16th International Workshop on Top-Quark Physics (TOP 2023)

Recent results on associated $t\bar{t}Z$ and $t\bar{t}\gamma$ from the ATLAS and CMS experiments

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on behalf of the ATLAS & CMS Collaborations

Overview

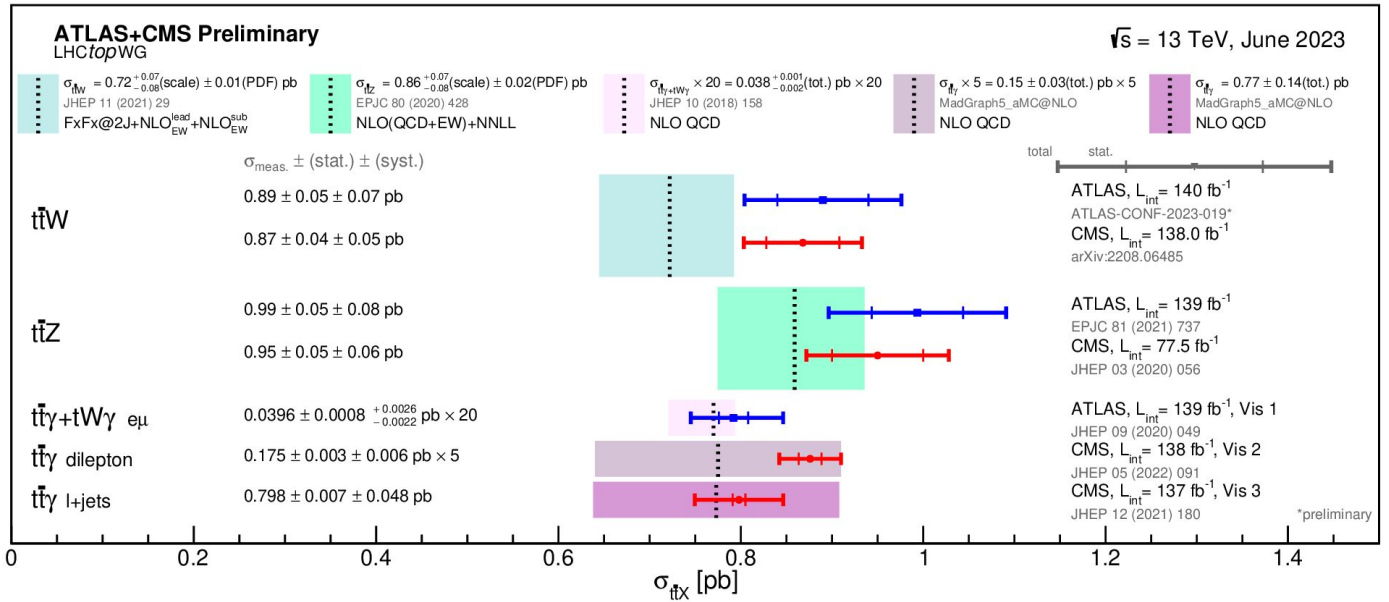
$t\bar{t}Z$

inclusive + differential
13 TeV; 139 fb^{-1}
EPJC 81 (2021) 737

inclusive + differential + EFT
13 TeV; 140 fb^{-1}
ATLAS-CONF-2023-065

inclusive + differential + EFT
13 TeV; 77.5 fb^{-1}
JHEP 03 (2020) 056

boosted $t\bar{t}Z$ + $t\bar{t}H$
13 TeV; 138 fb^{-1}
PRD 108 032008 (2023)



$t\bar{t}\gamma$

inclusive + differential $t\bar{t}\gamma$+tWγ
13 TeV; 139 fb^{-1}
JHEP 09 (2020) 049

charge asymmetry $t\bar{t}\gamma$
13 TeV; 139 fb^{-1}
Phys.Lett.B 843 (2023) 137848

Covered in Hugo's talk

inclusive + differential + EFT 1l
13 TeV; 138 fb^{-1}
JHEP 12 (2021) 180

inclusive + differential + EFT 2l
13 TeV; 138 fb^{-1}
JHEP 05 (2022) 091

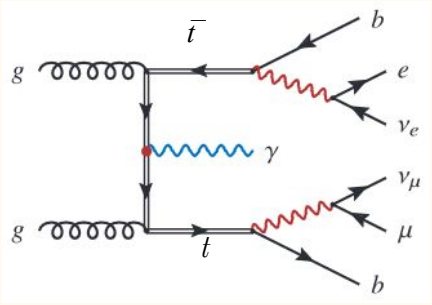
$t\bar{t}\gamma$

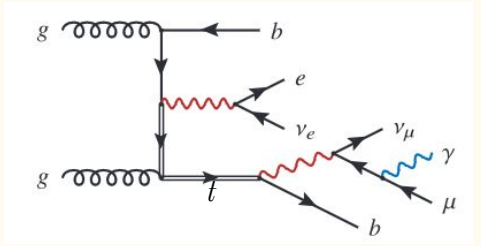
ATLAS: $t\bar{t}\gamma$+tWγ inclusive + differential xs

JHEP 09 (2020) 049

139 fb^{-1}

- **Combined measurement** of $t\bar{t}\gamma$ and tWγ
- Probes **tγ EW coupling**, sensitive to the **new physics through top quark anomalous dipole moments**
- **Only eμ channel** (clean dataset, no need for MVA)





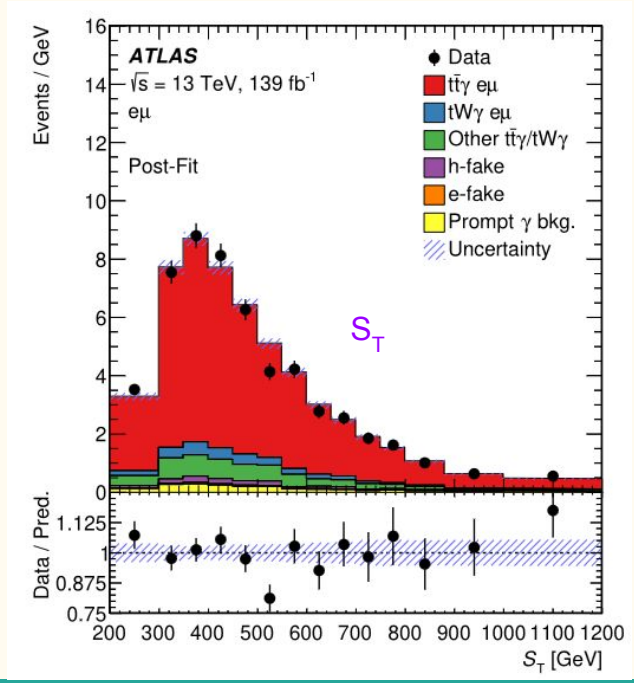
Inclusive xs measurement:

- **Binned PLF** to the S_T distribution (scalar sum of p_T of l, jets, γ and p_T^{miss})
- **Result:**
  - **Measured:** 6.3%

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

- Compatible with NLO prediction within uncertainties

- syst. uncert. dominated by **signal and background modelling and tWγ parton definition**



Signal selection:

- **one electron** and **muon** with **opposite charges**
- **one** isolated **high-p_T photon**
- at least **2 jets** (≥1 b-tag)

ATLAS: $t\bar{t}\gamma$+tWγ inclusive + differential xs

JHEP 09 (2020) 049

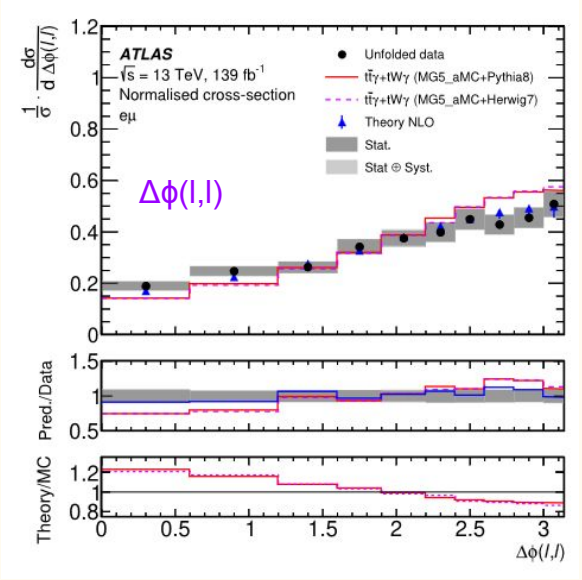
139 fb^{-1}

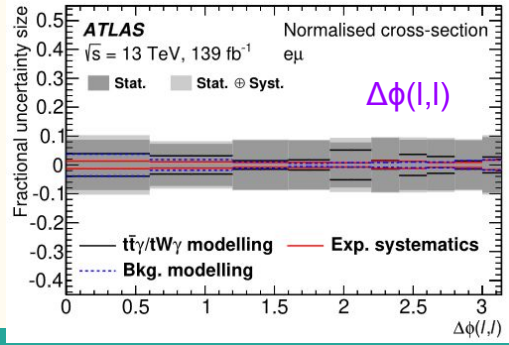
Differential xs measurements:

- **IBU** with 2 iterations
- 5 observables unfolded to parton-level (absolute and normalised)
  - $\mathbf{p_T(\gamma)}$, $\mathbf{|\eta(\gamma)|}$, $\mathbf{\Delta R(\gamma,l)_{min}}$, $\mathbf{\Delta\phi(l,l)}$, $\mathbf{|\Delta\eta(l,l)|}$
  - sensitive to tγ coupling, tγ separation and $t\bar{t}$ spin correlations
- Binning optimised for **high resolution** and **small migrations**

Results:

- Compared to:
  - **NLO** dedicated theory predictions
  - **LO** parton-level $t\bar{t}\gamma$ + tWγ (only for normalised)
- Overall **good agreement** (better compatibility with NLO calculations)
- Dominated by **statistical uncertainty**





Normalised xs

Predictions	$p_T(\gamma)$		$\lvert\eta(\gamma)\rvert$		$\Delta R(\gamma,\ell)_{\min}$		$\Delta\phi(\ell,\ell)$		$\lvert\Delta\eta(\ell,\ell)\rvert$	
	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
$t\bar{t}\gamma$+tWγ (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
$t\bar{t}\gamma$+tWγ (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

CMS: $t\bar{t}\gamma$ inclusive + differential (l+jets)

JHEP 12 (2021) 180

137 fb^{-1}

Signal selection:
- **one electron** or **muon**
- **one isolated high-p_T photon, $|\eta(\gamma)|<1.44$**
- two SRs based on jet multiplicity

Backgrounds:
- **Non-prompt γ (23%), missID e (19%) -** from data

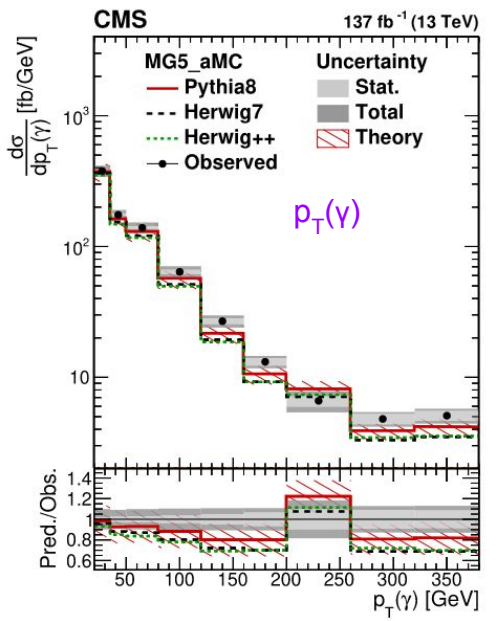
Differential xs:
- **3 observables** unfolded to **particle-level** (absolute xs)
- **Matrix inversion without regularisation** (TUnfold) - backgrounds constrained in CRs via ML fit
- **Observables:**
  - **$p_T(\gamma)$, $|\eta(\gamma)|$, $\Delta R(l,\gamma)$** - sensitive to t-γ coupling
- Dominated by **syst. uncertainties** -JES, γ ID efficiency, color reconnection

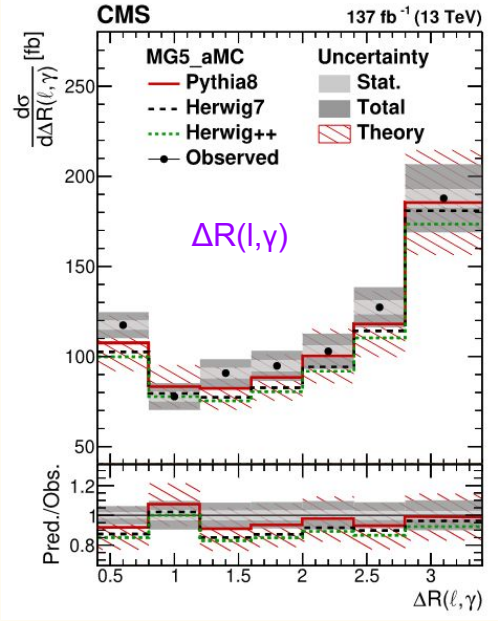
Inclusive xs:
- Simultaneous **PLF** in all SRs and CRs
- Fitted **M_3 distribution** (invariant mass of 3-jet combination with highest p_T sum)
- Measured: 6.1%

$$\sigma(t\bar{t}\gamma) = 798 \pm 7\,(\text{stat}) \pm 48\,(\text{syst})\ \text{fb}$$

- **Good agreement with SM NLO prediciton**
- Highly systematically dominated (Wγ normalisation, non-prompt γ bckg, lumi)

- **SMEFT** interpretation - more sensitive than dilepton analysis!





