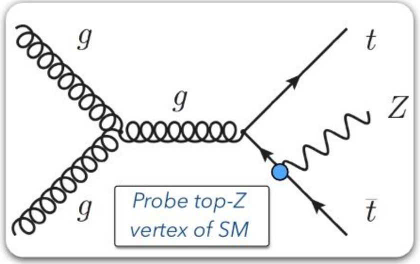
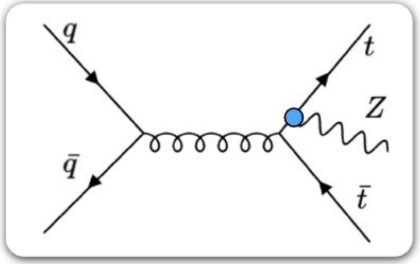
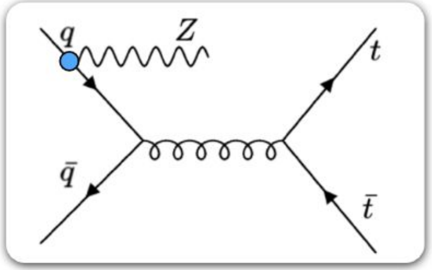
on behalf of the ATLAS Collaboration

LHC TOP WG meeting (29.11.2023)

Introduction



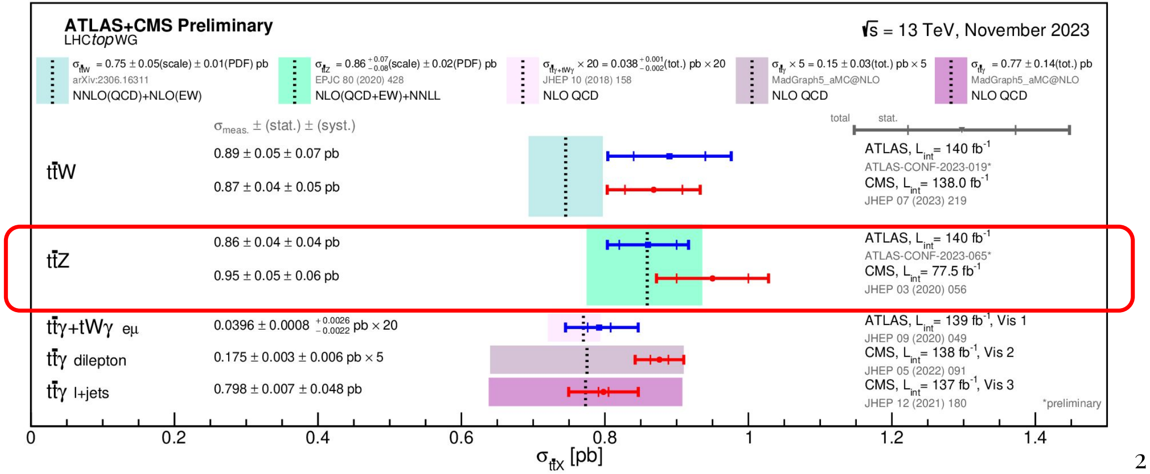




- tt̄Z - **rare process** → provides stringent tests of SM
- **Important background** for LHC searches (tt̄H, tt̄tt̄, tZ, BSM searches)
- Sensitivity to **BSM physics** affecting **tZ coupling**
- Measurements aimed at improving previous <u>inclusive</u> and <u>differential</u> results + adding <u>SMEFT</u> and <u>spin-correlations</u> interpretation

ATLAS-CONF-2023-065

- Refined measurement **building upon previous ATLAS result** (*EPJC 81 (2021) 737*)
- **Z→ee̅/μμ̅**, 3 channels according to **tt̄** decay →**2l** - all hadronic, **3l** - l+jets, **4l** - dileptonic)



Analysis overview

Previous ttZ results:

inclusive + **differential** 13 TeV; 139 fb^{-1}

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$$\sigma_{t\bar{t}Z} = 0.99 \pm 0.05(\text{stat.}) \pm 0.08(\text{syst.})\ \text{pb}$$

$$\frac{\delta\sigma_{t\bar{t}Z}}{\sigma_{t\bar{t}Z}} \approx 9.5\%$$

inclusive + **differential** + **EFT** 13 TeV; 77.5 fb^{-1}

JHEP 03 (2020) 056

$$\sigma_{t\bar{t}Z} = 0.95 \pm 0.05(\text{stat.}) \pm 0.06(\text{syst.})\ \text{pb}$$

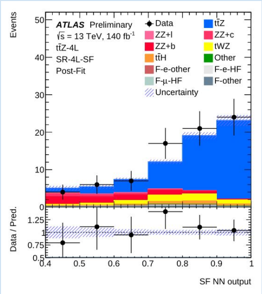
$$\frac{\delta\sigma_{t\bar{t}Z}}{\sigma_{t\bar{t}Z}} \approx 8.2\%$$

This analysis:

- **Full Run 2 data** (140 fb^{-1})
- Legacy $t\bar{t}Z$ measurement
- Improving previous result **using same dataset**

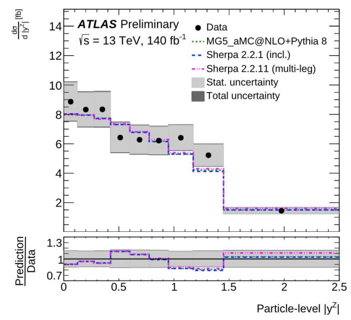
1.) Inclusive xs

- Addition of **2lOS channel** (previously only 3l and 4l)
- **DNNs** for region definitions and fit input



2.) Differential xs

- **New variables** (17 vs. 9)
- New unfolding technique (**PLU**) with regularisation



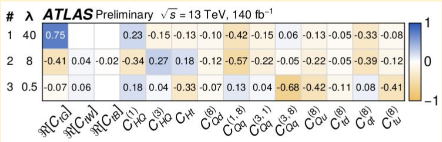
3.) Spin correlations

- **First** interpretation for $t\bar{t}Z$
- **9 angular distributions**
- **Detector-level fit**

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

4.) EFT interpretation

- **20 dim-6 operators**
- Linear and quadratic fits
- **Fisher information matrix**



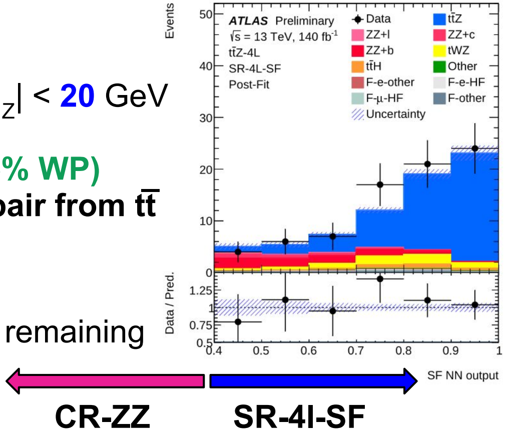
Analysis regions

Dilepton

- 1 **OSSF (opposite-sign-same-flavour) lepton pair** with $|m_{ll}-m_Z| < 10$ GeV
- $p_T^l >$ **30, 15** GeV
- SRs inspired by the **36 fb^{-1} analysis**
- **3 SRs based on jet and b-jet multiplicity:**
    - **SR-2l-5j2b, SR-2l-6j1b, SR-2l-6j2b**

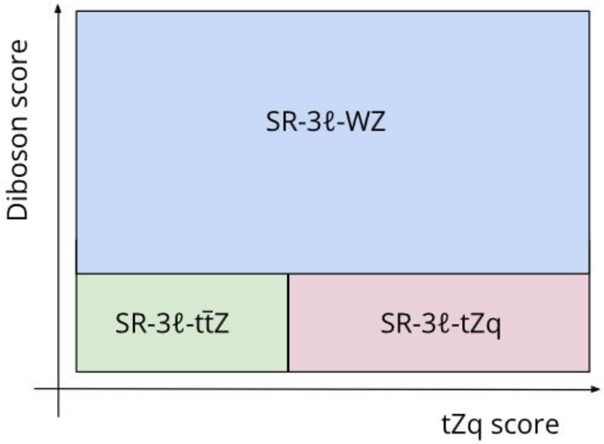
Tetralepton

- At least **1 OSSF lepton pair** with $|m_{ll}-m_Z| < 20$ GeV
- $p_T^l >$ **27, 7, 7, 7** GeV
- At least 2 jets and **1 b-tagged jet (@85% WP)**
- **2 SRs based on flavor of the lepton pair from $t\bar{t}$**
    - **SR-4l-SF, SR-4l-DF**
- **DNN > 0.4 used to define SF region** - remaining part used for ZZ control region



