$t\bar{t}$+X measurements using the full Run 2 dataset with the ATLAS experiment

ICHEP 2024 | PRAGUE

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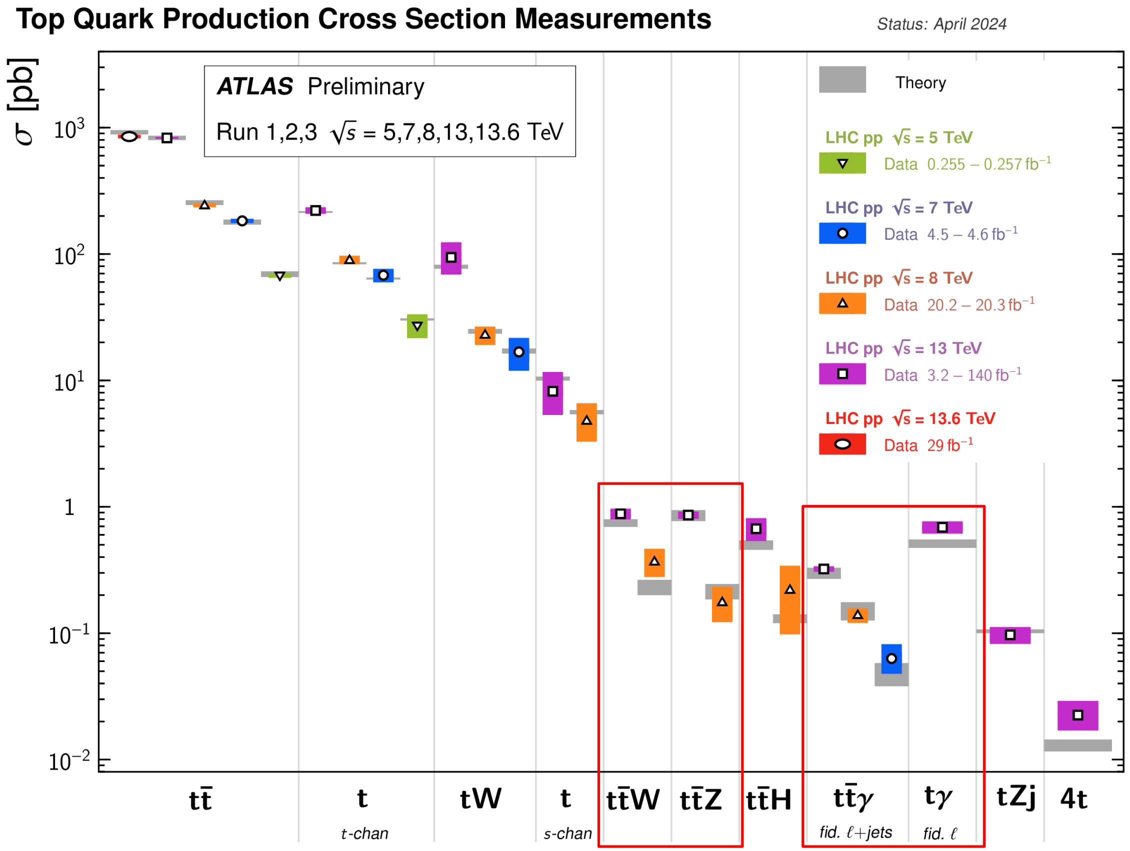
Jan Hahn
on behalf of the ATLAS Collaboration

FSP ATLAS
Erforschung von Universum und Materie

CPPS Center for Particle Physics Siegen

Motivation for top+X processes

- Processes probe the electroweak coupling of top quarks
  - This talk focuses on top production with W, Z and γ
  - Couplings may be sensitive to new physics → EFT interpretations
- Important backgrounds for BSM searches and SM measurements
  - Often contributions to irreducible background
- Differential measurements also of interest for MC modelling
- Focus on leptonic final states
- Rare processes → Profit from full Run 2 dataset



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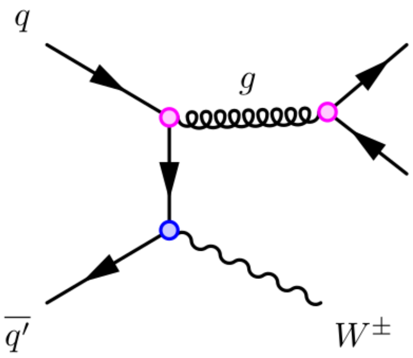
$t\bar{t}W$

JHEP 05 (2024) 131

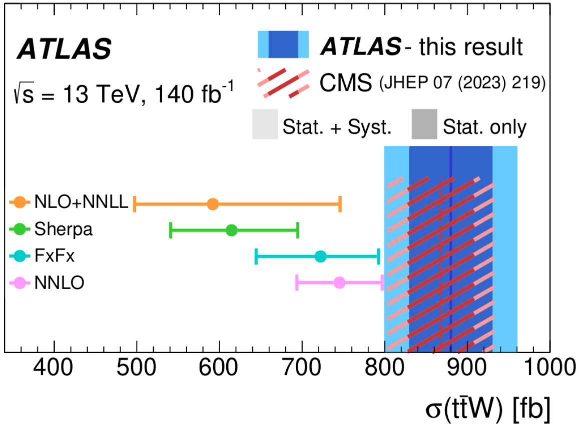
- Complex higher-order QCD and EWK corrections