JHEP 05 (2022) 091

CMS: $t\bar{t}\gamma$ inclusive + differential (dilepton)

138 fb^{-1}

Signal selection:

- $t\bar{t}$ **dilepton selection** ($e^{\pm}\mu^{\mp}$, $e^{+}e^{-}$, $\mu^{+}\mu^{-}$)
- **one high-p_T photon** in barrel region

Backgrounds:

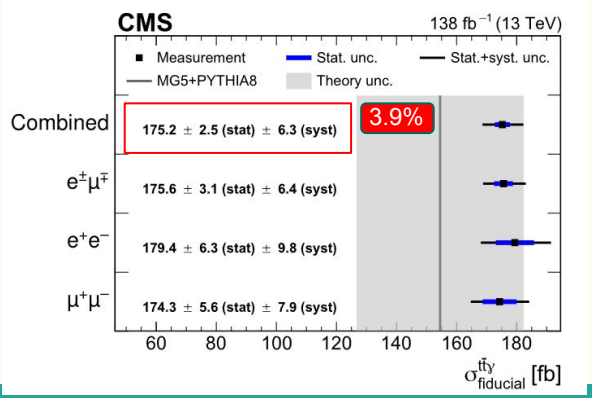
- ➢ **Prompt γ bckg (13%)** - **Zγ** (from data), **tγ** (from MC)
- ➢ **Nonprompt γ bckg (13%) -** from data

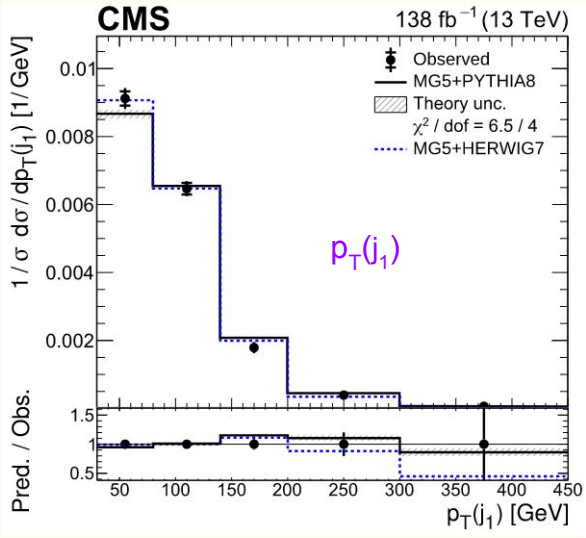
Inclusive xs:

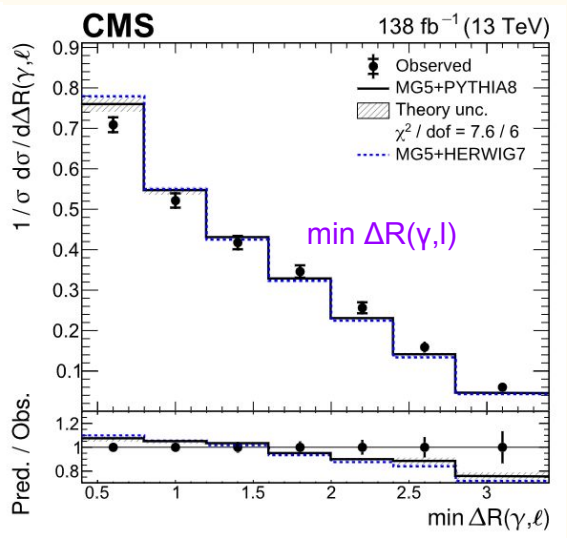
- **PLF to reconstructed $p_T(\gamma)$** - 9 bins (separate fit for $e^{\pm}\mu^{\mp}$, $e^{+}e^{-}$, $\mu^{+}\mu^{-}$ and combined)
- **Dominated by syst. uncertainty** (Lumi, signal modelling, flavour tagging)
- Agrees with the SM prediction within uncertainties
- **Lower prediction** (12%) caused by neglecting γ radiation from t decay products in LO sample

Differential xs:

- **12 observables** unfolded to **particle level**
- Small migrations →**matrix inversion** without regularisation (**TUnfold**)
- **Observables** related to photon kinematics, separation of γ from l, jets ,b-jets, and leptons p_T
- **Slight trends in l+γ and l+l variables** - hints on mismodelling of γ origin in LO simulation
- Large differences between predictions for high p_T bins, but **overall good agreement**







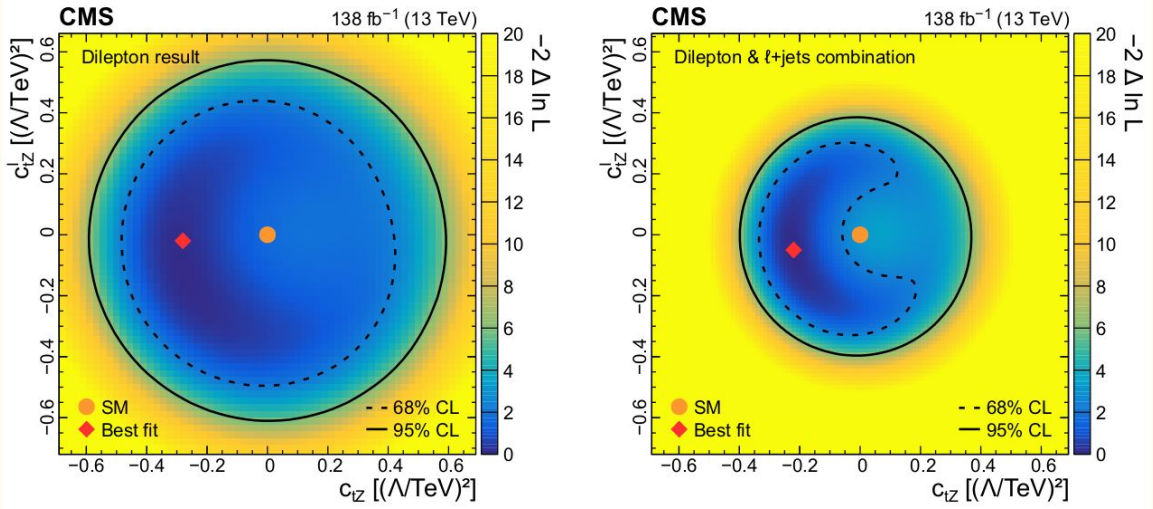
JHEP 05 (2022) 091

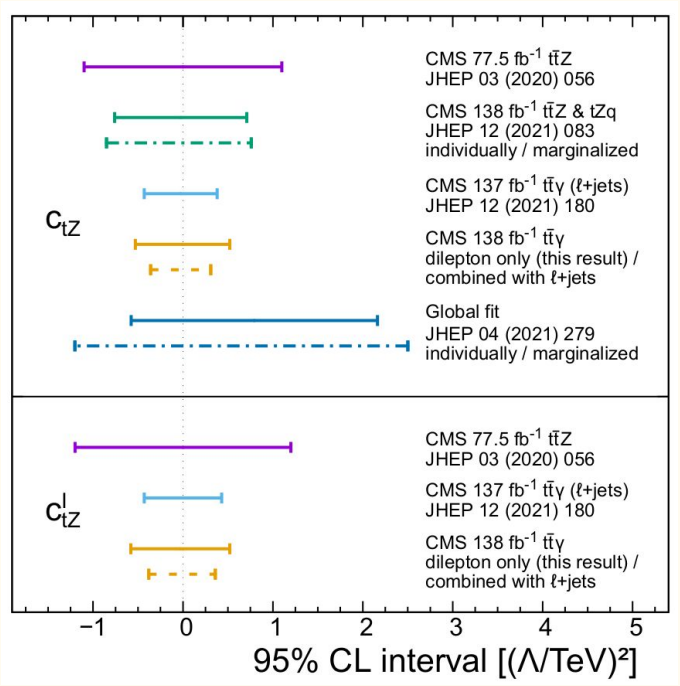
CMS: $t\bar{t}\gamma$ inclusive + differential (dilepton)

138 fb^{-1}

EFT interpretation:

- **Two WCs** considered - $\mathbf{c_{tZ}}$, $\mathbf{c_{tZ}^{I}}$ (complementary to $c_{t\gamma}$, $c_{t\gamma}^{I}$)
- Using $\mathbf{p_T(\gamma)}$, differential observables insensitive
- **l+jets** analysis more sensitive for EFT effects - larger statistics at high p_T
- **1D** and **2D scans** in **dilepton channel only** and also **combined with l+jets**
- Results in agreement with SM - most stringent limits on these WCs to date





$t\bar{t}Z$

CMS: $t\bar{t}Z$ inclusive + differential xs

JHEP 03 (2020) 056

77.5 fb^{-1}

Signal selection:

- **1 OSSF lepton pair** and at least **1 jet**
- **3SR** 3l channel and **2SR** in 4l channel based on **b-jet multiplicity**

Backgrounds:

- **t($\bar{t}$)X** where **X=W,Z,H** - from MC
- **WZ+jets** (3l), **ZZ+jets** (4l) - from data - WZ/ZZ CR
- **Nonprompt leptons** - from data - CR

Differential xs:

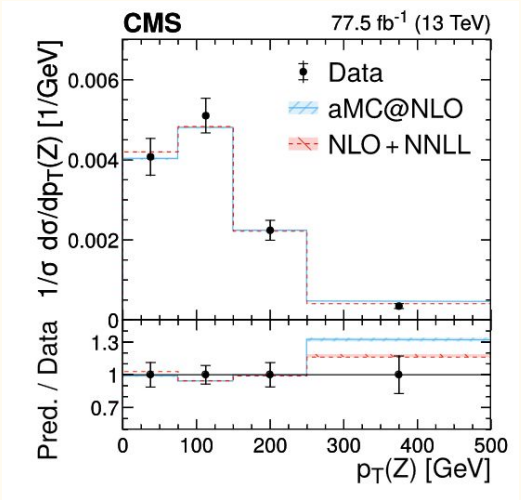
- **Only in 3l** channel ($N_j \geq 3$, $N_b \geq 1$)
- **2 observables** unfolded to **parton level** (absolute and normalised xs)
  - p_T^Z (t-Z coupling) and **cos** θ_Z^* (anomalous dipole moments)
- **Small migrations →matrix inversion** without regularisation - TUnfold
- Overall good agreement

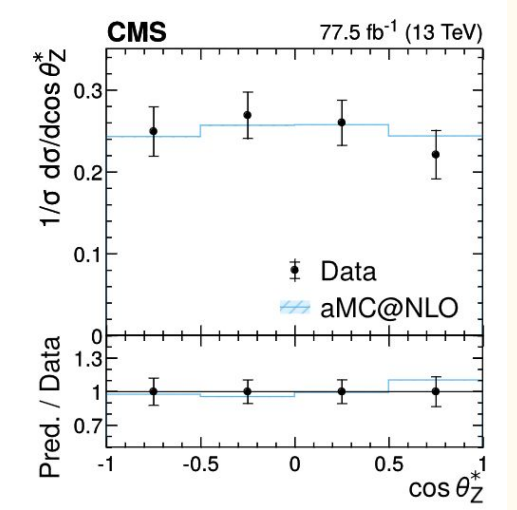
Inclusive xs:

- Simultaneous **PLF to event yields** in 5 SRs and 2 CRs
- **Measured:** 8.2%

$$\sigma(pp \to t\bar{t}Z) = 0.95 \pm 0.05\,(stat) \pm 0.06\,(syst)\,pb,$$

- **Good agreement with NLO+NNLL prediction**, total unc. competitive with theory
- Leading systematics: lepton selection eff., PS, t($\bar{t}$)X and WZ modelling





CMS: $t\bar{t}Z$ inclusive + differential xs

JHEP 03 (2020) 056

77.5 fb^{-1}

Search for anomalous $t\bar{t}Z$ couplings:

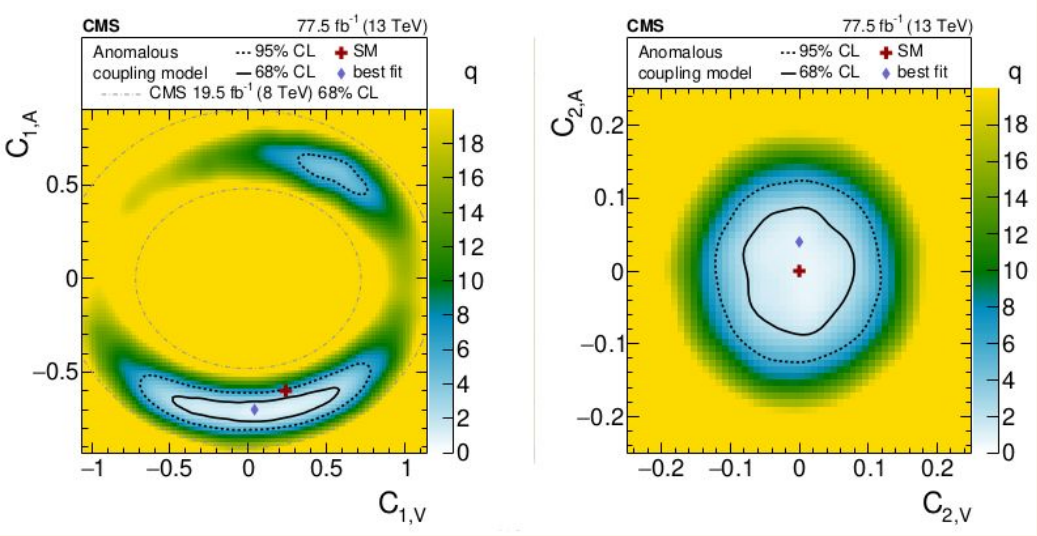
- Testing SM predictions for $C_{1,V}$, $C_{1,A}$ (non-zero in SM) and $C_{2,V}$, $C_{2,A}$ (0 at LO, ~10^{-3} overall)

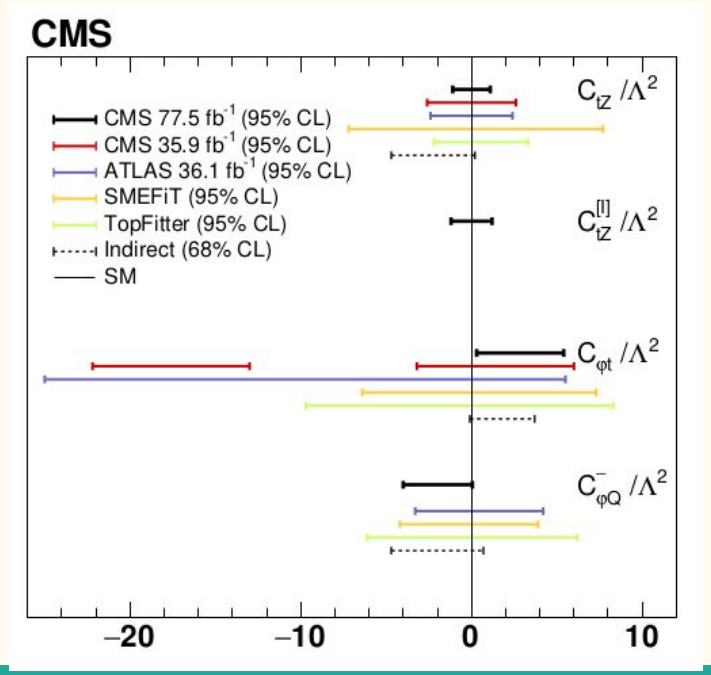
$$\mathcal{L} = e\bar{u}_t \left[\gamma^\mu (C_{1,V} + \gamma_5 C_{1,A}) + \frac{i\sigma^{\mu\nu} p_\nu}{m(Z)} (C_{2,V} + i\gamma_5 C_{2,A}) \right] v_{\bar{t}} Z_\mu,$$

- **cos θ_Z^*** provide high sensitivity
- Obtained **results agree with SM**

EFT interpretation:

- **4 dim-6 WCs** constrained
- 12 SRs and CRs in **3l**
- 3 SRs and CRs in **4l**
- **1D** and **2D** likelihood scans
- All results in agreement with SM predictions





ATLAS-CONF-2023-065

ATLAS: Refined $t\bar{t}Z$ inclusive + differential xs

140 fb^{-1}

Improving previous $t\bar{t}Z$ measurement (*EPJC 81 (2021) 737*):
- Addition of **2l channel** in inclusive xs
- MVA for SR definitions and PLF
- Improved **unfolding technique**

Signal selection:
- 3 SRs in **2l** →jet and b-jet multiplicity
- 3 SRs in **3l** → output nodes of multiclass NN
- 2 SRs in **4l** → SF, DF + cut on NN output in SF

Also covered in Harriet's talk

Backgrounds:
- **2l** dominated by **Z+jets** and **$t\bar{t}$** - from data
- **3l** dominated by **WZ+jets** - from CR
- **4l** dominated by **ZZ+jets** - from CR
- **3 CRs for fakes** in 3l and 4l