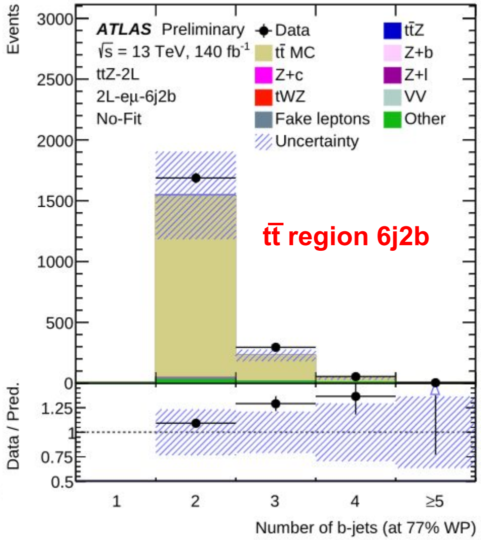
Trilepton

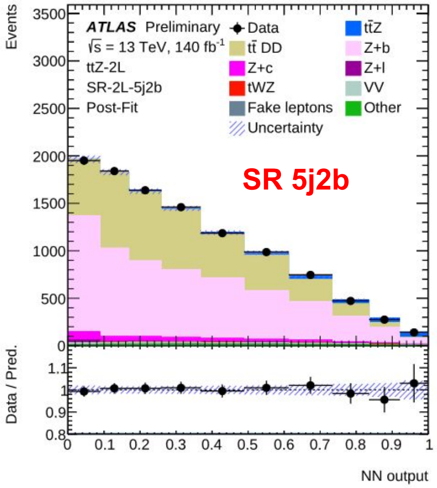
- At least **1 OSSF lepton pair** with $|m_{ll}-m_Z| < 10$ GeV
- $p_T^l >$ **27, 20, 15** GeV
- At least 3 jets and **1 b-tagged jet (@85% WP)**
- **3 orthogonal SRs** based on output nodes from **multi-class DNN**:
    - **SR-3l-$t\bar{t}$Z, SR-3l-tZq, SR-3l-WZ**

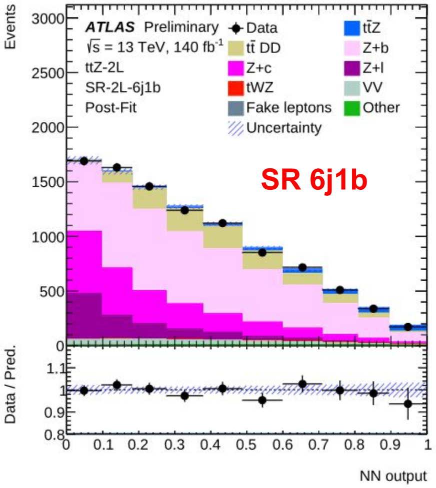


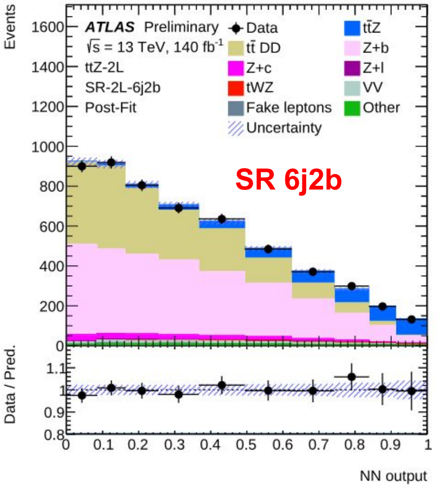
2l channel strategy

- 2l channel **only in the inclusive** measurement
- **DNN outputs** in each SR **used for Profile likelihood fit (PLF)**
- Dominant backgrounds: dileptonic $t\bar{t}$ and Z+jets
- **Normalisations** of **Z+b** and **Z+c** free parameters of the fit









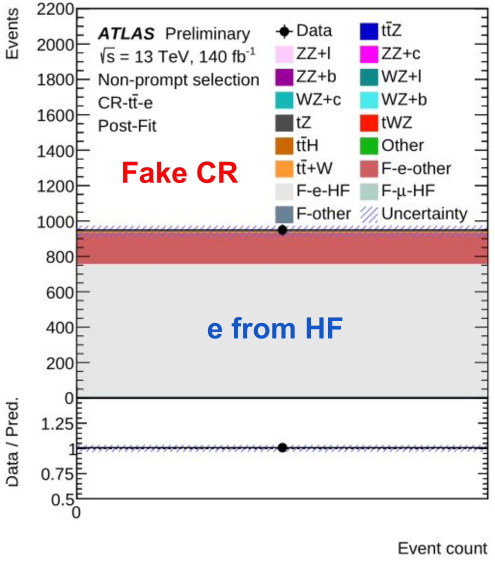
$t\bar{t}$ poorly modelled → **data-driven estimate**:

- $t\bar{t}$ regions defined **similar to SRs**, but **OSSF → OSDF**
- Very pure regions
- **$t\bar{t}$ estimation in SRs** = (**data in $t\bar{t}$ regions** - **non-$t\bar{t}$ background in $t\bar{t}$ regions**) * $\mathbf{C_{t\bar{t}}}$

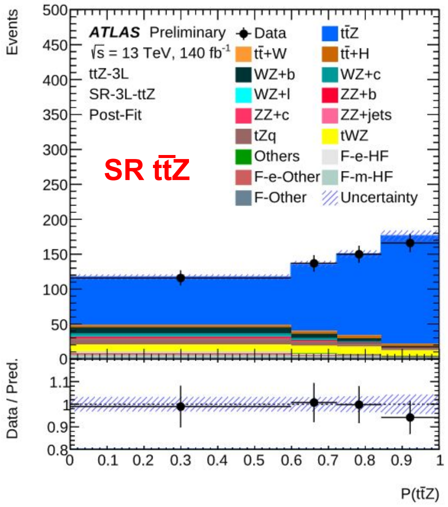
$$C_{t\bar{t}} = \frac{N^{\ell\ell}_{t\bar{t}}}{N^{e\mu}_{t\bar{t}}},$$

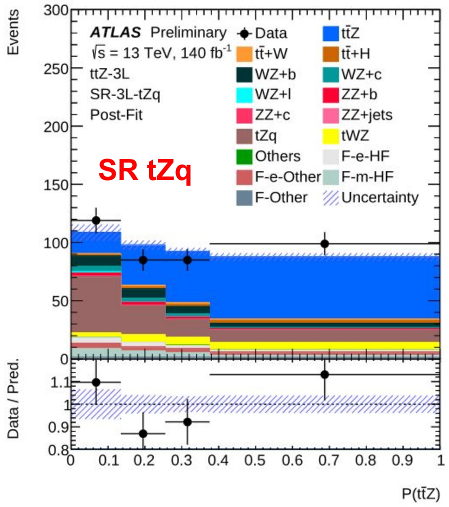
3l channel strategy

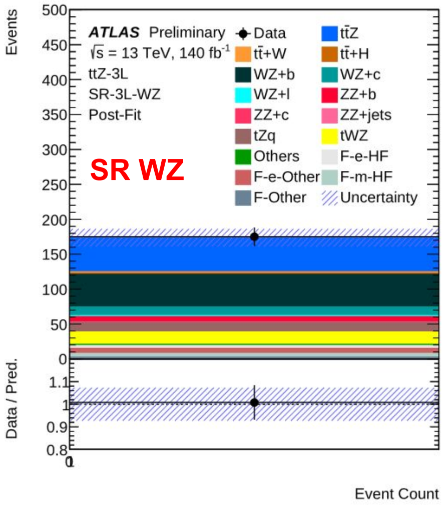
- **Multi-class DNN** - **$t\bar{t}Z$**, **tZq**, **WZ** output nodes
- **$t\bar{t}Z$** node output fitted, **tZq** and **WZ** used for SR definitions
- **WZ+b** normalisation **measured in the fit**
- **tZq fixed** to SM (low stats)



- **Non-prompt/fake leptons** relevant for **3l** and **4l** - **dedicated CRs**
- **4 categories** defined using <u>loose selection</u>
  - **F-e-HF**
  - **F-μ-HF**
  - **F-e-Other**
  - **F-Other** (form MC)

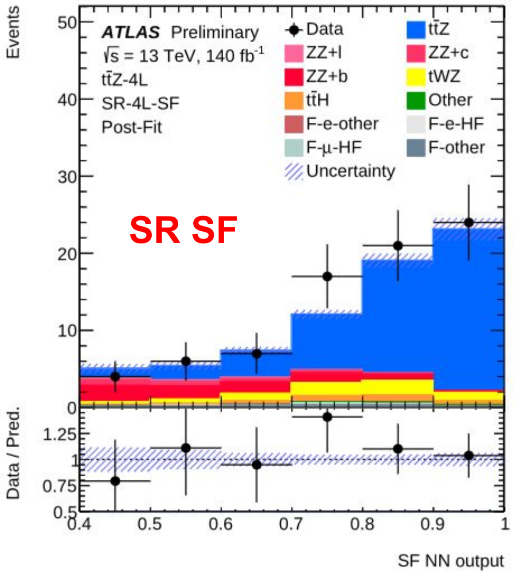


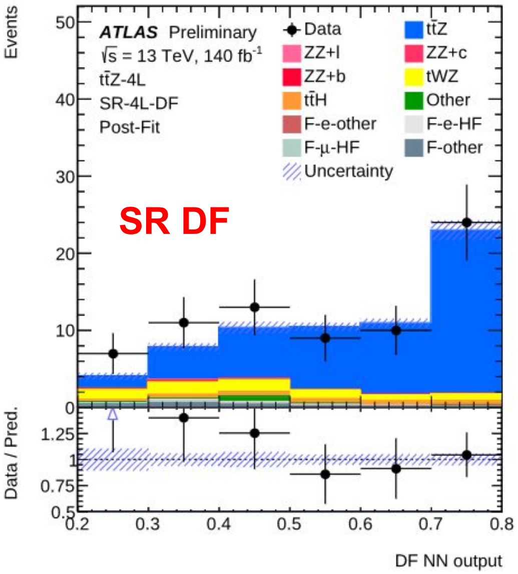


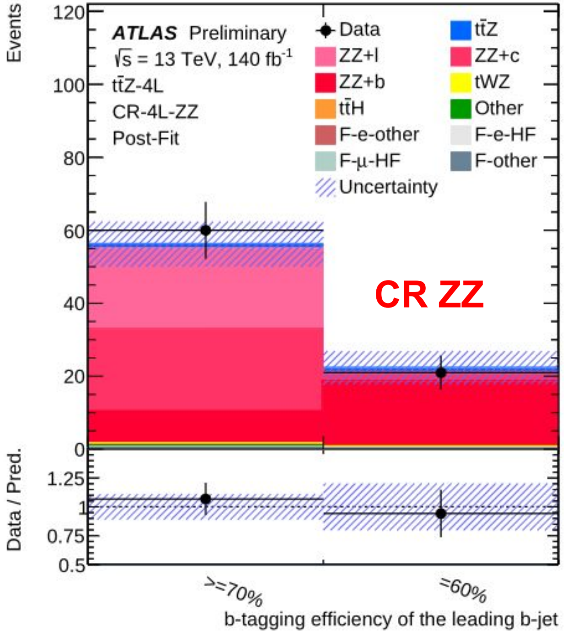


4l channel strategy

- Leading backgrounds: **tWZ** and **ZZ+jets**
- **DNN outputs** used as an input for the fit
- Irreducible **tWZ** - estimated **from MC** (low stats)







- **ZZ+jets** mostly in **SF region**
- **ZZ CR** for SF selection - defined with DNN < 0.4
- **ZZ+b** normalisation **extracted in the fit** → **CR** with **two bins based on b-tagging efficiency**

Inclusive xs measurement

- Simultaneous **profile likelihood fit** in all SRs and CRs
- **12 regions** (8 SRs and 4 CRs) and **8 free parameters** in the combined fit
- Extracted **signal strength ($\mu_{t\bar{t}Z}$) translated to the cross section** and corrected to match fiducial region (**70 < $m_{f\bar{f}}$ < 110 GeV**)
- **Main improvements:** DNNs, better modelling, region definitions, addition of 2l channel
- **35% reduction in uncertainty when compared to previous $t\bar{t}Z$**

Channel	$\sigma_{t\bar{t}Z}$
Dilepton	0.84 ± 0.11 pb $= 0.84 \pm 0.06$ (stat.) ± 0.09 (syst.) pb
Trilepton	0.84 ± 0.07 pb $= 0.84 \pm 0.05$ (stat.) ± 0.05 (syst.) pb
Tetralepton	$0.97^{+0.13}_{-0.12}$ pb $= 0.97 \pm 0.11$ (stat.) ± 0.05 (syst.) pb
Combination ($2\ell, 3\ell$ & 4ℓ)	0.86 ± 0.06 pb $= 0.86 \pm 0.04$ (stat.) ± 0.04 (syst.) pb

Uncertainty Category	$\Delta\sigma_{t\bar{t}Z}/\sigma_{t\bar{t}Z}$ [%]	Previous $t\bar{t}Z$	
Background normalisations	2.0		
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	1.9		
b-tagging	1.7	2.9	
$t\bar{t}Z$ μ_F and μ_R scales	1.6		
Leptons	1.6	2.3	
Z +jets modelling	1.5		
tWZ modelling	1.1	2.9	sub-leading
$t\bar{t}Z$ showering	1.0	3.1	leading
$t\bar{t}Z$ A14	1.0		
Luminosity	1.0		
Diboson modelling	0.8	2.8	
tZq modelling	0.7	2.6	
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		

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$$\sigma^{\mathrm{NLO}}_{t\bar{t}Z} = 0.86 \pm 0.08(\mathrm{scale}) \pm 0.03(\mathrm{PDF})\ \mathrm{pb}$$

$$\frac{\delta\sigma_{t\bar{t}Z}}{\sigma_{t\bar{t}Z}} \approx 6.5\%$$

$$\frac{\delta\sigma^{\mathrm{NLO}}_{t\bar{t}Z}}{\sigma^{\mathrm{NLO}}_{t\bar{t}Z}} \approx 10\%$$

Differential measurements

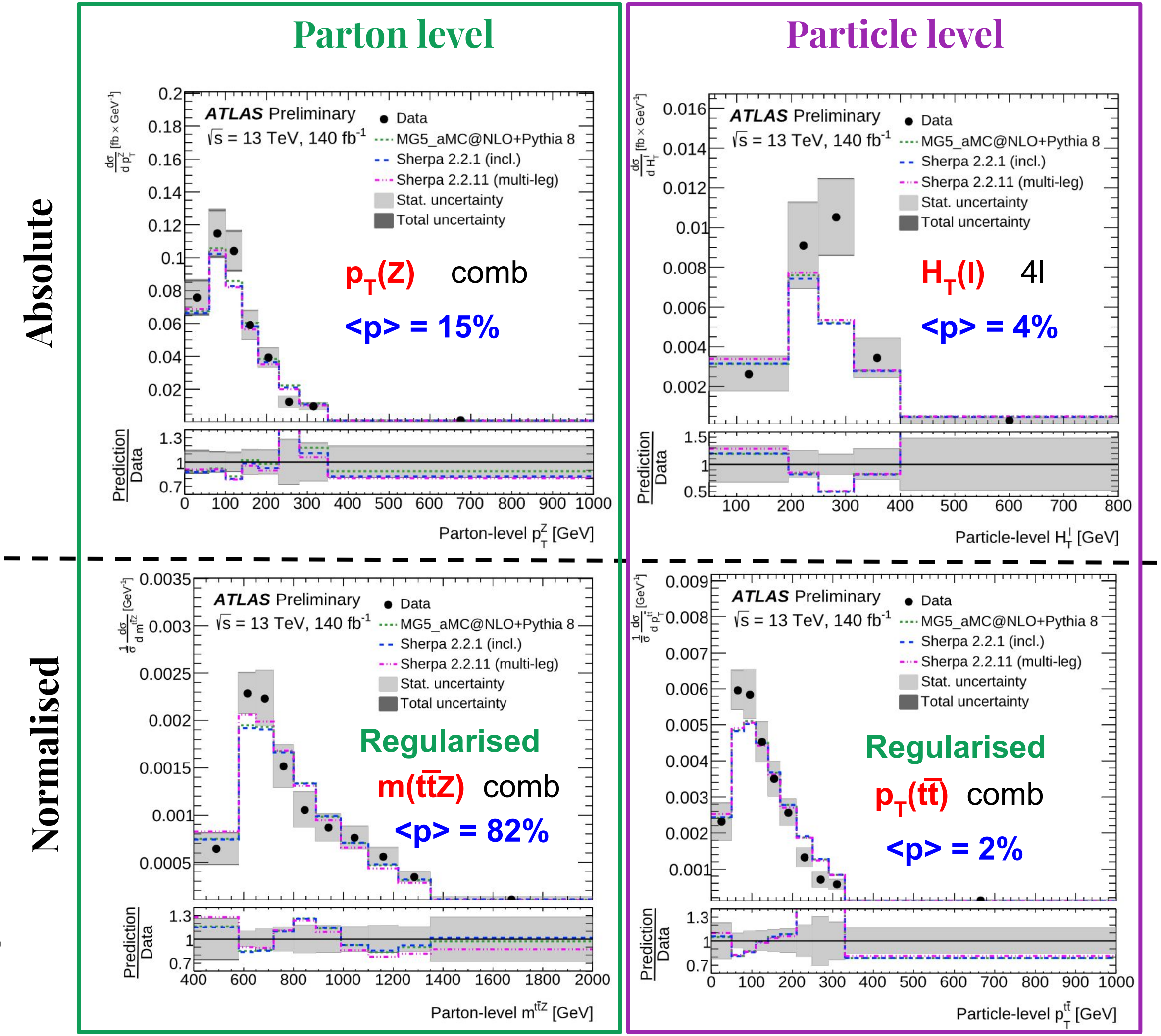
- **Only in 3l and 4l channels**
- **Profile likelihood unfolding (PLU)** to particle and parton level
- PLU allows for:
  - inclusion of **multiple SRs and CRs**,
  - free floating normalisation of the leading backgrounds,
  - **pulls and constraints** of the uncertainties
- Absolute and normalised distributions
- **17** observables (**5 in 3l**, **3 in 4l** and **9 in combination**)
- **Tikhonov regularisation** for observables featuring hadronic top

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

	Variable	Regularisation	τ^{particle}	τ^{parton}
$3\ell + 4\ell$	p_T^Z	No	-	-
	$\lvert y^Z \rvert$	No	-	-
	$\cos\theta_Z^*$	No	-	-
	p_T^t	Yes	1.5	1.4
	$p_T^{t\bar{t}}$	Yes	1.6	1.5
	$\lvert\Delta\phi(t\bar{t}, Z)\rvert$	Yes	2.4	2.1
	$m^{t\bar{t}Z}$	Yes	1.5	1.6
	$m^{t\bar{t}}$	Yes	1.5	1.4
	$\lvert y^{t\bar{t}Z}\rvert$	Yes	1.5	1.5
3ℓ	H_T^ℓ	No	-	-
	$\lvert\Delta\phi(Z, t_{\text{lep}})\rvert$	No	-	-
	$\lvert\Delta y(Z, t_{\text{lep}})\rvert$	No	-	-
	$p_T^{\ell,\text{non}-Z}$	No	-	-
	N_{jets}	No	-	-
4ℓ	H_T^ℓ	No	-	-
	$\lvert\Delta\phi(\ell_t^+, \ell_{\bar{t}}^-)\rvert$	No	-	-
	N_{jets}	No	-	-

Differential results

- Unfolded distributions **compared to**:
  - **MG5_aMC@NLO + Pythia 8** (nominal)
  - **Sherpa 2.2.1 (inclusive)**
  - **Sherpa 2.2.11 (multi-leg)**
- In general **good agreement** - some observables **suffer from bad modelling** → lower p-values for $H_T(l)$, $|\Delta y(Z,t^l)|$, $p_T^{t\bar{t}}$
- **Particle level more precise** (more diagonal migration matrices)
- Measurement **statistically limited** (but **30% improvement** when compared to previous $t\bar{t}Z$ analysis thanks to PLU, DNN, ...)