Differential xs measurement:
- **Profile Likelihood Unfolding** in 3l and 4l
  - Regularisation for observables featuring hadronic top
- **17 observables** unfolded to particle and parton level
  - sensitive to MC modelling, tZ coupling, BSM effects
- **Good agreement** - lower p values (2%) for **H_T(l)** →bad modelling

Inclusive xs:

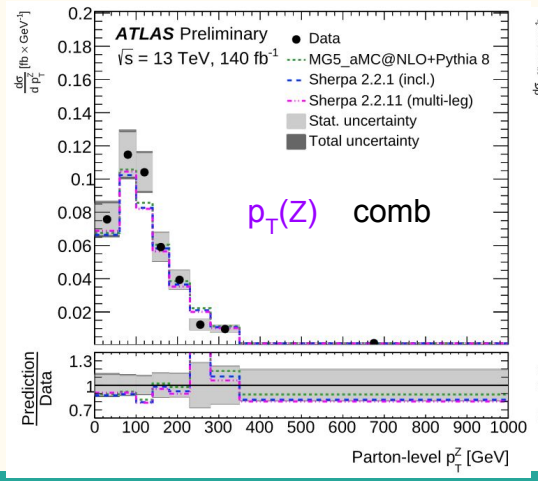
NLO: $\sigma(pp \to t\bar{t}Z) = 0.84^{+0.09}_{-0.10}$ pb

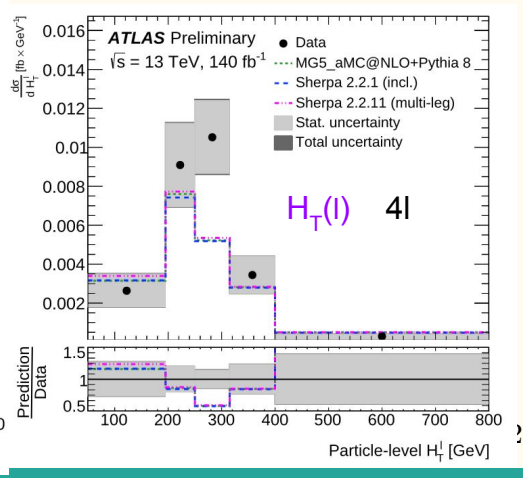
- Simultaneous **PLF to NN outputs**

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 ($2\ell, 3\ell\&4\ell$)	0.86 ± 0.06 pb $= 0.86 \pm 0.04$ (stat.) ± 0.04 (syst.) pb

- Compatible with SM prediction
- **6%** relative precision (**10%** in previous ATLAS $t\bar{t}Z$)
- Leading systematics: background normalisations, jets+E_T^{miss} and b-tagging

6.5%





ATLAS-CONF-2023-065

ATLAS: Refined $t\bar{t}Z$ inclusive + differential xs

140 fb^{-1}

Spin correlations interpretation:

- **First evidence** of top-quark spin correlations **in $t\bar{t}Z$**
- 6 independent observables (in $t\bar{t}$ 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 $t\bar{t}$** (or **lepton** + **down-type quark** from W decay)

Strategy:

- **Template fit** of detector-level distributions
- Each observable *O* fitted to **lin. combination of spin-on and spin-off hypotheses:**

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

- POI (**=1** for SM-like correlations and **=0** in absence of spin. corr.)
- Template **with** SM spin. corr.
- Template **without** spin. corr.

Result:

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

- Measurement **stat. dominated**,
- Spin-off hypothesis rejected with **1.8σ**

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

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

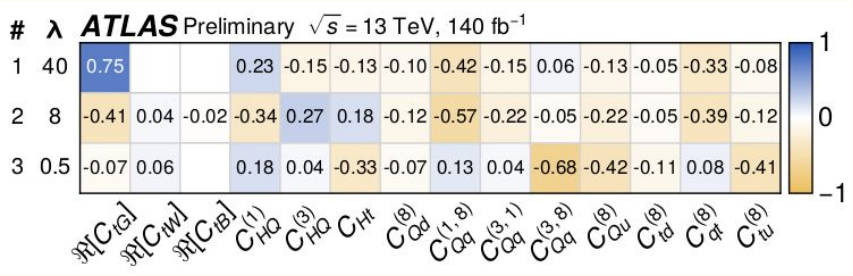
ATLAS-CONF-2023-065

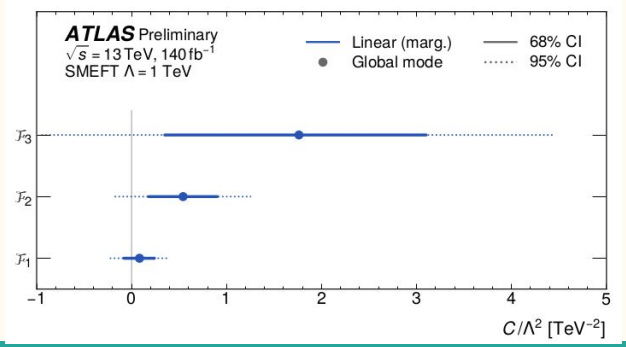
ATLAS: Refined $t\bar{t}Z$ inclusive + differential xs

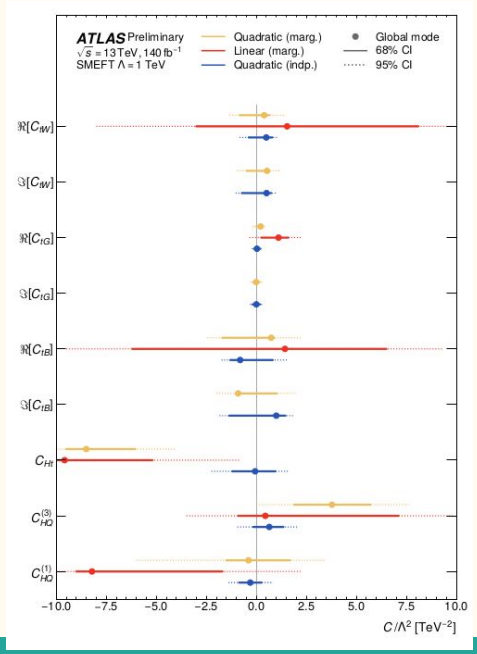
140 fb^{-1}

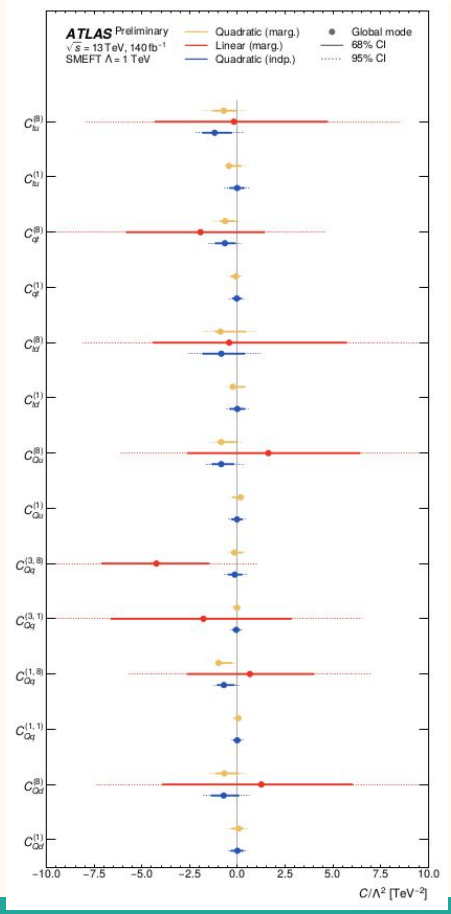
EFT interpretation:

- **20 dim-6 EFT operators**
- Particle-level diff. distributions taken as input
- **Linear and quadratic fits** (other WCs profiled, and fixed to 0)
- Fisher information matrix
  - inverse covariance matrix rotated into the space of the WCs
  - **measure of sensitivity** achieved along directions in WC space
- Results **compatible with SM predictions** within uncertainties









CMS: Boosted $t\bar{t}Z + t\bar{t}H$

PRD 108 032008 (2023)

138 fb^{-1}

- Probes **t - Z/H couplings**
- **Z/H→b$\bar{b}$** and **t$\bar{t}$→l+jets**
- one **e or μ**, one **AK8 high-p_T** jet (H/Z candidate), ≥5 **AK4** jets (≥2 b-tagged)

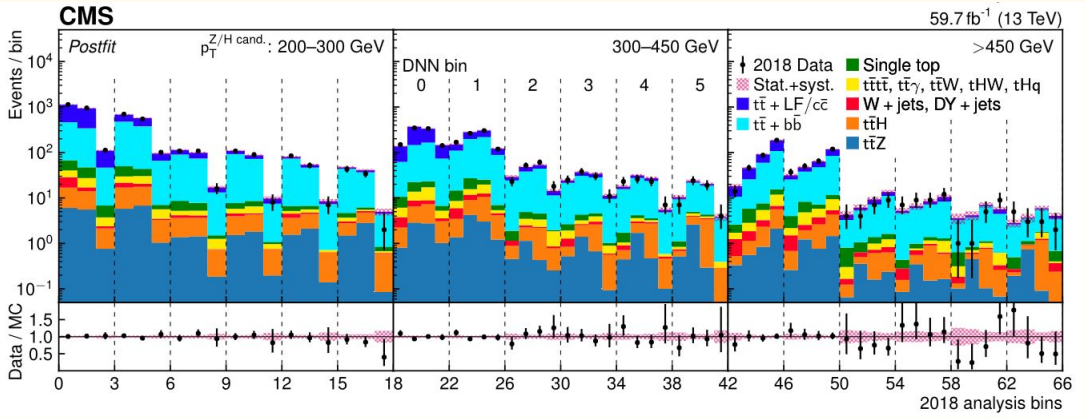
Signal strength extraction:

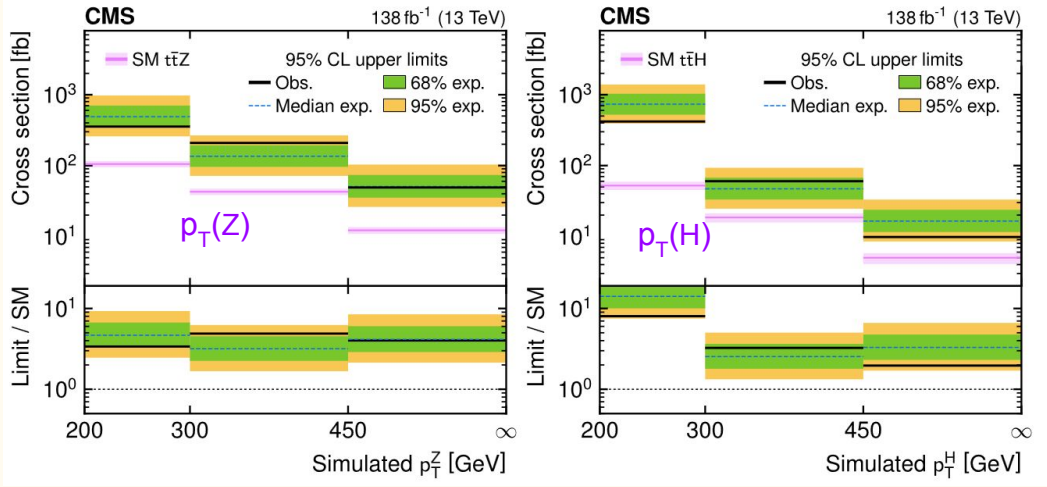
- **Simultaneous profile likelihood fit** to event yields in 198 analysis bins ($p_T^{Z/H}$, m_{SD} and **DNN output**)
- **POIs:** $\mu_{t\bar{t}Z}$, $\mu_{t\bar{t}H}$
- Normalisation of **t$\bar{t}$+b$\bar{b}$ free floating**
- Low correlation between $\mu_{t\bar{t}Z}$ and $\mu_{t\bar{t}H}$ (-10%)
- Results **stat. dominated**

Signal strength	Observed	Stat.	MC stat.	Exp. syst.	Theo. syst.	Expected
$\mu_{t\bar{t}Z}$	$0.65^{+1.04}_{-0.98}$	$^{+0.80}_{-0.75}$	$^{+0.36}_{-0.38}$	$^{+0.38}_{-0.31}$	$^{+0.43}_{-0.38}$	$1.00^{+0.91}_{-0.84}$
$\mu_{t\bar{t}H}$	$-0.27^{+0.86}_{-0.83}$	$^{+0.72}_{-0.65}$	$^{+0.31}_{-0.33}$	$^{+0.19}_{-0.19}$	$^{+0.28}_{-0.35}$	$1.00^{+0.79}_{-0.72}$

Upper limits on differential xs:

- **Profile likelihood unfolding** to obtain **95% CL** upper limits for p_T^Z and p_T^H
- Same fiducial volume as for μ extraction
- **Higher sensitivity on H than Z** due to larger H→b$\bar{b}$ branching fraction





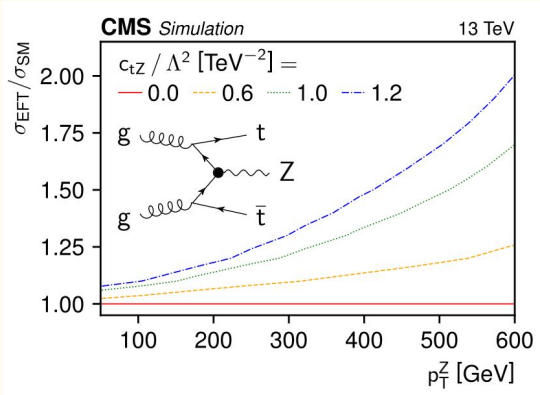
CMS: Boosted $t\bar{t}Z$ + $t\bar{t}H$

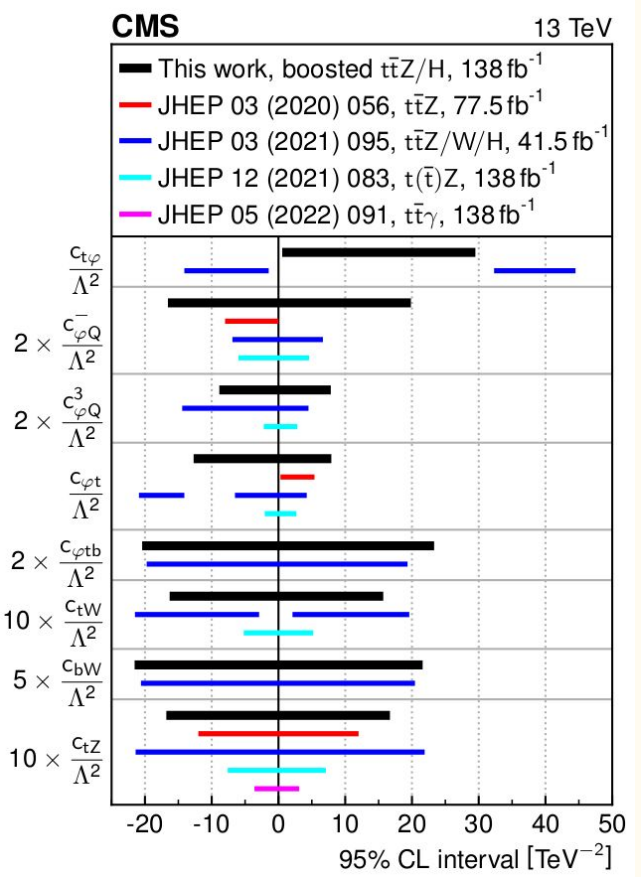
PRD 108 032008 (2023)