Spin correlations interpretation

- **First evidence** of top-quark spin correlations **in tt̄Z** (SM expectations modified by the Z boson)
- <u>6 independent observables</u> (in tt̄ rest frame):

$$\cos\theta_k^+, \quad \cos\theta_k^-, \quad \cos\theta_n^+, \quad \cos\theta_n^-, \quad \cos\theta_r^+, \quad \cos\theta_r^-,$$

- Observables defined using **leptons from tt̄** (or **lepton + down-type quark** from W decay)

Coefficient	Expression	
c_{rr}	$-9\langle\cos\theta_r^+ \cdot \cos\theta_r^-\rangle$	spin corr.
c_{kk}	$-9\langle\cos\theta_k^+ \cdot \cos\theta_k^-\rangle$	spin corr.
c_{nn}	$-9\langle\cos\theta_n^+ \cdot \cos\theta_n^-\rangle$	spin corr.
c_{rk}	$-9\langle\cos\theta_r^+ \cdot \cos\theta_k^- + \cos\theta_r^- \cdot \cos\theta_k^+\rangle$	spin cross corr.
c_{kn}	$-9\langle\cos\theta_k^+ \cdot \cos\theta_n^- + \cos\theta_k^- \cdot \cos\theta_n^+\rangle$	spin cross corr.
c_{rn}	$-9\langle\cos\theta_r^+ \cdot \cos\theta_n^- + \cos\theta_r^- \cdot \cos\theta_n^+\rangle$	spin cross corr.
c_r	$-9\langle\cos\theta_k^+ \cdot \cos\theta_n^- - \cos\theta_k^- \cdot \cos\theta_n^+\rangle$	spin cross corr.
c_k	$-9\langle\cos\theta_n^+ \cdot \cos\theta_r^- - \cos\theta_n^- \cdot \cos\theta_r^+\rangle$	spin cross corr.
c_n	$-9\langle\cos\theta_r^+ \cdot \cos\theta_k^- - \cos\theta_r^- \cdot \cos\theta_k^+\rangle$	spin cross corr.
b_r^+	$3\langle\cos\theta_r^+\rangle$	polarisations
b_r^-	$3\langle\cos\theta_r^-\rangle$	polarisations
b_k^+	$3\langle\cos\theta_k^+\rangle$	polarisations
b_k^-	$3\langle\cos\theta_k^-\rangle$	polarisations
b_n^+	$3\langle\cos\theta_n^+\rangle$	polarisations
b_n^-	$3\langle\cos\theta_n^-\rangle$	polarisations

Consider only 9 coefficient that are non-0 within theoretical uncertainties

Strategy:

- **Template fit** of <u>detector-level distributions</u> (unfolded distributions unusable -> would require regularisation in 4l)
- Each observable *O* fitted to **lin. combination of spin-on and spin-off hypotheses**

$$O = f_{\mathrm{SM}} \cdot O_{\text{spin-on}} + (1 - f_{\mathrm{SM}}) \cdot O_{\text{spin-off}}.$$

<u>POI</u> (**=1** for SM-like correlations and **=0** in absence of spin. corr.)

Template **with** SM spin. corr.

Template **without** spin. corr.

$$O = f_{SM} \cdot O_{\text{spin-on}} + (1 - f_{SM}) \cdot O_{\text{spin-off}}.$$

Spin correlations interpretation

- Coefficients fitted **individually** and then **combined** using profiled χ^2 fit (with stat. and syst. correlations)

opening angle between charged leptons (or lepton and s-jet)

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

- Measurement consistent with the SM prediction, but **statistically limited**
- **Spin-off hypothesis rejected with 1.8σ**
- Main systematics from **MC modelling**, E_T^{miss} and **flavour tagging**

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

SMEFT interpretation

- **$t\bar{t}Z$ sensitive to 20 dim-6 operators** (**6 top-boson**, **14 four-quark**)
- Particle level normalised **differential distributions** taken as an input (reweighted with **LO** parametrisation)
- **Separate fits** for top-boson and four-quark operators

linear quadratic

$$O = O_{\text{SM}} + \sum_i C_i A_i + \sum_{i,j} C_i C_j B_{ij}.$$

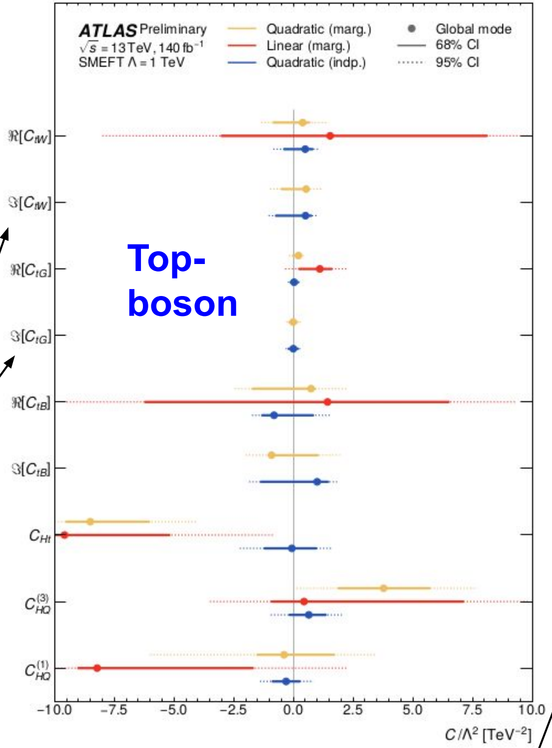
- **3 fit strategies**:
  - Simple **linear fit** (linear term A → interference between SM and SMEFT)
  - Full **quadratic fit** (both linear A and quadratic B terms)
  - Individual **quadratic fit** (all other operators set to 0, for comparison with other analyses)

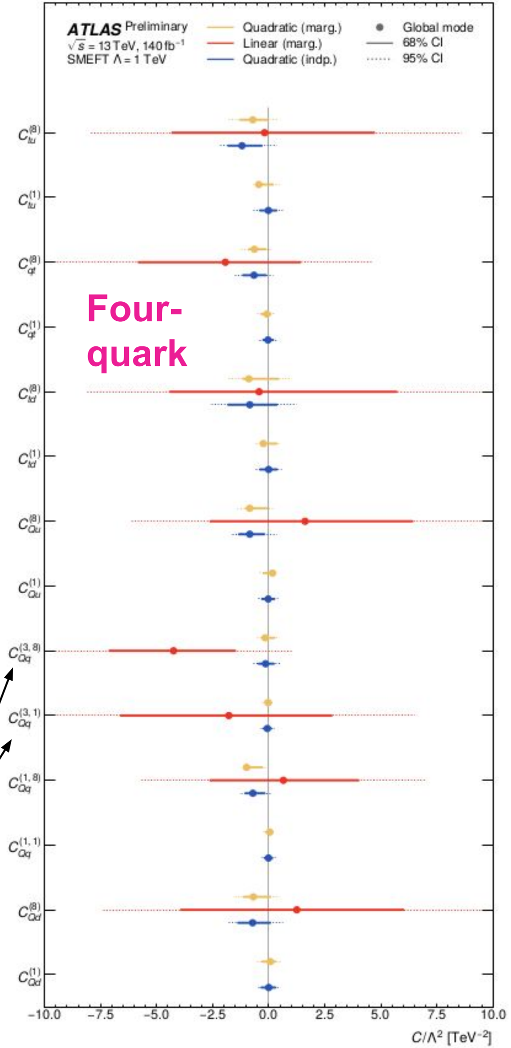
Observables used:

- p_T^Z (top-boson)
- $|y^Z|$
- $\cos\theta_Z^*$
- p_T^t (four-quark)
- $|\Delta\phi(t\bar{t},Z)|$
- $|y^{t\bar{t}Z}|$

SMEFT results

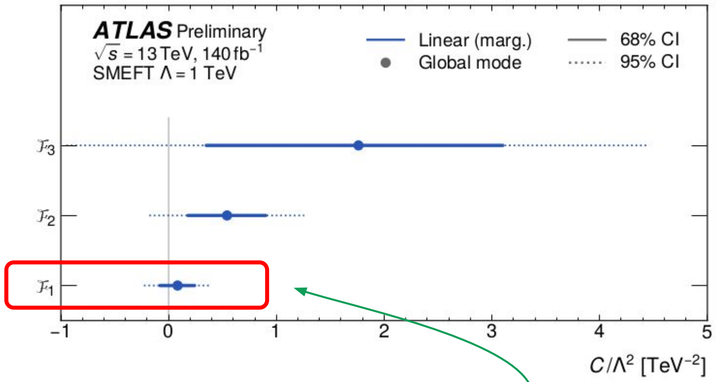
- **No significant deviations** from the SM prediction
- **Quadratic** terms particularly **important for four-quark operators**
- For some operators (C_{tG}, C_{tW}, ...) linear terms missing due to vanishing interference at LO in QCD
- **Linear combinations** of operators could provide **more stringent limits** → Fisher information matrix