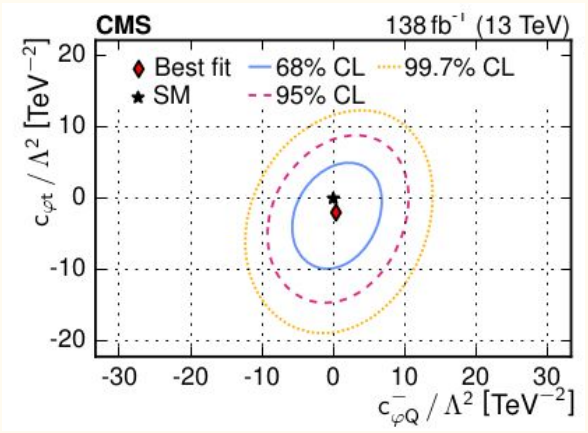
138 fb^{-1}

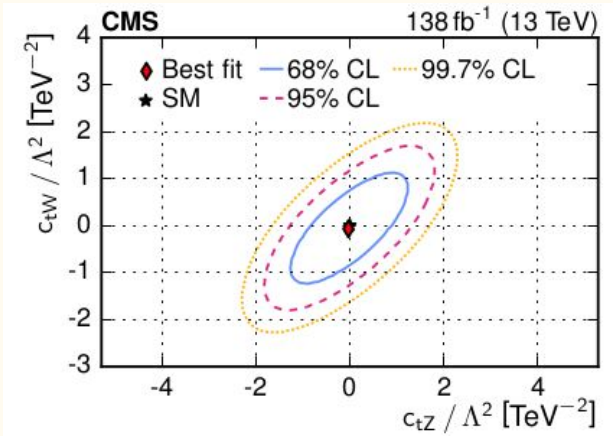
EFT interpretation:

- EFT effects more pronounced in **high p_T regions**
- **8 dim-6 WCs**
- Varying **$t\bar{t}Z$, $t\bar{t}H$** and **$t\bar{t}+b\bar{b}$** samples
- Likelihood scan for each WC while others:
  - fixed to 0
  - profiled (floating)
- **2D scans** for 3 pairs (remaining 6 fixed to 0)
- 95% CL limits **in agreement with SM**
- Comparable sensitivity to other results









Summary

Analysis	Inclusive xs	Differential xs	EFT	Extra
$t\bar{t}\gamma$+tWγ (ATLAS)	39.6 fb ± **6.3%**	**5** observables	no	—
$t\bar{t}\gamma$ (l+jets) (CMS)	798 fb ± **6.1%**	**3** observables	yes	—
$t\bar{t}\gamma$ (dilepton) (CMS)	175.2 fb ± **3.9%**	**12** observables	yes	—
$t\bar{t}Z$ (CMS)	0.95 pb ± **8.2%**	**2** observables	yes	Limits on **anomalous couplings**
$t\bar{t}Z$ refined NEW! (ATLAS)	0.86 pb ± **6.5%**	**15** observables	yes	$t\bar{t}Z$ **spin correlations**
$t\bar{t}Z$ + $t\bar{t}H$ boosted (CMS)	—	**2** observables (upper limits)	yes	**Signal strengths** for $t\bar{t}Z$ and $t\bar{t}H$

- Latest $t\bar{t}Z$ and $t\bar{t}\gamma$ inclusive results now **beating precision of NLO calculations**
- **Inclusive** measurements become **systematically limited**, **differential** remain **statistically limited**

Thank you for your attention !

BACKUP

ATLAS: $t\bar{t}\gamma$+tWγ inclusive + differential xs

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139 fb^{-1}

Signal selection:

- **one electron** and **muon** with p_T>25GeV and **opposite charges**
- **$m_{e\mu}$>15GeV**
- **one** reconstructed **photon** with $\Delta R(l,\gamma)>0.4$
- at least **2 jets** (≥1 b-tag)

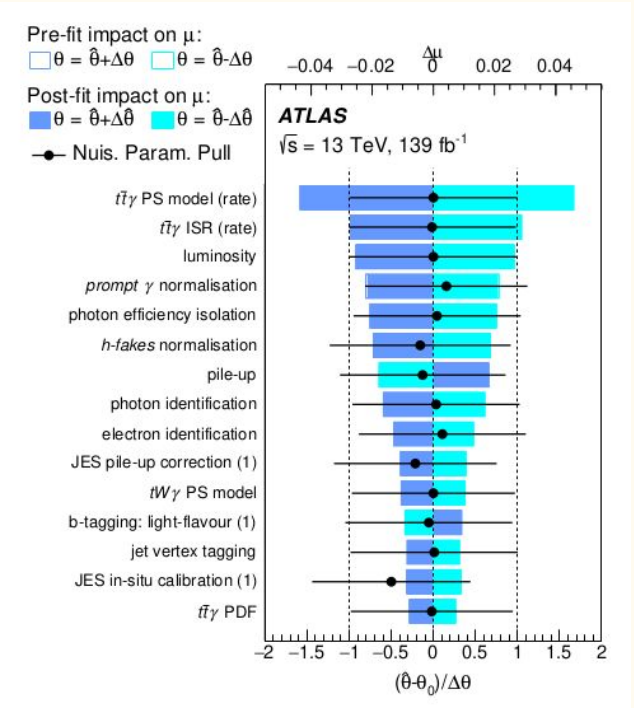
- **S_T** provides good S/B separation and is less sensitive to systematics than jets N or p_T
- Measured in **fiducial phase space** emulating event selection from dedicated theory calculation (parton level)

- **Predicted** NLO (JHEP 01 (2019) 188):

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

Backgrounds:

- All estimated from MC:
- **other $t\bar{t}\gamma$/tWγ (9%)**
- **prompt γ bckg. (3%)**
- **γ from hadron decays $\pi^0\rightarrow\gamma\gamma$ (3%)** = h-fake
- **electron mimicking γ (0.8%)** = e-fake



Category	Uncertainty
$t\bar{t}\gamma/tW\gamma$ modelling	3.8%
Background modelling	2.1%
Photons	1.9%
Luminosity	1.8%
Jets	1.6%
Pile-up	1.3%
Leptons	1.1%
Flavour-tagging	1.1%
MC statistics	0.4%
Soft term E_T^{miss}	0.2%
$tW\gamma$ parton definition	2.8%
Total syst.	6.3%

- tWy parton def. - sample produced with only one b, second b produced in PS, but sometimes missing (30% in Herwig, 50% in Pythia)

ATLAS: $t\bar{t}\gamma$+tWγ inclusive + differential xs

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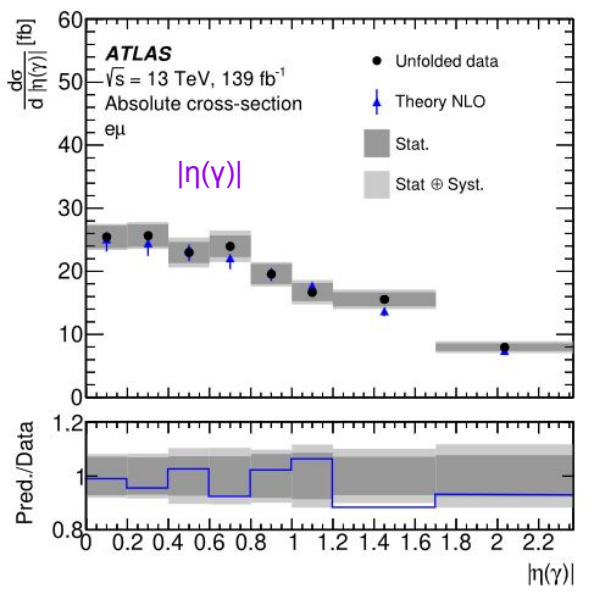

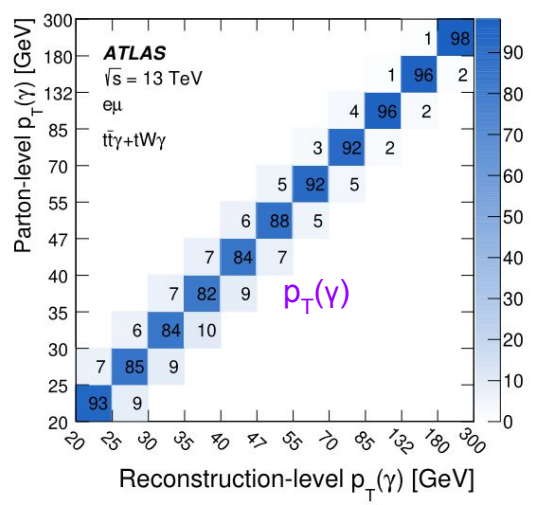

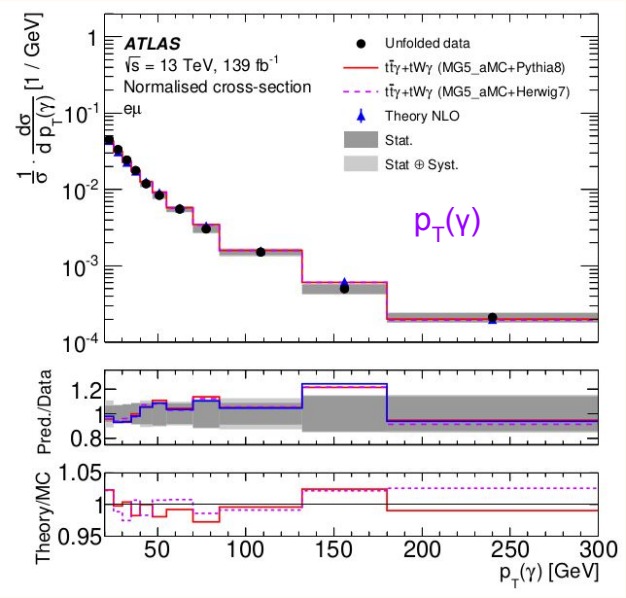

Table 3: χ^2/ndf and p-values between the measured absolute cross-sections and the NLO calculation.

Predictions	$p_T(\gamma)$		$\lvert\eta(\gamma)\rvert$		$\Delta R(\gamma,\ell)_{\min}$		$\Delta\phi(\ell,\ell)$		$\lvert\Delta\eta(\ell,\ell)\rvert$	
	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
Theory NLO	6.1/11	0.87	4.5/8	0.81	11.7/10	0.31	5.8/10	0.83	6.2/8	0.62

- Binning:
  - bin widths larger than **twice the resolution**
  - stat. uncert. **less than 10%** in each bin
  - high resolution→**small migrations** (on diagonal >80%)

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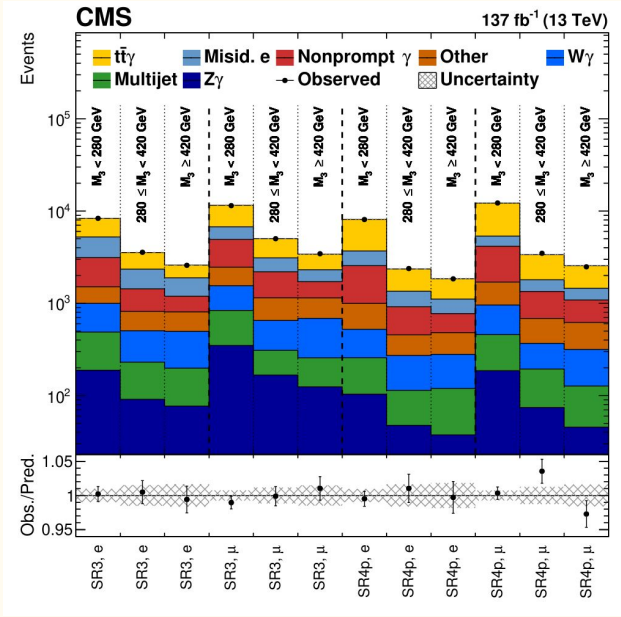
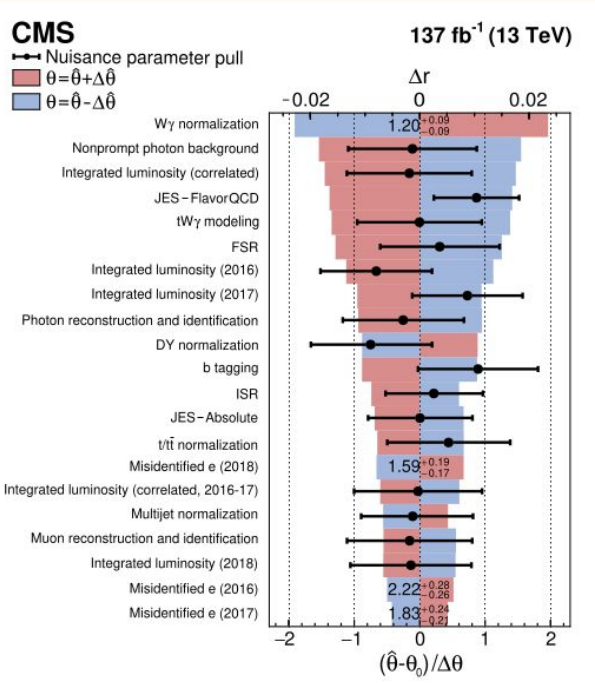
137 fb^{-1}

CMS: $t\bar{t}\gamma$ inclusive + differential (l+jets)

Backgrounds:

- **Non-prompt γ (23%):**
  - dominant, estimated **from data** in sideband CR
  - signal and other bckgs. subtracted from data
- **Misidentified e (19%):**
  - **from data**, dedicated CRs ($N_b = 0$)
  - *high mass* (Wγ), *low mass* (Wγ, Zγ) and *Z mass* ($|m(l,\gamma)-m_Z| \leq 10$ GeV, Z→ee)
  - **Wγ** normalisation → **free parameter of the fit**
- **Multijet (< 0.5%):**
  - **from data** in sideband region
  - CRs with loosened isol. criteria (pass loose, fail tight), N_b=0
  - template fit of m_T(W)





Photon	e (μ)	Jet	b jet
$p_T > 20$ GeV	$p_T > 35\,(30)$ GeV	$p_T > 30$ GeV	$p_T > 30$ GeV
$\lvert\eta\rvert < 1.4442$	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.4$
no hadronic origin	no hadronic origin	$\Delta R(\text{jet},\ell) > 0.4$	$\Delta R(\text{b jet},\ell) > 0.4$
$\Delta R(\ell,\gamma) > 0.4$		$\Delta R(\text{jet},\gamma) > 0.1$	$\Delta R(\text{b jet},\gamma) > 0.1$
isolated			matched to b hadrons