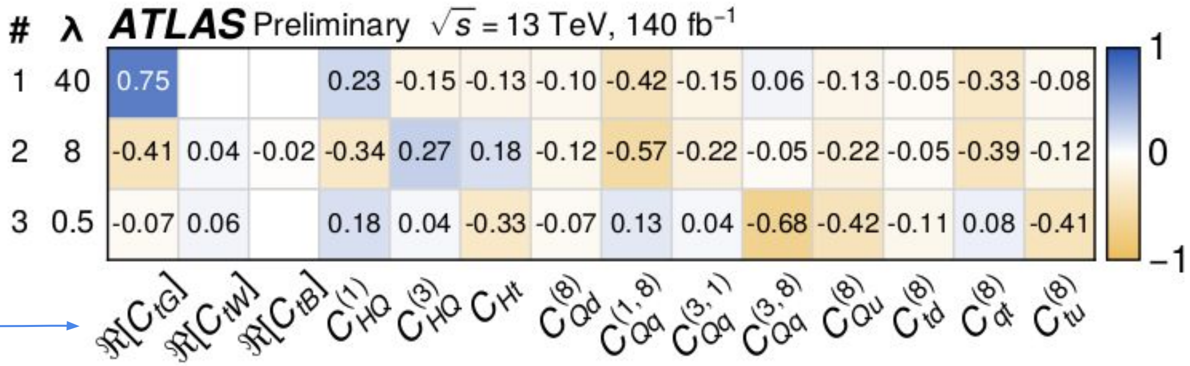
$C_{Qq}^{(3,1)}$, $C_{Qq}^{(3,8)}$ reduced by factor **6-30** when adding quadratic terms

Fisher information matrix



- SMEFT interpretation in the **rotated Warsaw basis**
- **3** most prominent directions of sensitivity
- **Fisher information matrix:**
  - **Inverse covariance matrix** from the linear fit rotated into the space of Wilson coefficients
  - Provides **measure of sensitivity** achievable along directions given by the **eigenvectors**
  - Inverse square root of **eigenvalues λ** estimates expected limits for F_1 - F_3
- **Final EFT fit** of 3 best linear combinations → yields **most stringent limits on F_1** [-0.08, 0.24]

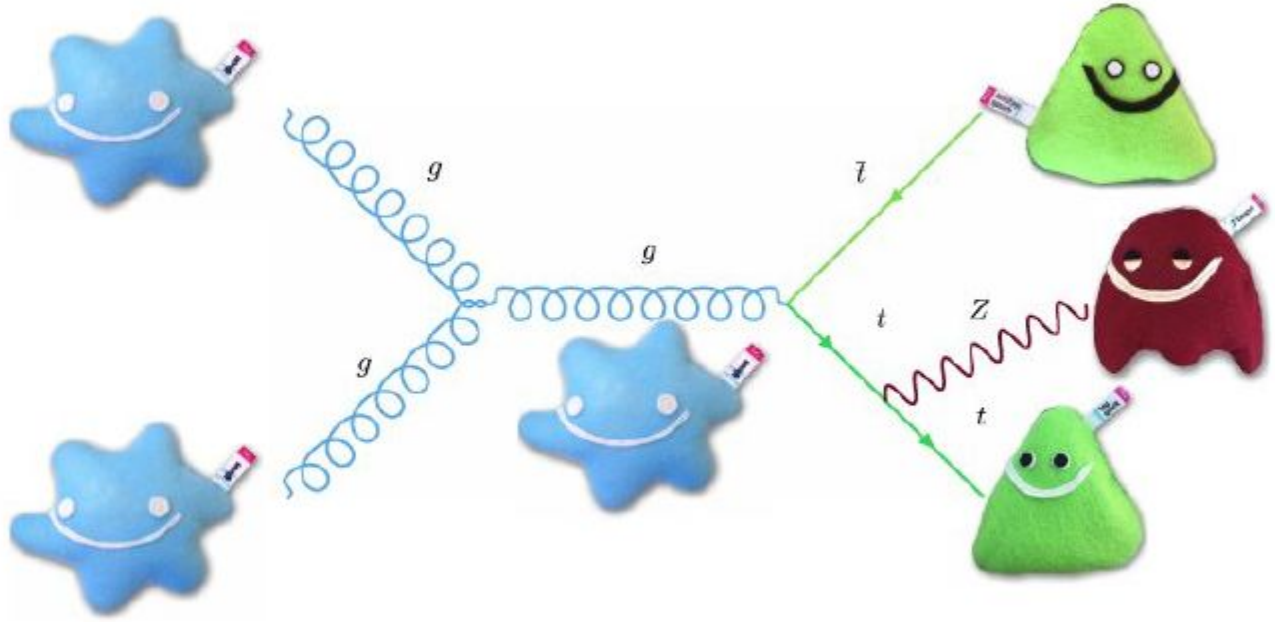
Dominates because of large impact on gg → $t\bar{t}$



Summary

- **Legacy $t\bar{t}Z$ measurement** with full Run 2 data
- **Improves previous ATLAS results** re-using the same data but with novel techniques
- Very **precise inclusive xs measurement** (**6.5%** precision) → even more than NLO theory (**10%**)
  - Good compatibility with the theory prediction
- **Differential measurements improved significantly** by using PLU instead of IBU (**30% reduction** of uncertainties)
  - In agreement with the SM, but still **statistically limited**
- **First spin correlation interpretation** for the $t\bar{t}Z$ process (analysis **statistically limited**)
  - Result consistent with the SM value, **spin-off hypothesis rejected with 1.8σ**
- **Thorough SMEFT interpretation** (20 operators), including **Fisher information matrix** to identify sensitive directions in the coefficient space

Analysis strategy adapted for future combinations!



Thank you for your attention!

BACKUP

MC Samples

Process	Generator	Parton Shower	PDF	Reference Cross Section (fb)
$t\bar{t}Z$	MadGraph5_aMC@NLO 2.8.1	Pythia 8.244	NNPDF3.0NLO	876.4 [19, 54]
$t\bar{t}H$	MadGraph5_aMC@NLO 2.6.0	Pythia 8.230	NNPDF3.0NLO	507.4 [19]
$t\bar{t}W/t\bar{t}Wj$	Sherpa 2.2.10	Sherpa 2.2.10	NNPDF3.0NNLO	722.4 [68]
tZq	MadGraph5_aMC@NLO 2.9.5	Pythia 8.245	NNPDF3.0NLO	38.72
tWZ	MadGraph5_aMC@NLO 2.2.2	Pythia 8.212	NNPDF2.3LO	16.08
$t\bar{t}$	Powheg Box 2	Pythia 8.230	NNPDF3.0NLO	87,710 [69]
WZ+jet/ZZ+jets	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0NNLO	7,334
V+jets	Sherpa 2.2.1	Sherpa 2.2.1	NNPDF3.0NNLO	$6{,}255\times10^3$ [67]
$t\bar{t}t\bar{t}$	MadGraph5_aMC@NLO 2.3.3	Pythia 8.230	NNPDF3.1NLO	11.97 [70]
$tt\bar{t}$	MadGraph 2.2.2	Pythia 8.186	NNPDF2.3LO	1.64
VH	Pythia 8.186	Pythia 8.186	NNPDF2.3LO	2,250 [71–77]
VVV	Sherpa 2.2.2	Sherpa 2.2.2	NNPDF3.0NLO	13.74

Region Definitions

Trilepton

Variable	Preselection		
$N_\ell \ (\ell = e, \mu)$	$= 3$		
	≥ 1 OSSF lepton pair with $\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV		
	for all OSSF combinations: $m_{\mathrm{OSSF}} > 10$ GeV		
$p_\mathrm{T}(\ell_1, \ell_2, \ell_3)$	$> 27,\ 20,\ 15$ GeV		
$N_\mathrm{jets}\ (p_\mathrm{T} > 25$ GeV$)$	≥ 3		
$N_{b\text{-tagged jets}}$	≥ 1@85%		
	SR-3ℓ-ttZ	**SR-3ℓ-tZq**	**SR-3ℓ-WZ**
DNN-tZq output	< 0.40	≥ 0.40	—
DNN-WZ output	< 0.22	< 0.22	≥ 0.22
$N_{b\text{-tagged jets}}$	—	—	≥ 1@60%

Dilepton

Variable	Preselection		
$N_\ell \ (\ell = e, \mu)$	$= 2$		
	$= 1$ OSSF lepton pair with $\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV		
$p_\mathrm{T}(\ell_1, \ell_2)$	$> 30,\ 15$ GeV		
	SR-2ℓ-5j2b	**SR-2ℓ-6j1b**	**SR-2ℓ-6j2b**
$N_\mathrm{jets}\ (p_\mathrm{T} > 25$ GeV$)$	$= 5$	≥ 6	≥ 6
$N_{b\text{-tagged jets@77\%}}$	≥ 2	$= 1$	≥ 2