- Predicted NLO:

$$\sigma^{\text{NLO}}(t\bar{t}\gamma) = 773 \pm 135\,\text{fb}.$$

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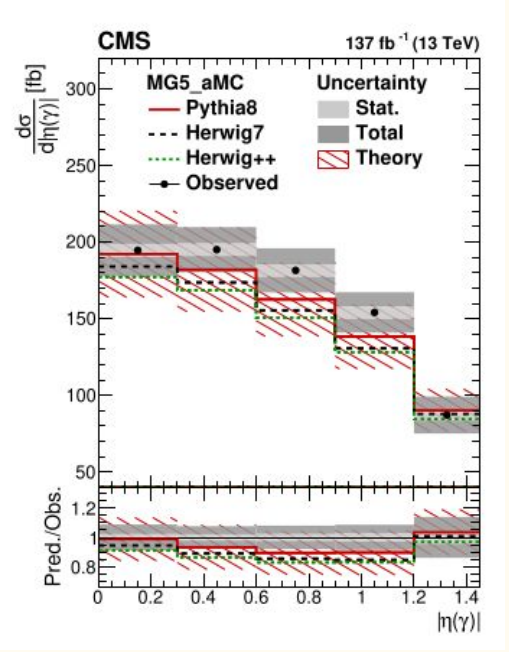
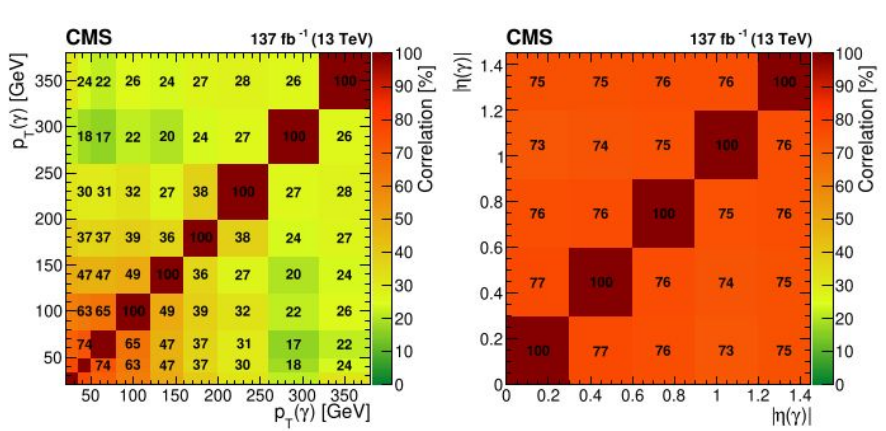
137 fb^{-1}

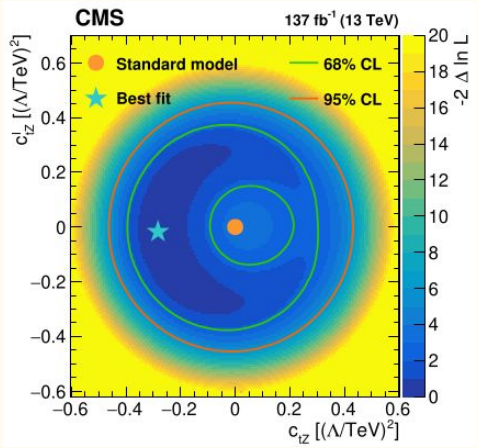
CMS: $t\bar{t}\gamma$ inclusive + differential (l+jets)

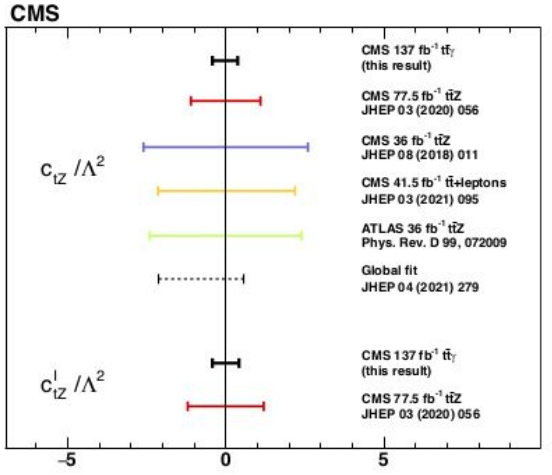




	$p_T(\gamma)$	$\lvert\eta(\gamma)\rvert$	$\Delta R(l,\gamma)$
χ^2	12.0	5.2	6.3
NDF	9	5	7

$$c_{tZ} = \mathrm{Re}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right),$$
$$c_{tZ}^{I} = \mathrm{Im}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right),$$
$$c_{t\gamma} = \mathrm{Re}\left(\cos\theta_W C_{uB}^{(33)} + \sin\theta_W C_{uW}^{(33)}\right),$$
$$c_{t\gamma}^{I} = \mathrm{Im}\left(\cos\theta_W C_{uB}^{(33)} + \sin\theta_W C_{uW}^{(33)}\right),$$





CMS: $t\bar{t}\gamma$ inclusive + differential (dilepton)

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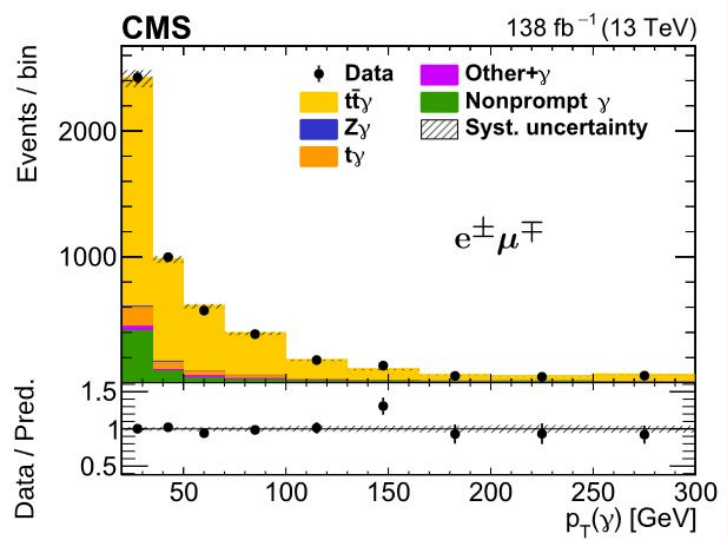
138 fb^{-1}

Signal selection:

Leptons	Photons	Jets	b jets	Events
$p_T > 25\ (15)$ GeV	$p_T > 20$ GeV	$p_T > 30$ GeV	$p_T > 30$ GeV	$N_\ell = 2$ (OC)
$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 1.44$	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.4$	$N_\gamma = 1$
	$\Delta R(\gamma, \ell) > 0.4$	$\Delta R(\text{jet}, \ell) > 0.4$	$\Delta R(\text{jet}, \ell) > 0.4$	$N_b \geq 1$
	isolated	$\Delta R(\text{jet}, \gamma) > 0.1$	$\Delta R(\text{jet}, \gamma) > 0.1$	$m(\ell\ell) > 20$ GeV
			matched to b hadron	

+ $|m_{ll}-m_Z|>15$GeV and $|m_{ll\gamma}-m_Z|>15$GeV for **SF** leptons



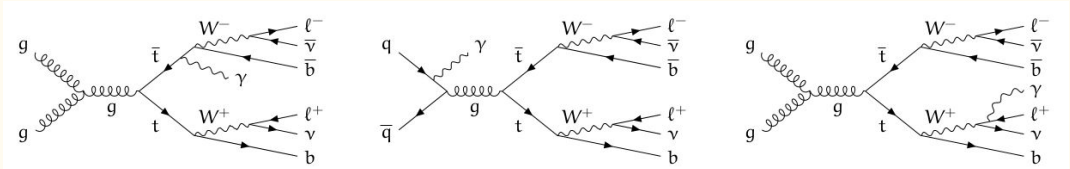
Backgrounds:

➢ **Prompt γ bckg (13%):**
- dominated by **Zγ**, **tγ**
- Zγ from data, others from MC
- Zγ CR:
  - $|m_{ll\gamma}-m_Z|<15$GeV; only SF leptons

➢ **Nonprompt γ bckg (13%):**
- estimated **from data in sideband region** (99.5% purity)
- **"tight-to-loose ratio"** method applied to $t\bar{t}$
- corr. factor as ratio of events passing and failing ID criteria for γ

- Predicted (NLO MG5_aMC@NLO):

$$\sigma_{SM}(pp \to t\bar{t}\gamma) = 155 \pm 27\,\text{fb}$$



CMS: $t\bar{t}\gamma$ inclusive + differential (dilepton)

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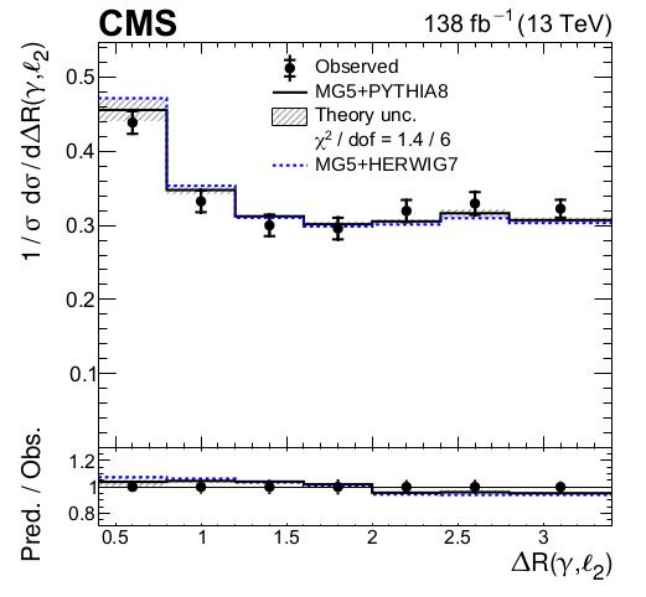

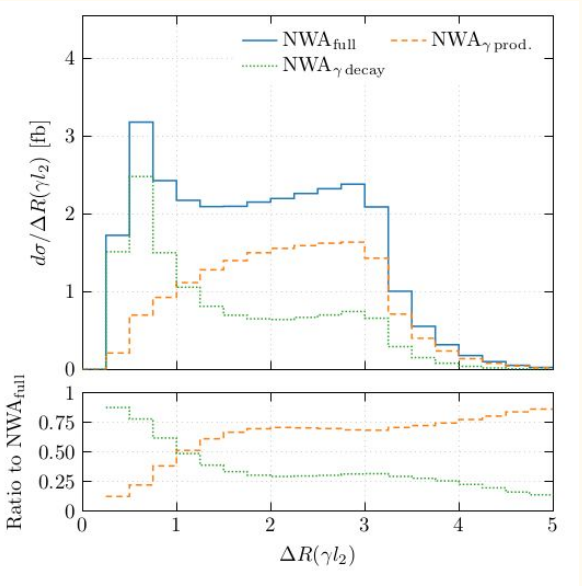

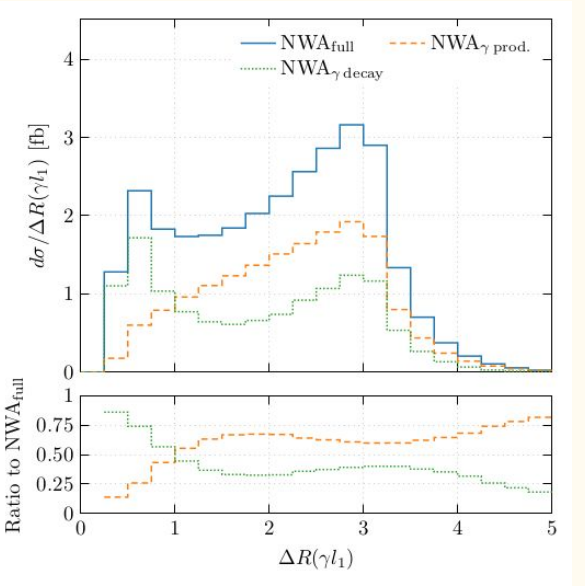

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- ΔR<1 - 80% γ from top decay
- ΔR>1 - only 20-40% γ from top decay, majority from production

CMS: $t\bar{t}Z$ inclusive + differential xs

JHEP 03 (2020) 056

77.5 fb^{-1}

Signal selection:

- 3l channel:
  - **3 leptons** with p_T > 40, 20, 10 GeV
  - **1 OSSF lepton pair** with $|m_{ll}-m_Z|$ < **10 GeV**
  - **$N_j \geq 1$**
  - **3SR** based on **N_b = 0, 1, ≥2**
- 4l channel:
  - **4 leptons** with p_T > 40, 10, 10, 10 GeV
  - **1 OSSF lepton pair** with $|m_{ll}-m_Z|$ < **20 GeV**
  - **$N_j \geq 1$**
  - **2SR** based on **N_b = 0, ≥1**
- For differential xs only 3l channel with **$N_j \geq 3$, $N_b \geq 1$**

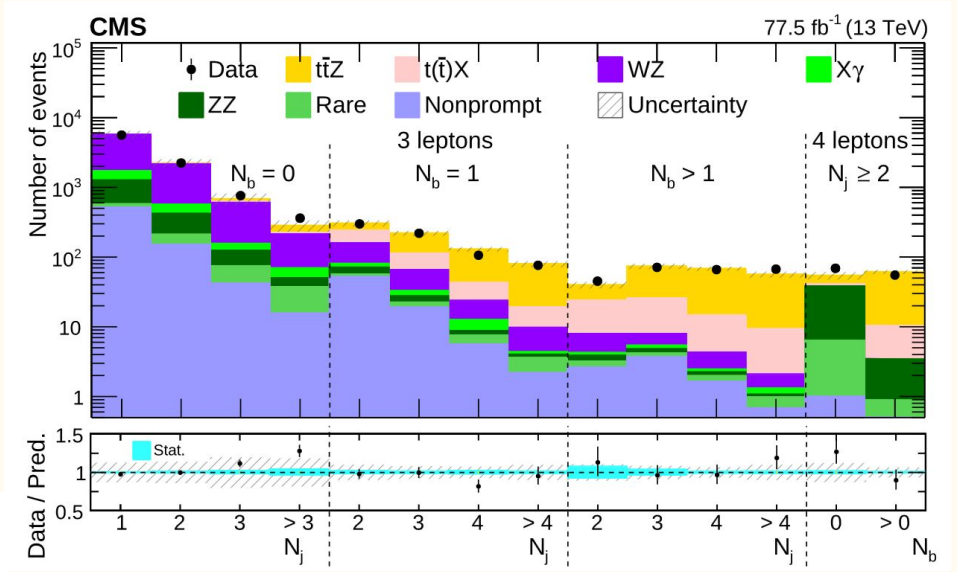
Backgrounds:

- Main contribution from **t($\bar{t}$)X** where **X=W,Z,H**
  - estimated from MC
- **WZ+jets** (3l), **ZZ+jets** (4l)
  - from data - WZ/ZZ CR
- **Nonprompt leptons** - subdominant
  - from data - CR (3l events without Z candidate)
- Minor contribution from **VVV** ("Rare") and **Zγ^***, **$t\bar{t}\gamma$** (Xγ)
  - from MC

Lepton requirement	Measured cross section
3ℓ	$0.97 \pm 0.06\,(\text{stat}) \pm 0.06\,(\text{syst})$ pb
4ℓ	$0.91 \pm 0.14\,(\text{stat}) \pm 0.08\,(\text{syst})$ pb
Total	$0.95 \pm 0.05\,(\text{stat}) \pm 0.06\,(\text{syst})$ pb