Tetralepton

Variable	Preselection	
$N_\ell \ (\ell = e, \mu)$	$= 4$	
	≥ 1 OSSF lepton pair with $\lvert m_{\ell\ell} - m_Z \rvert < 20$ GeV	
	for all OSSF combinations: $m_{\mathrm{OSSF}} > 10$ GeV	
$p_\mathrm{T}(\ell_1, \ell_2, \ell_3, \ell_4)$	$> 27,\ 7,\ 7,\ 7$ GeV	
The sum of lepton charges	$= 0$	
$N_\mathrm{jets}\ (p_\mathrm{T} > 25$ GeV$)$	≥ 2	
$N_{b\text{-tagged jets}}$	≥ 1@85%	
	SR-4ℓ-SF	**SR-4ℓ-DF**
$\ell\ell^{\text{non-Z}}$	e^+e^- or $\mu^+\mu^-$	$e^\pm\mu^\mp$
DNN output	≥ 0.4	—

Particle & parton-level selection

Particle - after ttZ decay, including hadronisation
- simulates detector level selection

Parton - before ttZ decay, after QCD radiation
- tau leptons excluded

Leptons dressed with additional photons at particle level, but not parton

Particle-level selection	
3ℓ channel	4ℓ channel
Exactly 3 leptons, with $p_T(\ell_1, \ell_2, \ell_3) > 27, 20, 15$ GeV	Exactly four leptons, with $p_T(\ell_1, \ell_2, \ell_3, \ell_4) > 27, 7, 7, 7$ GeV
The sum of charges is ± 1	The sum of charges is $= 0$
At least 3 jets, with $p_T > 25$ GeV	At least 2 jets, with $p_T > 25$ 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
$t\bar{t} \to e^\pm/\mu^\pm$ + jets	$t\bar{t} \to e^\pm\mu^\mp/e^\pm e^\mp/\mu^\pm\mu^\mp$
$Z \to e^\pm e^\mp/\mu^\pm\mu^\mp$	
$\lvert m_{\ell\ell} - m_Z \rvert < 15$ GeV	

Top quark reconstruction

- **2l**
  - **Multihypothesis t/W reconstruction**
    - targets fully hadronic tt system; several hypotheses for the number of missing and present top quarks and W bosons
    - 5 different scenarios (1t1W, 2t, 2W, 1t, 1W) tested for each jets-quarks assignment, one with the highest output weight considered correct
    - output weights used as discriminating variables for DNNs
  - **SPANet**
    - symmetry preserving attention neural network, originally developed for the all-hadronic tt events
    - redesigned for the ttZ topology, inputs are jet kinematic and b-tagging info + correct jet assignments
    - trained on the 6j1b events, used to construct discriminating variables for separation DNNs
- **3l**
  - first reconstructed **leptonic-side top**
  - neutrino momentum in z direction from the quadratic equation, most likely top candidate from comparison with $m_{bl\nu}$ distribution
  - second b used for the reconstruction of **hadronic top**, two light jets from interpolation of m_{jj}
- **4l**
  - full tt reconstruction using **Two Neutrino Scanning Method**
  - whole eta-phi space scanned for the two neutrinos + 2 leptons not associated with the Z + 2 jets with the highest b-tagging score
  - kinematic constraints from reference distributions used to create output weight - largest taken as correct + weight used as a discriminating variable in DNNs

2l NN variables

Variable	Definition
H_T	sum of p_T of all objects (jets and leptons) in the event
$H_{\mathrm{T}}^{\mathrm{jets}}$	sum of p_T of all jets in the event
$p_{\mathrm{T}}^{X.\mathrm{jet}}$	p_T of the Xth jet, where only the first 8 jets are considered
$p_{\mathrm{T}}^{X.\mathrm{lep}}$	p_T of the Xth lepton
W_{1t1W}	weight for one-top hypothesis and 1W from multihypothesis hadronic t/W reconstruction. It is the probability that the event contains all 3 jets from one of the top quark and two light jets from the decay of the other top quark. More details are provided in Section 5.5.
W_{1t}	weight for one-top hypothesis from multihypothesis hadronic t/W reconstruction. The same as W_{1t1W}, with one top quark only.
$Centr_{\mathrm{jets}}$	scalar sum of p_T divided by sum of E for all jets
$\Delta R(b_1, b_2)$	ΔR between two jets with highest b-tagging working point. The jets with the same working point are ordered by p_{T}.
H_1^{jets}	first Fox-Wolfram moment built from jets only. The first Fox-Wolfram moment is defined as $H_1 = \sum_{i,j} \frac{\vec{p}_i \cdot \vec{p}_j}{E_{vis}^2}$, where $\vec{p}_i$ and $\vec{p}_j$ are 3-momenta of i-th and j-th object (jet or lepton) and E_{vis} is all visible energy in the event.
$N_{jj}^{m<50\mathrm{GeV}}$	number of jj combinations with mass lower than 50 GeV
$m_Z, y^Z, p_{\mathrm{T}}^Z$	mass, rapidity and transverse momentum of Z boson
$minM_{jj}^{\mathrm{ave}}$	average (over the number of jets in event) minimum invariant mass of jet pairs. For each jet, the other jet which results in the minimum dijet invariant mass is found. The observable is the average of these masses over all jets in the event.
$\Delta R(l, l)$	ΔR between two leptons
PCBT_{Xj}	discretised b-tagging efficiency (100-85-77-70-60%) of the Xth jet
$N_{\mathrm{lep}}^{\mathrm{top}}$	number of leptonic top candidates
$N_{\mathrm{had}}^{\mathrm{top}}$	number of hadronic top candidates
N_{had}^{W}	number of hadronic W candidates
$E_{\mathrm{T}}^{\mathrm{miss}}$	missing transverse energy in the event
H_1	first Fox-Wolfram momentent built from jets and leptons
$p_{\mathrm{T}}^{t\bar{t},\mathrm{spanet}}$	transverse momentum of the $t\bar{t}$ system reconstructed from jets predicted by SPANet

3l NN variables

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 $p_{\mathrm{T},i}$	transverse momentum of the i'th jet in the event where $i \in [1,4]$
$E_{\mathrm{T}}^{\mathrm{miss}}$	missing transverse energy of the event
Lepton $p_{\mathrm{T},i}$	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 $i \in [1,3]$
$p_{\mathrm{T},i}^{Z}$	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 $p_{\mathrm{T}}^{\mathrm{non-}Z}$	transverse momentum of the remaining lepton not assigned to the Z boson

4l NN variables

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	—	✓

Backgrounds

Dilepton tt regions

Variable	Preselection		
N_ℓ $(\ell = e, \mu)$	$= 2$		
	$= 1$ OSDF lepton pair with $\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV		
$p_T(\ell_1, \ell_2)$	$> 30,\ 15$ GeV		
	2ℓ-eμ-5j2b	**2ℓ-eμ-6j1b**	**2ℓ-eμ-6j2b**
N_{jets} $(p_T > 25$ GeV$)$	$= 5$	≥ 6	≥ 6
$N_{b\text{-tagged jets}@77\%}$	≥ 2	$= 1$	≥ 2

Tetralepton ZZ CR

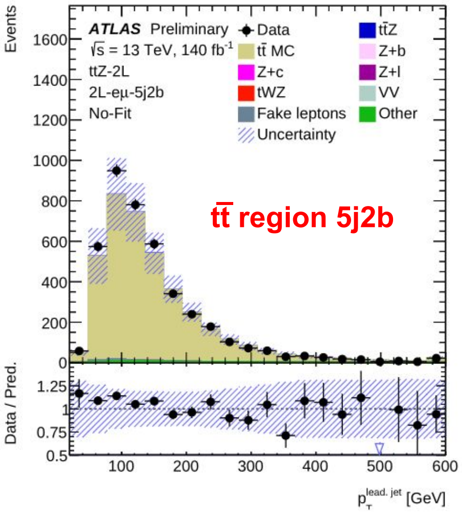
Variable	Preselection
N_ℓ $(\ell = e, \mu)$	$= 4$
	≥ 1 OSSF lepton pair with $\lvert m_{\ell\ell} - m_Z \rvert < 20$ GeV
	for all OSSF combinations: $m_{OSSF} > 10$ GeV
$p_T(\ell_1, \ell_2, \ell_3, \ell_4)$	$> 27,\ 7,\ 7,\ 7$ GeV
The sum of lepton charges	$= 0$
N_{jets} $(p_T > 25$ GeV$)$	≥ 2
$N_{b\text{-tagged jets}}$	$\geq 1@85\%$
	CR-4ℓ-ZZ
$\ell\ell^{\text{non-Z}}$	e^+e^- or $\mu^+\mu^-$
DNN-SF output	< 0.4