- **Based on the previous CMS $t\bar{t}Z$** analysis (*JHEP 08 (2018) 011*) at 36 fb^{-1}
- Improved trigger and lepton (MVA) selection
- Fiducial phase space defined by **$70 \leq m_{ll} \leq 110$ GeV**
- **Predicted (NLO+NNLL):**

$$\sigma(pp \to t\bar{t}Z) = 0.84^{+0.09}_{-0.10}\ \text{pb}$$



CMS: $t\bar{t}Z$ inclusive + differential xs

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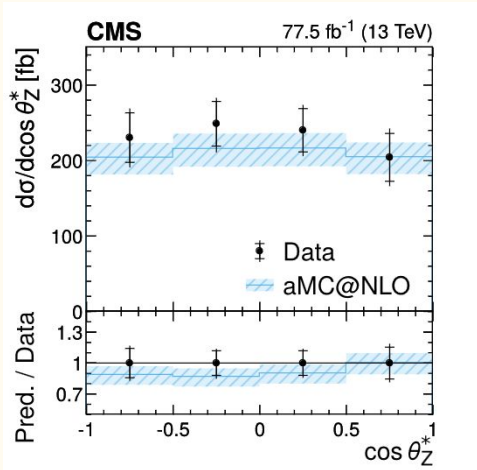
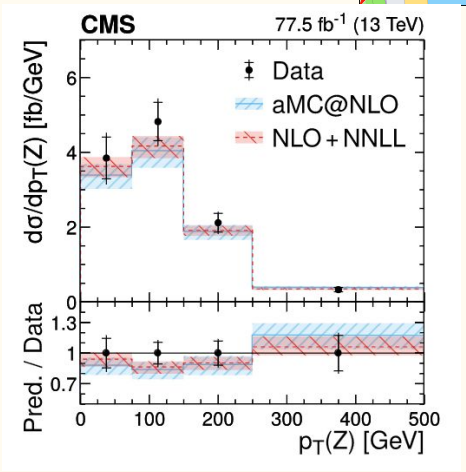
77.5 fb^{-1}

N_ℓ	N_b	N_j	N_Z	$p_T(Z)$ (GeV)	$-1 \le \cos\theta_Z^* < -0.6$	$-0.6 \le \cos\theta_Z^* < 0.6$	$0.6 \le \cos\theta_Z^*$
3	≥1	≥3	1	0–100	SR1	SR2	SR3
				100–200	SR4	SR5	SR6
				200–400	SR7	SR8	SR9
				≥400	SR10	SR11	SR12
4	≥1	≥1	1	0–100		SR13	
				100–200		SR14	
				≥200		SR15	
3	0	≥1	1	0–100	CR1	CR2	CR3
				100–200	CR4	CR5	CR6
				200–400	CR7	CR8	CR9
				≥400	CR10	CR11	CR12
4	≥0	≥1	2	0–100		CR13	
				100–200		CR14	
				≥200		CR15	





$$C_{1,V}^{SM} = \frac{I_{3,q}^f - 2Q_f \sin^2\theta_W}{2\sin\theta_W\cos\theta_W} = 0.2448\,(52),$$

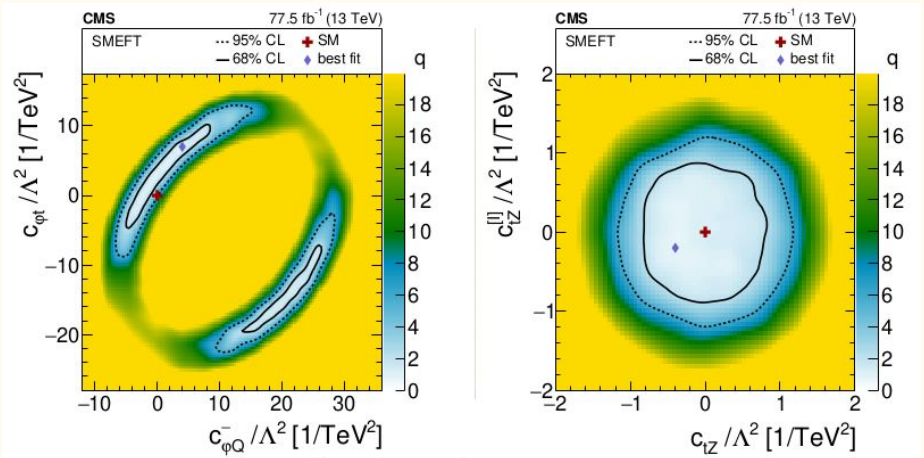
$$C_{1,A}^{SM} = \frac{-I_{3,q}^f}{2\sin\theta_W\cos\theta_W} = -0.6012\,(14),$$

$$c_{tZ} = \mathrm{Re}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right)$$

$$c_{tZ}^{[I]} = \mathrm{Im}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right)$$

$$c_{\phi t} = C_{\phi t} = C_{\phi u}^{(33)}$$

$$c_{\phi Q}^- = C_{\phi Q} = C_{\phi q}^{1(33)} - C_{\phi q}^{3(33)},$$



ATLAS: Refined $t\bar{t}Z$ inclusive + differential xs

140 fb^{-1}

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

Variable	Preselection		
N_ℓ $(\ell = e, \mu)$	= 2		
	= 1 OSSF lepton pair with $\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV		
p_T (ℓ_1, ℓ_2)	> 30, 15 GeV		
	SR-2ℓ-5j2b	**SR-2ℓ-6j1b**	**SR-2ℓ-6j2b**
N_{jets} $(p_T > 25$ GeV)	= 5	≥ 6	≥ 6
$N_{b\text{-tagged jets@77\%}}$	≥ 2	= 1	≥ 2

Variable	Preselection		
N_ℓ $(\ell = e, \mu)$	= 3		
	≥ 1 OSSF lepton pair with $\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV		
	for all OSSF combinations: $m_{\text{OSSF}} > 10$ GeV		
p_T (ℓ_1, ℓ_2, ℓ_3)	> 27, 20, 15 GeV		
N_{jets} $(p_T > 25$ 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%

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: $m_{\text{OSSF}} > 10$ 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	
$N_{b\text{-tagged jets}}$	≥ 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	—

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ATLAS: Refined $t\bar{t}Z$ inclusive + differential xs

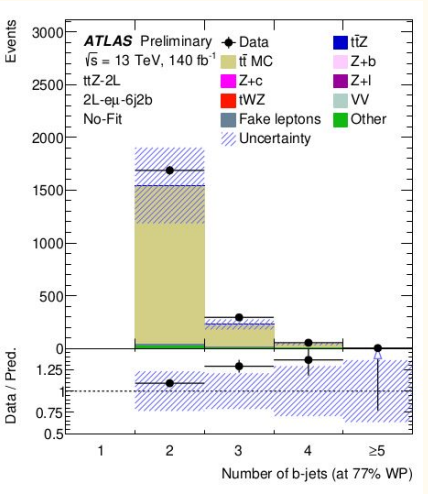
Backgrounds:

- **2l channel:**
  - Dominated by **Z+jets** and **$t\bar{t}$**
  - Z+l from MC, Z+b/c from data
  - $t\bar{t}$ from data - 3 regions (OSSF → OSDF)
- **3l channel:**
  - Dominated by **WZ+jets** and **tZq**
  - WZ+b from data, all other from MC
- **4l channel:**
  - Main bckg. is **ZZ+jets** - dedicated CR
- **3 CRs for fakes** (F-e-HF, F-e-other, F-μ-HF) in 3l and 4l (in 2l from MC)

DD tt selection

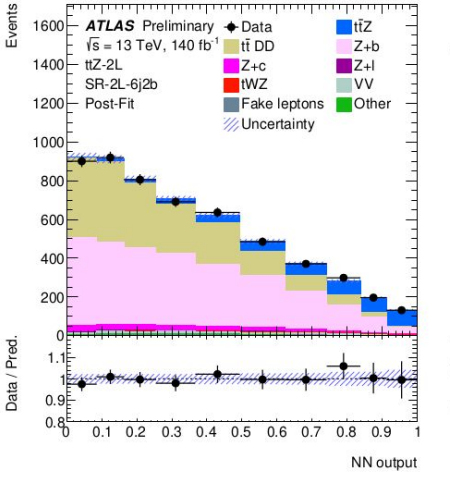
140 fb^{-1}

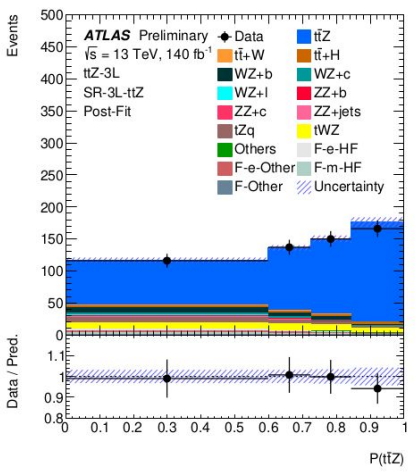
Variable	Preselection		
N_ℓ $(\ell = e, \mu)$	= 2		
	= 1 OSDF lepton pair with $\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV		
p_T (ℓ_1, ℓ_2)	> 30, 15 GeV		
	2ℓ-eμ-5j2b	**2ℓ-eμ-6j1b**	**2ℓ-eμ-6j2b**
N_{jets} $(p_T > 25$ GeV)	= 5	≥ 6	≥ 6
$N_{b-\text{tagged jets@77\%}}$	≥ 2	= 1	≥ 2

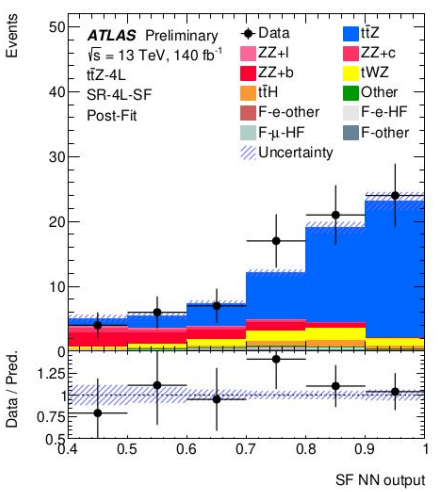


ZZ+jets CR in 4l

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: $m_{\text{OSSF}} > 10$ 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
$N_{b-\text{tagged jets}}$	≥ 1@85%
	CR-4ℓ-ZZ
$\ell\ell^{\text{non-Z}}$	e^+e^- or $\mu^+\mu^-$
DNN-SF output	< 0.4







ATLAS: Refined $t\bar{t}Z$ inclusive + differential xs

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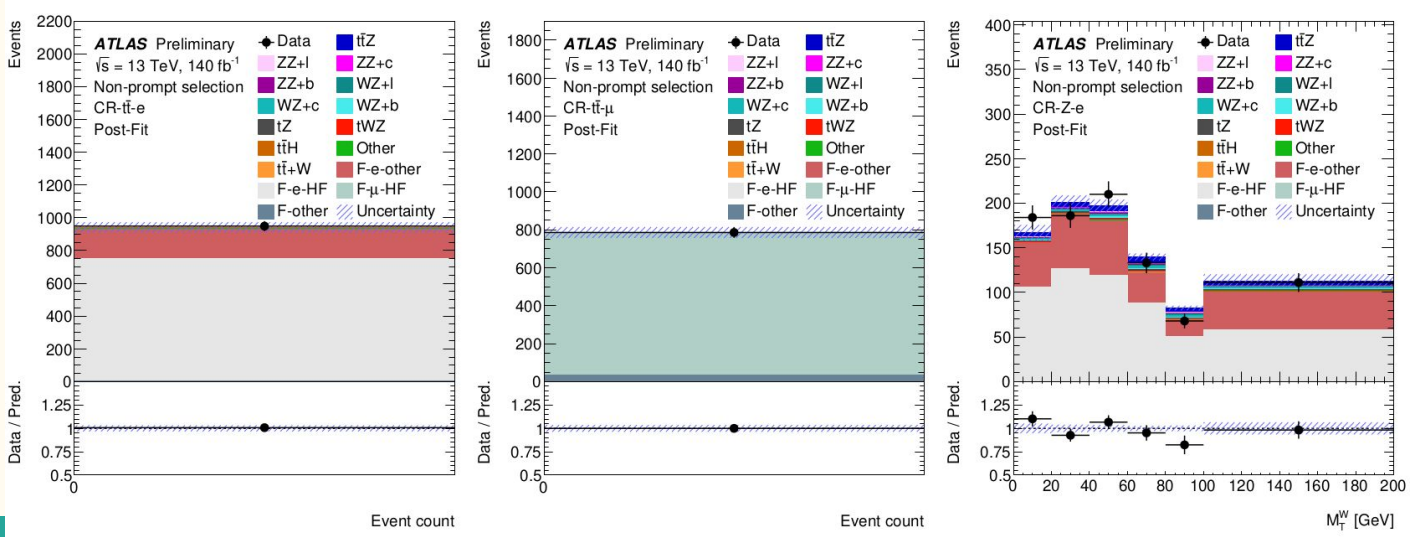
Variable	Preselection		
N_ℓ ($\ell = e, \mu$)	= 3 (of which = 1 loose non-tight)		
$p_T(\ell_1, \ell_2, \ell_3)$	> 27, 20, 15 GeV		
Sum of lepton charges	±1		
N_{jets} (p_T > 25 GeV)	≥ 3		
$N_{b-\text{tagged jets}}$	≥ 1@85%		
	CR-$t\bar{t}$-e	**CR-$t\bar{t}$-μ**	**CR-Z-e**
Lepton flavours	no OSSF pair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



ATLAS: Refined $t\bar{t}Z$ inclusive + differential xs

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

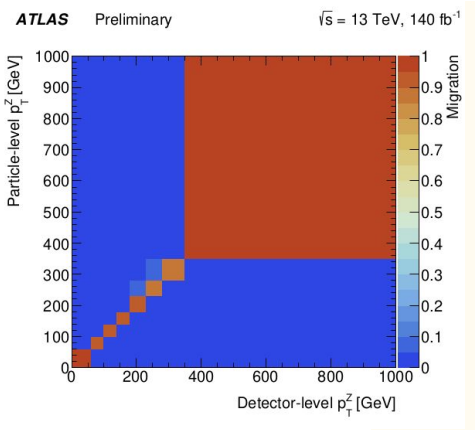
Observables:

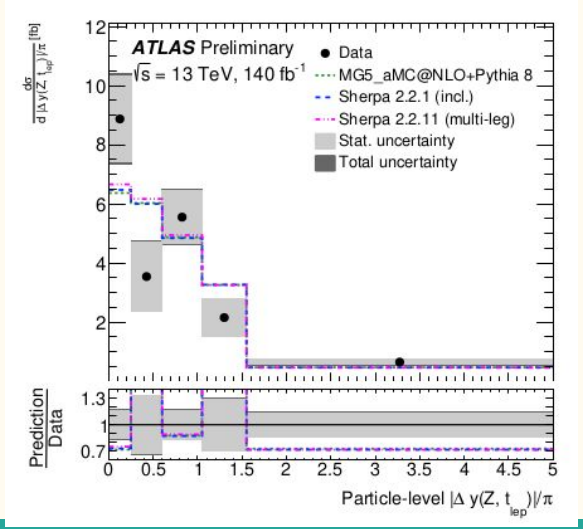
- **3l channel**: N_{jets}, $p_T^{l,non\text{-}Z}$, $|\Delta\phi(Z,t_{lep})|$, $|\Delta y(Z,t_{lep})|$, H_T^l
- **4l channel**: N_{jets}, $|\Delta\phi(l_t^+,l_t^-)|$, H_T^l
- **combination**: p_T^Z, $|y^Z|$, $\cos\theta_Z^*$, p_T^t, $p_T^{t\bar{t}}$, $|\Delta\phi(t\bar{t},Z)|$, $m^{t\bar{t}Z}$, $m^{t\bar{t}}$, $|y^{t\bar{t}Z}|$