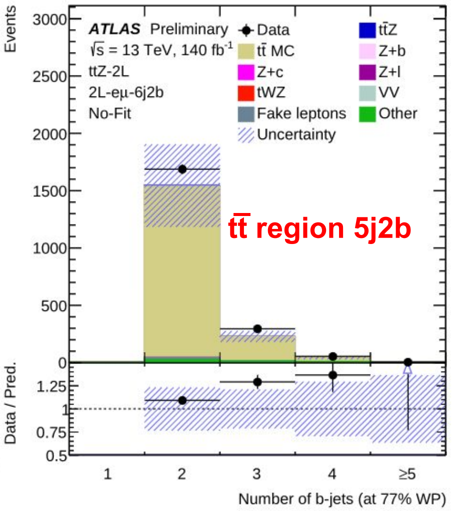
Fake CRs in 3l and 4l

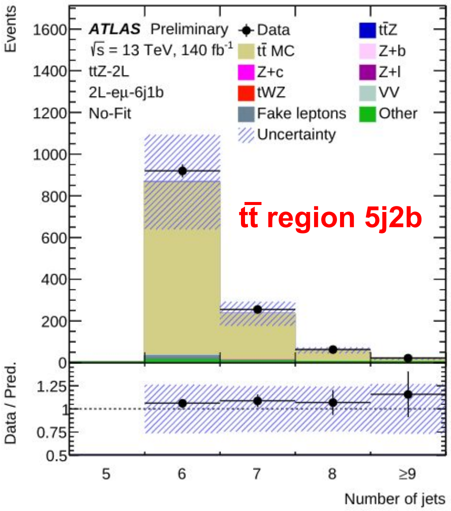
Variable	Preselection		
N_ℓ $(\ell = e, \mu)$	$= 3$ (of which $= 1$ loose non-tight)		
$p_T(\ell_1, \ell_2, \ell_3)$	$> 27,\ 20,\ 15$ GeV		
Sum of lepton charges	± 1		
N_{jets} $(p_T > 25$ GeV$)$	≥ 3		
$N_{b\text{-tagged jets}}$	$\geq 1@85\%$		
	CR-$t\bar{t}$-e	**CR-$t\bar{t}$-μ**	**CR-Z-e**
Lepton flavours	no OSSF pair	no OSSF pair	OSSF pair
	(loose lepton is an electron)	(loose lepton is a muon)	(exactly 3 electrons)
E_T^{miss}	—	—	< 80 GeV

Backgrounds

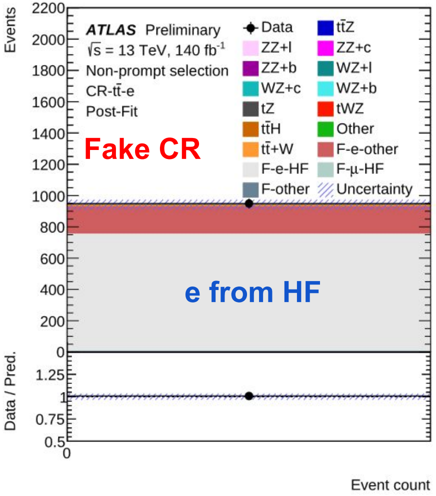
- $t\bar{t}$ regions in 2l channel

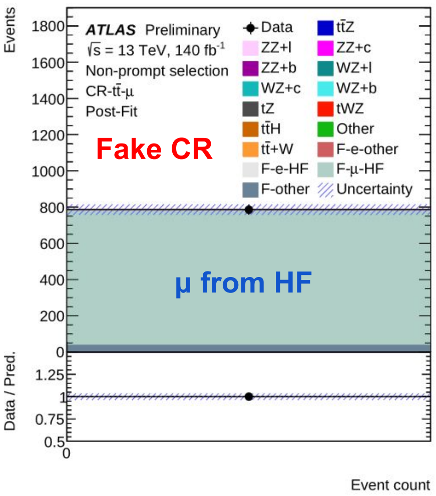


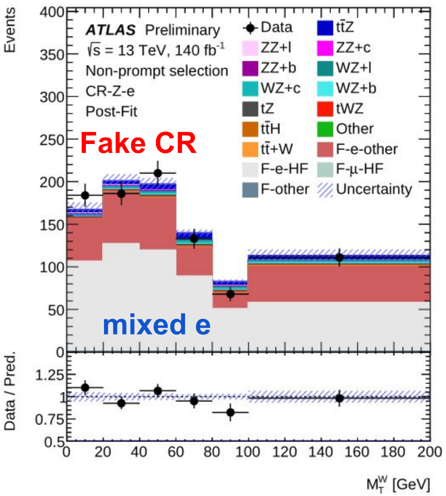




- Fake CRs in 3l and 4l channels







Systematics

Theory

Signal:

- **Nominal $t\bar{t}Z$**: aMC@NLO + Pythia 8
- **Parton shower:** Pythia 8 vs. Herwig 7
- **Scales:** μ_R, μ_F varied up and down by a factor of 2
- **ISR:** varying Var3c parameter of Pythia A14 tune
- **PDF:** PDF4LHC prescription
- modelling cross-checked with Sherpa 2.2.1

Background:

- **WZ/ZZ + jets:** CKKW, QSF, μ_R, μ_F, PDFs, normalisations 10-30%
- **tZq:** parton shower (P8 vs. H7), PDFs, ISR and μ_R, μ_F
- **tWZ:** DR1 vs. DR2 diagram removal scheme, PDFs, μ_R, μ_F
- **Z+jets:** CKKW, QSF, PDFs, μ_R, μ_F , 10% normalisation for Z+l

Experimental

- **Luminosity** (0.83%)
- **Pileup** reweighting
- **Lepton selection** (1-3%)
- Jet selection: **JER, JES, JVT**
- **Flavor tagging** (1.7%)
- E_T^{miss}

Experimental uncertainties allow for the future combinations !

2l post-fit yields and norm. factors

	SR-2ℓ-5j2b	SR-2ℓ-6j2b	SR-2ℓ-6j1b
$t\bar{t}Z$	297 ± 20	443 ± 27	305 ± 28
$t\bar{t}$ DD	4 001 ± 72	1 913 ± 45	1 161 ± 35
$Z+b$	5 710 ± 170	2 680 ± 110	4 830 ± 280
$Z+c$	349 ± 95	189 ± 47	2 020 ± 480
$Z+l$	59 ± 25	19.6 ± 8.1	1 020 ± 240
tWZ	23.2 ± 0.92	34.4 ± 2.1	40.2 ± 1.9
Diboson	150 ± 80	95 ± 52	340 ± 180
Fake leptons	28 ± 14	18.6 ± 9.2	25 ± 12
Other	55 ± 25	49 ± 22	23 ± 10
Total	10 700 ± 100	5 440 ± 68	9 760 ± 110
Data	10 702	5 435	9 737

Norm. factor	Value
$\mathcal{N}_{ZZ+b}$	$1.1\,^{+0.4}_{-0.4}$
$\mathcal{N}_{WZ+b}$	$0.9\,^{+0.4}_{-0.4}$
$\mathcal{N}_{Z+b}$	$1.08\,^{+0.11}_{-0.10}$
$\mathcal{N}_{Z+c}$	$0.61\,^{+0.23}_{-0.20}$
$\mathcal{N}_{e,\mathrm{HF}}$	$0.89\,^{+0.09}_{-0.09}$
$\mathcal{N}_{e,\mathrm{other}}$	$1.2\,^{+0.4}_{-0.4}$
$\mathcal{N}_{\mu,\mathrm{HF}}$	$1.02\,^{+0.08}_{-0.08}$

3l & 4l post-fit yields

	SR-3ℓ-ttZ	SR-3ℓ-WZ	SR-3ℓ-tZq	SR-4ℓ-SF	SR-4ℓ-DF	CR-4ℓ-ZZ
$t\bar{t}Z$	441 ± 21	49.0 ± 3.7	151 ± 11	49.4 ± 3.0	51.1 ± 2.9	2.36 ± 0.23
$t\bar{t}W$	4.3 ± 2.2	2.2 ± 1.1	5.3 ± 2.6	—	—	—
$t\bar{t}H$	11.9 ± 1.1	1.43 ± 0.13	6.70 ± 0.57	2.79 ± 0.24	2.82 ± 0.24	0.32 ± 0.04
$WZ + b$	21.1 ± 7.4	47 ± 16	27.1 ± 9.5	—	—	—
$WZ + c$	8.9 ± 3.6	12.2 ± 5.0	11.1 ± 4.6	—	—	—
$WZ + l$	1.19 ± 0.52	1.70 ± 0.76	1.81 ± 0.80	—	—	—
$ZZ + b$	4.3 ± 2.5	6.9 ± 4.0	7.3 ± 4.2	7.5 ± 2.0	0.46 ± 0.12	26.7 ± 6.9
$ZZ + c$	1.23 ± 0.42	1.22 ± 0.43	1.61 ± 0.53	2.13 ± 0.66	0.30 ± 0.09	24.6 ± 7.1
$ZZ + l$	0.42 ± 0.13	0.26 ± 0.09	0.53 ± 0.15	0.83 ± 0.24	0.34 ± 0.09	22.6 ± 5.2
tZq	20.8 ± 4.0	13.2 ± 2.3	99 ± 16	—	—	—
tWZ	40.0 ± 7.6	18.0 ± 4.2	24.2 ± 3.0	6.60 ± 0.82	7.3 ± 1.2	0.69 ± 0.10
$t\bar{t}t\bar{t}$	1.56 ± 0.78	0.13 ± 0.07	0.27 ± 0.14	—	—	—
Other	1.33 ± 0.61	1.40 ± 0.63	0.39 ± 0.19	0.55 ± 0.25	1.12 ± 0.52	0.55 ± 0.25
F-e-HF	4.6 ± 1.0	3.90 ± 0.87	12.0 ± 2.6	0.28 ± 0.07	0.45 ± 0.10	0.11 ± 0.03
F-e-Other	7.8 ± 2.7	7.3 ± 2.6	15.2 ± 5.4	0.39 ± 0.14	0.50 ± 0.18	0.10 ± 0.04
F-m-HF	6.98 ± 0.86	5.27 ± 0.66	18.2 ± 2.2	0.58 ± 0.07	0.62 ± 0.08	0.16 ± 0.02
F-Other	2.8 ± 1.2	2.7 ± 1.2	4.4 ± 2.0	0.90 ± 0.40	1.66 ± 0.74	0.33 ± 0.15
Total	580 ± 19	174 ± 13	386 ± 15	72.0 ± 3.4	66.7 ± 3.0	78.5 ± 8.0
Data	569	175	388	79	74	81