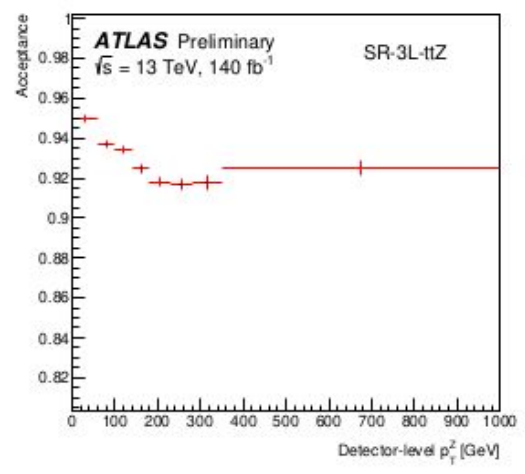
Binning:

- optimised with IBU (stat. only)
- **low stat.** uncertainty (<35%)
- **low migrations** between reco. and truth bins

- Uncertainties **between 15-40%** (dominated by stat. uncert.)
- Parton level more precise (more diagonal mig. matrices)







ATLAS: Refined $t\bar{t}Z$ inclusive + differential xs

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

		aMC@NLO +Pythia 8		Sherpa 2.2.1 (incl.)		Sherpa 2.2.11 (multi-leg)	
	Variable	parton	particle	parton	particle	parton	particle
3ℓ	$\lvert\Delta\phi(Z,t^{l})\rvert/\pi$	0.07	0.05	0.04	0.02	0.07	0.06
	$\lvert\Delta y(Z,t^{l})\rvert$	0.03	0.03	0.03	0.02	0.03	0.02
	H_{T}^{l}	0.02	0.02	0.02	0.04	0.05	0.07
	$p_{T}^{l,non-Z}$	0.63	0.63	0.29	0.5	0.29	0.41
	N_{jets}	-	0.42	-	0.81	-	0.75
4ℓ	N_{jets}	-	0.40	-	0.65	-	0.61
	$\lvert\Delta\phi l,l\rvert/\pi$	0.75	0.76	0.73	0.75	0.74	0.80
	H_{T}^{l}	0.03	0.02	0.03	0.02	0.03	0.02
$3\ell+4\ell$	$\lvert y^{Z}\rvert$	0.71	0.72	0.71	0.71	0.70	0.69
	p_{T}^{Z}	0.04	0.03	0.06	0.06	0.13	0.14
	$\cos\theta*^{Z}$	0.11	0.11	0.12	0.12	0.15	0.15
	$\lvert\Delta\phi(t\bar{t},Z)\rvert/\pi$	0.74	0.71	0.02	0.36	0.02	0.39
	$m^{t\bar{t}}$	0.79	0.88	0.87	0.73	0.27	0.43
	$m^{t\bar{t}Z}$	0.84	0.93	0.8	0.91	0.81	0.89
	p_{T}^{top}	0.03	0.23	0.01	0.29	0.01	0.1
	$p_{T}^{t\bar{t}}$	0.02	0.01	0.01	0.01	0.02	0.03
	$\lvert y^{t\bar{t}Z}\rvert$	0.87	0.52	0.85	0.64	0.59	0.28

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

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

- **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)

- **Template fit** of detector-level distributions (unfolded distribution cannot be used due to highly non-diagonal mig. matrices in 4l - would require regularisation →bias)
- **Only 9 coefficient** are non-0 within theoretical uncert. →improve stability of the fit
- Coefficients fitted **individually** and then **combined** using profiled χ^2 fit

- main systs. from MC modelling, E_T^{miss} and flavour tagging
- 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

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ATLAS: Refined $t\bar{t}Z$ inclusive + differential xs

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

- Observables used as an input to EFT fits - **particle level normalised distributions:**
  - p_T^Z (top-Z operators), $|y^Z|$, $\cos\theta_Z^*$, p_T^t (4-quark operators), $|\Delta\phi(t\bar{t},Z)|$, $|y^{t\bar{t}Z}|$

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

- For some operators the results of the linear fits are not quoted since the corresponding interference term is vanishing at LO in QCD
- For some operators by introducing pure EFT contributions in quadratic fits, the linearised limits are drastically reduced by factor 6 to 30, i.e. $C_{Qq}^{(3,1)}$, $C_{Qq}^{(3,8)}$

	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	$Q_{tu}^{(1)}$	$(\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u)$	
	$Q_{tu}^{(8)}$	$(\bar{t}T^a\gamma_\mu t)(\bar{u}T^a\gamma^\mu u)$	
	$Q_{td}^{(1)}$	$(\bar{t}\gamma_\mu t)(\bar{d}\gamma^\mu d)$	
	$Q_{td}^{(8)}$	$(\bar{t}T^a\gamma_\mu t)(\bar{d}T^a\gamma^\mu d)$	
	$Q_{qt}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{t}\gamma^\mu t)$	
	$Q_{qt}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{t}T^a\gamma^\mu t)$	
	$Q_{Qu}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$	
	$Q_{Qu}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{u}T^a\gamma^\mu u)$	
	$Q_{Qd}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$	
	$Q_{Qd}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{d}T^a\gamma^\mu d)$	
	$Q_{Qq}^{(1,1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q)$	
	$Q_{Qq}^{(3,1)}$	$(\bar{Q}\sigma^i\gamma_\mu Q)(\bar{q}\sigma^i\gamma^\mu q)$	
	$Q_{Qq}^{(1,8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{q}T^a\gamma^\mu q)$	
	$Q_{Qq}^{(3,8)}$	$(\bar{Q}\sigma^i T^a\gamma_\mu Q)(\bar{q}\sigma^i T^a\gamma^\mu q)$	

CMS: Boosted $t\bar{t}Z + t\bar{t}H$

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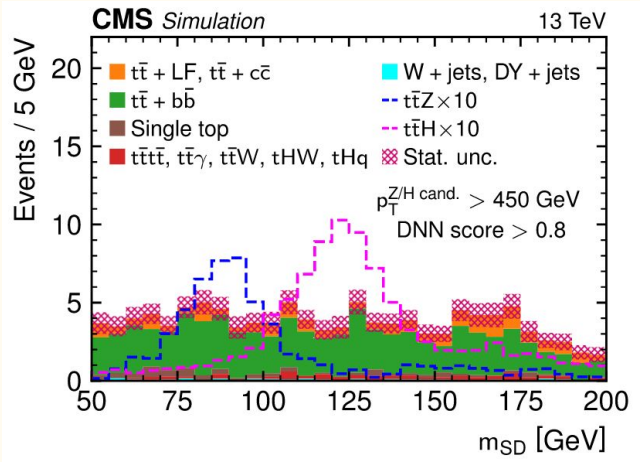
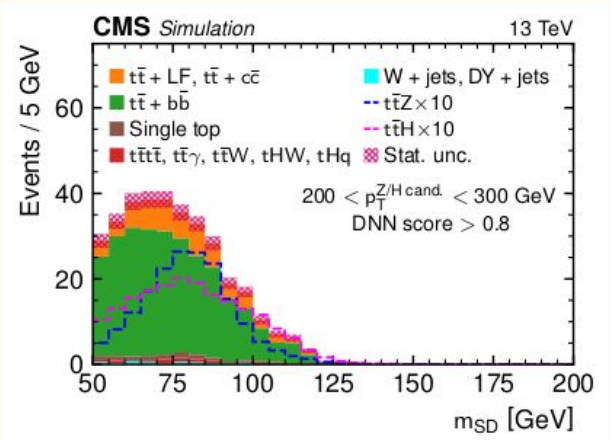
Signal selection:

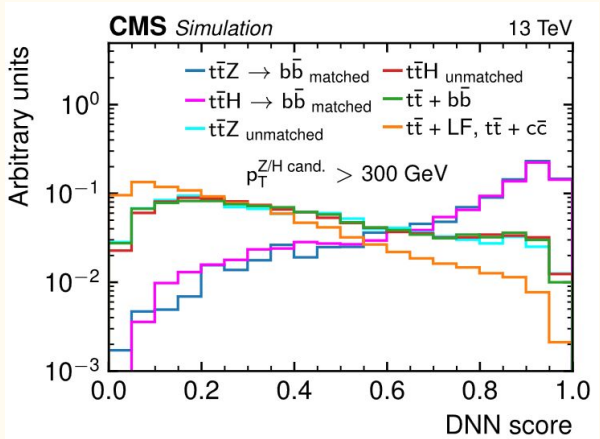
- **1 e or μ** with p_T>30 GeV
- At least **1 AK8 jet** (one H/Z candidate with $b\bar{b}$ tagger score >0.8, R=0.8) with p_T>200 GeV, 50<m_{SD}<200 GeV
- **≥5 AK4 jets** (R=0.4) - (3 or 4 jets not overlapping with AK8)
- **≥2 b-tagged AK4 jets** from $t\bar{t}$ (separated from H/Z by ΔR>0.8)
- **p_T^{miss}>20 GeV**
- **m_{l+l-}>12 GeV** (to eliminate J/Ψ and Y decays)

Strategy:

- 3 discriminating variables for S and B separation (**$p_T^{Z/H}$, m_{SD}** and **DNN output**)
- DNN:
  - **3** output nodes (signal $t\bar{t}Z/t\bar{t}H$, $t\bar{t}$+$b\bar{b}$, $t\bar{t}$+LF/$c\bar{c}$)
  - **Only S/B discrimination**
- **198 analysis bins** for signal strength extraction:
  - **3 data-taking** periods
  - **3** bins in **$p_T^{Z/H}$**
  - **3** (for lowest $p_T^{Z/H}$ bin) or **4** bins in **m_{SD}**
  - **6** bins in **DNN**
- **Upper limits for diff. xs** evaluated for **p_T^{Z}** and **p_T^{H}** (4bins, first one constrained to SM prediction)







CMS: Boosted $t\bar{t}Z$ + $t\bar{t}H$

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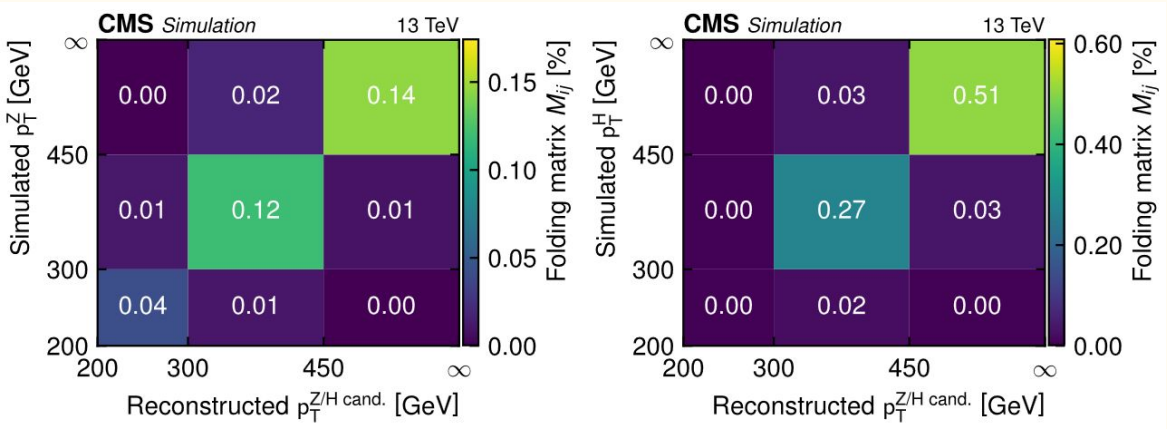
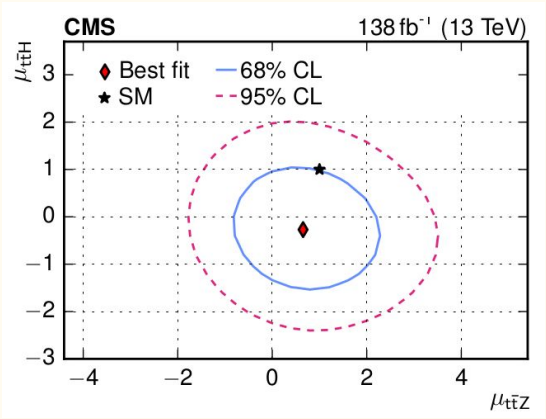
Source of uncertainty	$\Delta\mu_{t\bar{t}Z}$	$\Delta\mu_{t\bar{t}H}$
$t\bar{t}+c\bar{c}$ cross section	$^{+0.27}_{-0.23}$	$^{+0.14}_{-0.13}$
$t\bar{t}+b\bar{b}$ cross section	$^{+0.18}_{-0.24}$	$^{+0.16}_{-0.22}$
$t\bar{t}+2b$ cross section	$^{+0.03}_{-0.03}$	±0.09
μ_R and μ_F scales	$^{+0.12}_{-0.14}$	$^{+0.11}_{-0.15}$
Parton shower	$^{+0.16}_{-0.17}$	$^{+0.07}_{-0.06}$
b tagging efficiency	$^{+0.25}_{-0.13}$	±0.10
$b\bar{b}$ tagging efficiency	$^{+0.18}_{-0.13}$	$^{+0.07}_{-0.04}$
Jet energy scale and resolution	±0.11	$^{+0.11}_{-0.12}$
Jet mass scale and resolution	±0.10	±0.08





Signal	$p_T^{Z/H}$ interval [GeV]	95% CL upper limit [fb]		95% CL upper limit / SM	
		Observed	Expected	Observed	Expected
$t\bar{t}Z$	200–300	360	490^{+210}_{-140}	3.4	$4.7^{+2.0}_{-1.4}$
	300–450	209	135^{+58}_{-40}	4.9	$3.2^{+1.4}_{-0.9}$
	>450	49	51^{+23}_{-15}	4.0	$4.1^{+1.9}_{-1.3}$
$t\bar{t}H$	200–300	420	740^{+300}_{-210}	8.0	$14.1^{+5.7}_{-4.1}$
	300–450	60	47^{+20}_{-14}	3.2	$2.5^{+1.1}_{-0.8}$
	>450	9.8	$16.5^{+7.3}_{-4.9}$	2.0	$3.3^{+1.5}_{-1.0}$

CMS: Boosted $t\bar{t}Z$ + $t\bar{t}H$

PRD 108 032008 (2023)

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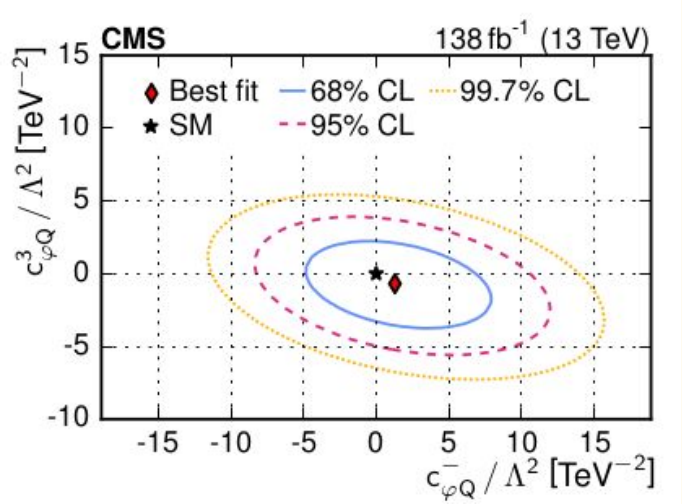