Profile likelihood unfolding procedure

The profile likelihood unfolding procedure uses the following formula for the likelihood

$$L\left(\vec{n}|\mu,\vec{\theta},\vec{k}\right) = \prod_{r\in\text{regions}}\prod_{i\in\text{bins}}\text{Pois}\left(n_{i,r}|\vec{\mu}\vec{S}_{i,r}(\vec{\theta}) + B_{i,r}(\vec{\theta},\vec{k})\right)\times\prod_{j\in\text{NPs}}\text{Gaus}\left(\theta_j\right)\times R(\vec{\mu}), \qquad (2)$$

where $n_{i,r}$ is the number of events observed in i-th bin of r-th region, $\vec{S}_{i,r}$ is the response matrix, $B_{i,r}(\vec{\theta},\vec{k})$ is the background contribution, $\vec{k}$ is vector of free-floating background normalisations and $\vec{\theta}$ is vector of nuisance parameters related to the systematic uncertainties. In case of the normalised distribution, the $\vec{\mu}$ is reparametrised in the way, that the last element of the vector is the overall signal normalisation. In this case, the content of the last bin of the unfolded distribution is dropped from the $\vec{\mu}$, since it is no longer a free parameter and it can be calculated based on the values in other bins and the overall normalisation.

$$\rho = \left\langle\sqrt{1-(C_{ii}C_{ii}^{-1})^{-1}}\right\rangle, \qquad (4)$$

where C_{ii} is the correlation matrix, C_{ii}^{-1} is inverted correlation matrix and the brackets represent the mean value over the diagonal elements. The τ value where the global correlation reaches its minimum was chosen as the optimal value.

Differential observables

Observable	Channels	Bins	Bin Ranges
p_T^Z [GeV]	$3\ell + 4\ell$	8	[0, 60, 100, 140, 180, 230, 280, 350, 1000]
$\lvert y^Z \rvert$	$3\ell + 4\ell$	9	[0, 0.125, 0.275, 0.425, 0.6, 0.775, 0.95, 1.175, 1.45, 2.5]
$p_T^{\ell,\text{non}-Z}$	3ℓ	5	[0, 35, 55, 80, 120, 500]
$\lvert \Delta y(Z, t_{\text{lep}}) \rvert$	3ℓ	5	[0, 0.25, 0.6, 1.05, 1.55, 5]
$\lvert \Delta\phi(Z, t_{\text{lep}}) \rvert$	3ℓ	6	[0, 0.16, 0.44, 0.66, 0.82, 0.93, 1]
$\lvert \Delta\phi(\ell_t^+, \ell_{\bar{t}}^-) \rvert$	4ℓ	7	[0, 0.2, 0.37, 0.53, 0.67, 0.79, 0.89, 1]
H_T^ℓ	3ℓ	8	[50, 130, 165, 195, 230, 275, 330, 405, 800]
H_T^ℓ	4ℓ	5	[50, 195, 250, 315, 400, 800]
N_{jets}	3ℓ	4	[2.5, 3.5, 4.5, 5.5, 10.5]
N_{jets}	4ℓ	3	[1.5,2.5,3.5,8.5]
p_T^t [GeV]	$3\ell + 4\ell$	10	[0, 48, 80, 112, 144, 176, 216, 256, 296, 352, 800]
$p_T^{t\bar{t}}$ [GeV]	$3\ell + 4\ell$	10	[0, 50, 80, 110, 140, 170, 210, 250, 290, 330, 1000]
$\lvert \Delta\phi(t\bar{t}, Z) \rvert / \pi$	$3\ell + 4\ell$	5	[0, 0.73, 0.86, 0.94, 0.98, 1]
$m_{t\bar{t}}$ [GeV]	$3\ell + 4\ell$	10	[0, 370, 420, 470, 530, 600, 680, 780, 890, 1010, 2000]
$m_{t\bar{t}Z}$ [GeV]	$3\ell + 4\ell$	10	[400, 580, 650, 720, 800, 890, 990, 1100, 1220, 1350, 2000]
$\lvert y^{t\bar{t}Z} \rvert$	$3\ell + 4\ell$	10	[0, 0.075, 0.2, 0.35, 0.5, 0.65, 0.8, 0.95, 1.1, 1.25, 2.5]
$\cos\theta_Z^*$	$3\ell + 4\ell$	8	[-1, -0.75, -0.5, -0.25, 0, 0.25, 0.5, 0.75, 1]

Spin correlations

- **k**, **n**, **r** - axes in orthonormal basis, +/- is charge of lepton/quark
- In **4l** observables defined using **leptons from $t\bar{t}$**
- In **3l** necessary to use **lepton** + **down-type quark** from W decay (c or s) - c tagged jets if pass at least 85% but fail 60% (its companion is s-quark)

- **Negative (or >1) f_{SM}** caused by large variability of the fit results under local excesses not compatible with either the spin-on or spin-off templates

- **Fit enhances the impact of systematic uncertainties with an important shape component** (alternative parton showers for ttZ, electron isolation and ZZ+b scale uncertainties in 4l)

- **Future spin density measurements** will be able to probe possible **CP-violation effects** and **4-fermion operators**

A final observable of interest can be constructed in both the 3ℓ and 4ℓ channels: the opening angle between the two charged leptons (charged lepton and s-jet) from the dileptonic (semi-leptonic) $t\bar{t}$ system, where each decay product is first boosted to the rest frame of its respective parent (anti-)top quark. This angle φ is particularly sensitive to spin correlations, and the following three relations hold [26]:

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\varphi} = \frac{1}{2}\left(1 - D\cos\varphi\right), \quad D = -\frac{c_{rr} + c_{kk} + c_{nn}}{3}, \quad D = -3\langle\cos\varphi\rangle. \tag{6}$$

SMEFT interpretation

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \mathcal{L}^{(d)}, \quad \mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)},$$

$$c_{tZ} = -\sin\theta_W C_{tB} + \cos\theta_W C_{tW},$$

$$c_{\varphi Q}^{-} = C_{HQ}^{(1)} - C_{HQ}^{(3)},$$

Wilson coefficient	68% CI (exp.)	95% CI (exp.)	68% CI (obs.)	95% CI (obs.)	Best-fit
$\mathcal{F}_1$ $O(\Lambda^{-2})$ (marg.)	$[-0.15, 0.16]$	$[-0.30, 0.31]$	$[-0.080, 0.24]$	$[-0.23, 0.39]$	0.08
$\mathcal{F}_2$ $O(\Lambda^{-2})$ (marg.)	$[-0.36, 0.36]$	$[-0.72, 0.70]$	$[0.18, 0.90]$	$[-0.18, 1.3]$	0.5
$\mathcal{F}_3$ $O(\Lambda^{-2})$ (marg.)	$[-1.4, 1.3]$	$[-2.7, 2.7]$	$[0.35, 3.1]$	$[-0.95, 4.5]$	2

	Operator	Definition	
top-boson	Q_{tW}	$(\bar{Q}\sigma^{\mu\nu}t)\sigma^i\tilde{H}W^i_{\mu\nu}$	(⋆)
	Q_{tB}	$(\bar{Q}\sigma^{\mu\nu}t)\tilde{H}B_{\mu\nu}$	(⋆)
	Q_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^a t)\tilde{H}G^a_{\mu\nu}$	(⋆)
	$Q_{HQ}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$	
	$Q_{HQ}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{Q}\sigma^i\gamma^\mu Q)$	
	Q_{Ht}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$	
four-quark	$Q_{tu}^{(1)}$	$(\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u)$	
	$Q_{tu}^{(8)}$	$(\bar{t}T^a\gamma_\mu t)(\bar{u}T^a\gamma^\mu u)$	
	$Q_{td}^{(1)}$	$(\bar{t}\gamma_\mu t)(\bar{d}\gamma^\mu d)$	
	$Q_{td}^{(8)}$	$(\bar{t}T^a\gamma_\mu t)(\bar{d}T^a\gamma^\mu d)$	
	$Q_{qt}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{t}\gamma^\mu t)$	
	$Q_{qt}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{t}T^a\gamma^\mu t)$	
	$Q_{Qu}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$	
	$Q_{Qu}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{u}T^a\gamma^\mu u)$	
	$Q_{Qd}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$	
	$Q_{Qd}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{d}T^a\gamma^\mu d)$	
	$Q_{Qq}^{(1,1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q)$	
	$Q_{Qq}^{(3,1)}$	$(\bar{Q}\sigma^i\gamma_\mu Q)(\bar{q}\sigma^i\gamma^\mu q)$	
	$Q_{Qq}^{(1,8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{q}T^a\gamma^\mu q)$	
	$Q_{Qq}^{(3,8)}$	$(\bar{Q}\sigma^i T^a\gamma_\mu Q)(\bar{q}\sigma^i T^a\gamma^\mu q)$	