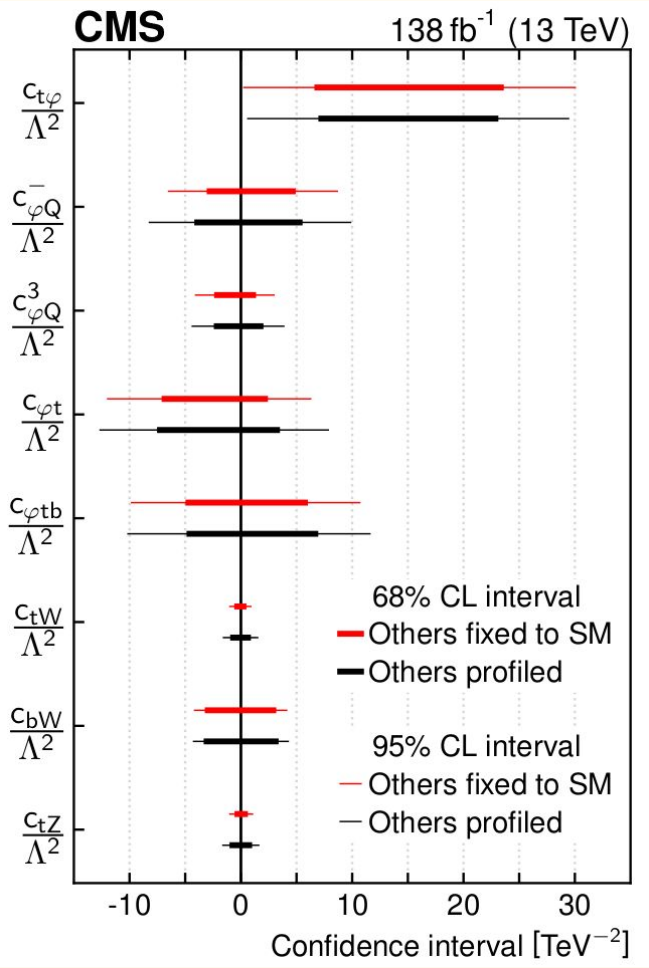

ATLAS: $t\bar{t}\gamma$ Charge Asymmetry

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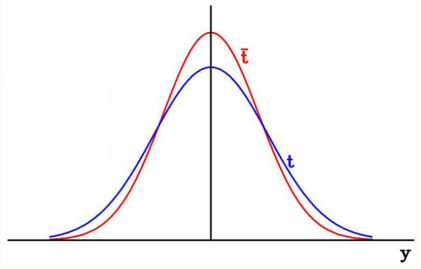
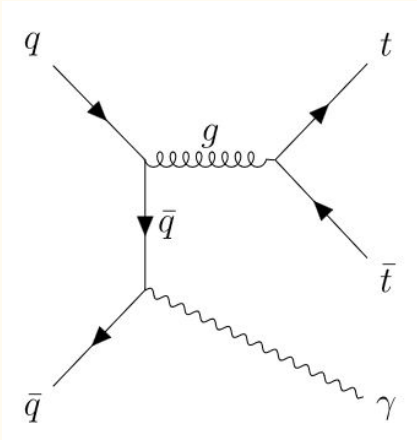
- Central-forward asymmetry predicted at the LHC

$$A_C = \frac{N(|y_t| > |y_{\bar{t}}|) - N(|y_t| < |y_{\bar{t}}|)}{N(|y_t| > |y_{\bar{t}}|) + N(|y_t| < |y_{\bar{t}}|)},$$





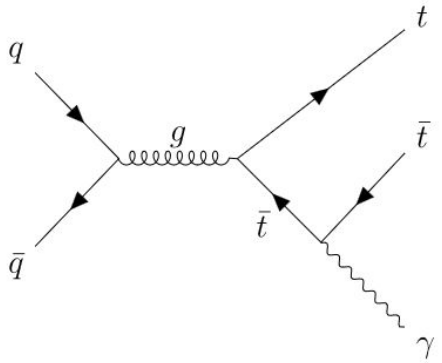
- **A_C=0 at LO** in QCD but **is non-zero at NLO** thanks to the interference between initial-state and final-state gluon emission and between box and Born diagrams
- **A_C in $t\bar{t}\gamma$** - largest contribution from interference between ISR and FSR in qq annihilation
- Predicted **A_C<0** for **$t\bar{t}\gamma$**

Signal selection:

- **one electron** or **muon**
- **one** reconstructed **photon** with $\Delta R(l,\gamma)>0.4$
- events with $|m_{e\gamma}-m_Z|<5$GeV rejected
- at least **4 jets** (≥1 b-tag)

Backgrounds:

- **$t\bar{t}\gamma$ decay (30%)**
  - only tty before the decay considered signal
  - estimated from MC
- **prompt γ bckg. (15%)**
  - estimated from MC
  - two VRs - Zγ and Wγ
- **electron mimicking γ (16%)** = e-fake
  - from data using tag-and-probe to Z→ee events
- **γ from hadron decay $\pi^0\to\gamma\gamma$ (7%)** = h-fake
  - from data using ABCD method



ATLAS: $t\bar{t}\gamma$ Charge Asymmetry

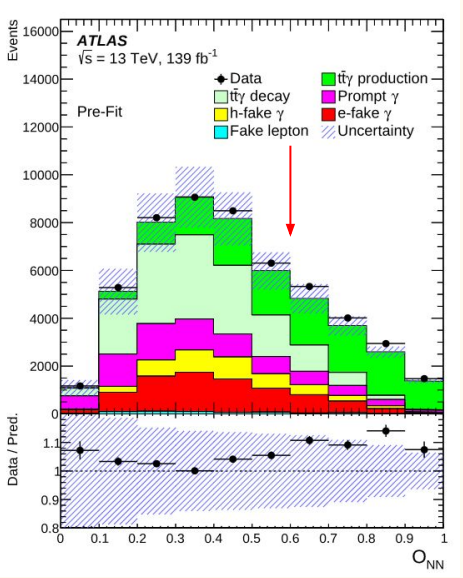
Signal discrimination:

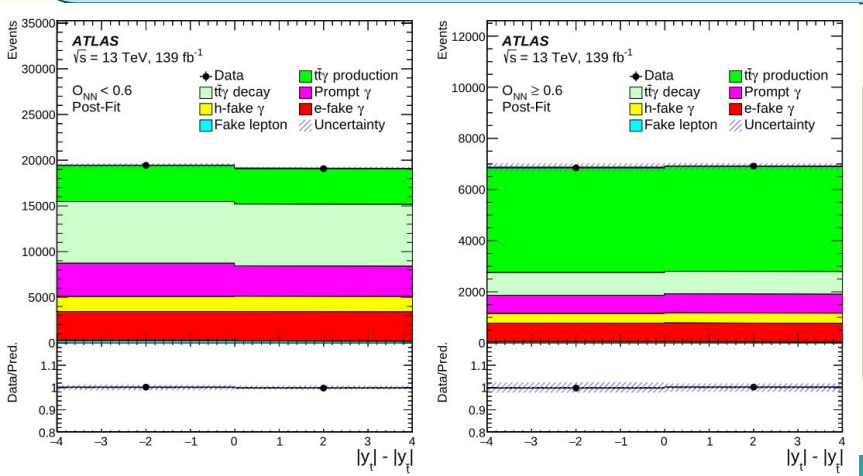
- **DNN** to discriminate signal $t\bar{t}\gamma$ from backgrounds
- NN discriminant used to design **signal-enriched** ($O_{NN} \geq 0.6$) and **background-enriched** ($O_{NN} < 0.6$) regions

Analysis strategy:

- A_C extracted from $|y_t|-|y_{\bar{t}}|$ **distribution** in a fiducial region defined at particle level
- Simultaneous **maximum likelihood unfolding** in two regions (2 bins in each - $|y_t|-|y_{\bar{t}}|>0$ and $|y_t|-|y_{\bar{t}}|<0$)
- Free parameters of the fit:
  - μ_+ - signal strength in bin $|y_t|-|y_{\bar{t}}|>0$
  - $A_C=(\mu_+T_+-\mu_-T_-)/(\mu_+T_++\mu_-T_-)$ instead of μ_-

(T_+ = number of $t\bar{t}\gamma$ events at particle level in bin $|y_t|-|y_{\bar{t}}|>0$)





Results:

- Measured:
  A_C= -0.003±0.029 =
  -0.003±0.024(stat.)±0.017(syst.)
- Predicted (MG5_aMC@NLO):
  A_C= -0.014±0.001(scale)
- Result **compatible with the SM** within uncertainty!
- Measurement statistically dominated!

Total uncertainty	0.029
Statistical uncertainty	0.024
MC statistical uncertainties	
Background processes	0.008
$t\bar{t}\gamma$ production	0.004
Modelling uncertainties	
$t\bar{t}\gamma$ production modelling	0.003
Background modelling	0.002
Prompt background normalisation	0.002
Experimental uncertainties	
Jet	0.009
Fake-lepton background estimate	0.005
E_T^{miss}	0.005
Fake-photon background estimates	0.003
Photon	0.001
b-tagging	0.001
Other experimental	0.004

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ATLAS: $t\bar{t}Z$ inclusive + differential xs

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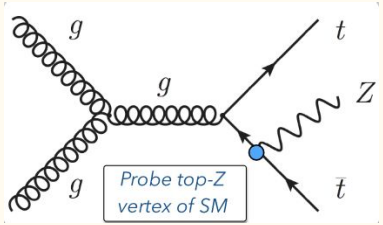
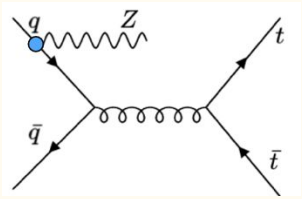
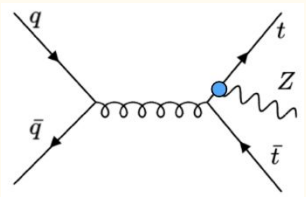
- Provides check of i**nternal consistency of SM** + hints of **new physics**
- Probes **coupling between t and Z**
- Differential xs useful for **MC modelling** improvements
- **$t\bar{t}Z$ irreducible bckg.** for several BSM searches and SM analyses ($t\bar{t}H$, tZ,...)







Signal selection:

- **3 signal regions** in 3l channel:
  - **1b4j** and **2b3j PCBT** - *inclusive xs*
  - **2b3j** fixed 85% btag WP - *differential xs*
- **4 signal regions** in 4l channel:
  - **1b2j SF, 2b2j SF, 1b2j DF, 2b2j DF**
  - separate for inclusive, combined for diff.
  - **E_T^{miss} cuts** to reduce ZZ+jets in SF regions
- At least **1 OSSF lepton pair** with $|m_{ll}-m_Z| < 10$ GeV
- **m_{OSSF}>10 GeV** for all OSSF lepton pairs

Backgrounds:

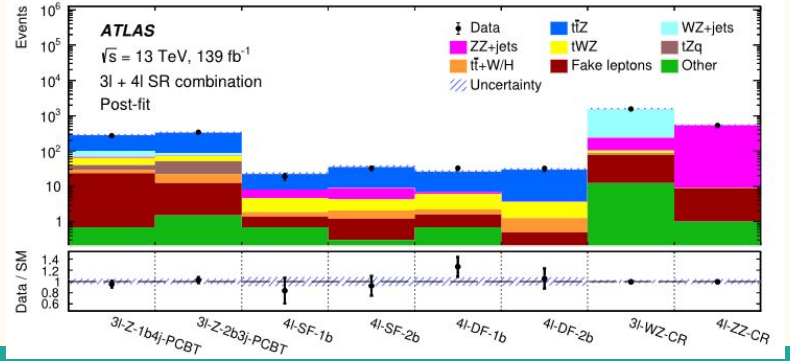
- **WZ/ZZ+ l jets** from data - 2 dedicated CRs (**WZ/ZZ + b** and **c** jets from MC)
- **tWZ** - important bckg., from MC
- **fake leptons** - from data using matrix method
- **others** ($t\bar{t}$+W/H, $t\bar{t}$WW, …) - from MC

Inclusive xs:

- **Simultaneous PLF** of event yields in 3l, 4l and 3l+4l regions
- **Free parameters of the fit**: $\mu_{t\bar{t}Z}$, N_{WZ+l}, N_{ZZ+l}
- Combined fit dominated by 3l channel
- Results **stat. limited** in 4l, **syst. limited** in 3l and comb.

- Measured: $\sigma(pp \to t\bar{t}Z) = 0.99 \pm 0.05\,(\text{stat.}) \pm 0.08\,(\text{syst.})\,\text{pb}.$

- Predicted NLO: $\sigma(pp \to t\bar{t}Z) = 0.84^{+0.09}_{-0.10}\,\text{pb}$ 9.5%



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
WZ/ZZ + jets modelling	2.8
tZq modelling	2.6
Lepton	2.3
Luminosity	2.2
Jets + E_T^{miss}	2.1
Fake leptons	2.1
$t\bar{t}Z$ ISR	1.6
$t\bar{t}Z$ μ_f and μ_r scales	0.9
Other backgrounds	0.7
Pile-up	0.7
$t\bar{t}Z$ PDF	0.2
Total systematic	8.4
Data statistics	5.2
Total	10

ATLAS: $t\bar{t}Z$ inclusive + differential xs

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Differential xs measurement:

- **Iterative Bayesian Unfolding**
- **9 observables** unfolded to particle and parton level
- Absolute and normalised distributions
- Reconstruction of **leptonic top in 3l** and **$t\bar{t}$ system** in transverse plane **in 4l**
- **Binning:**
  - as **many bins** as possible
  - **low stat.** uncertainty
  - **low migrations** between reco. and truth bins (>50% on diagonal)
- Number of **iterations between 2 and 5**

Observables:

- Sensitive to MC modelling, tZ coupling, BSM effects, spin correlations
  - **3l channel**: N_{jets}, $p_T^{l,non\text{-}Z}$, $|\Delta\phi(Z,t_{lep})|$, $|\Delta y(Z,t_{lep})|$
  - **4l channel**: N_{jets}, $p_T^{t\bar{t}}$, $|\Delta\phi(t\bar{t},Z)|$, $|\Delta\phi(l_t^+,l_{\bar{t}}^-)|$
  - **combination**: p_T^Z, $|y^Z|$

Results:

- Diff. distributions **compared to**:
  - **MG5_aMC@NLO + Pythia 8**
  - **MG5_aMC@NLO + Herwig 7**
  - **Sherpa 2.2.1 inclusive**
  - **Sherpa 2.2.1 multi-leg**
  - **Dedicated theory predictions** (NLO, NLO+NNLL, nNLO) - only at parton level
- Dominated by the **stat. uncertainty**
- Leading syst. related to **$t\bar{t}Z$/WZ modelling** and **b-tagging**