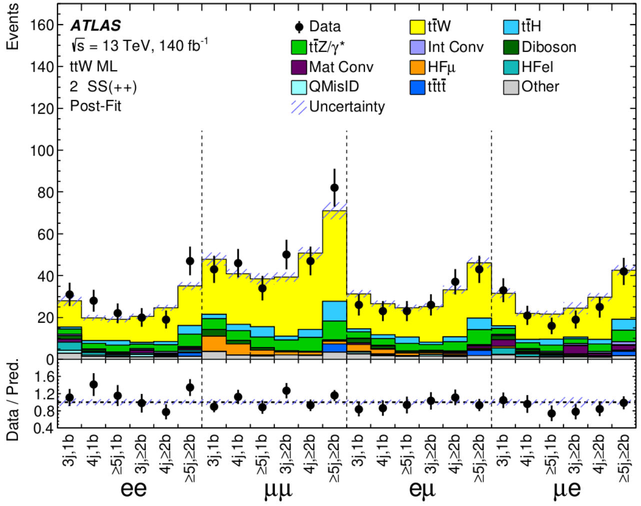


- Target 2 same-sign leptons (2LSS) or 3 leptons (3L)
  - Profile-likelihood fit to 48 (2L SS) and 8 (3L) signal regions (SR) and 10 control regions (CR) based on number of jets, b-jets and lepton flavour

- $\sigma_{t\bar{t}W}$=880 ± 50(stat.) ± 70(syst.) fb (9.1%)
  - 1.4σ larger than NNLO calculation PRL 131 (2023) 231901

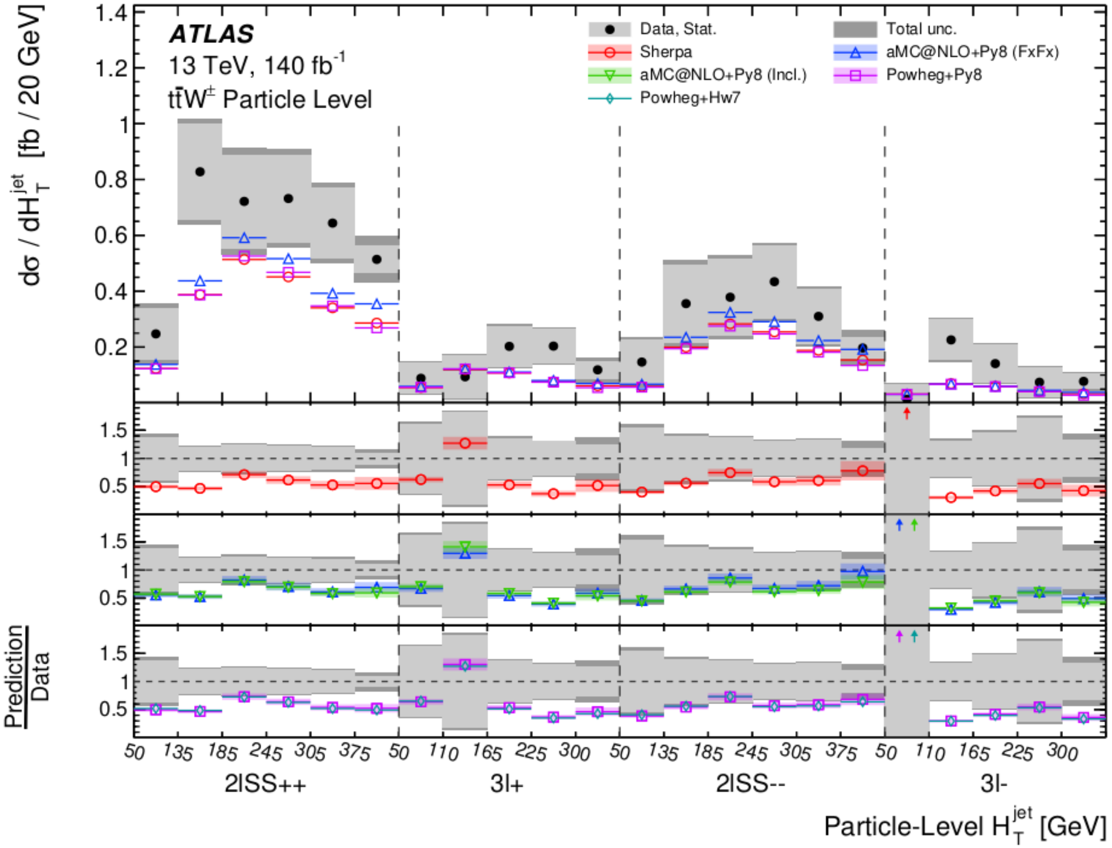
- Charge asymmetry: $\sigma(t\bar{t}W^+)/\sigma(t\bar{t}W^-)$= 1.96 ± 0.22
  - In agreement with SM





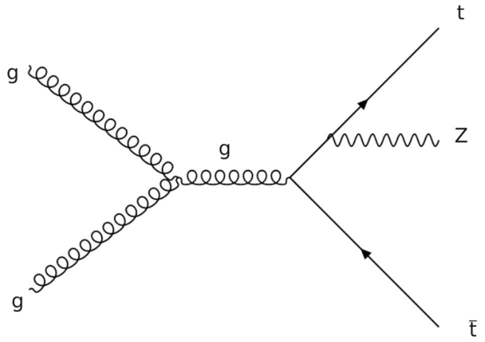
$t\bar{t}W$: Differential cross-section

- Measure six variables using profile-likelihood unfolding, absolute and normalised cross-section
  - Split in regions based on lepton multiplicity and charge
  - Tikhonov regularisation of generator level norm factors
  - Shown H_T, scalar sum of selected jet transverse momenta
  - No significant disagreement between data and prediction
  - Dominated by statistical uncertainty

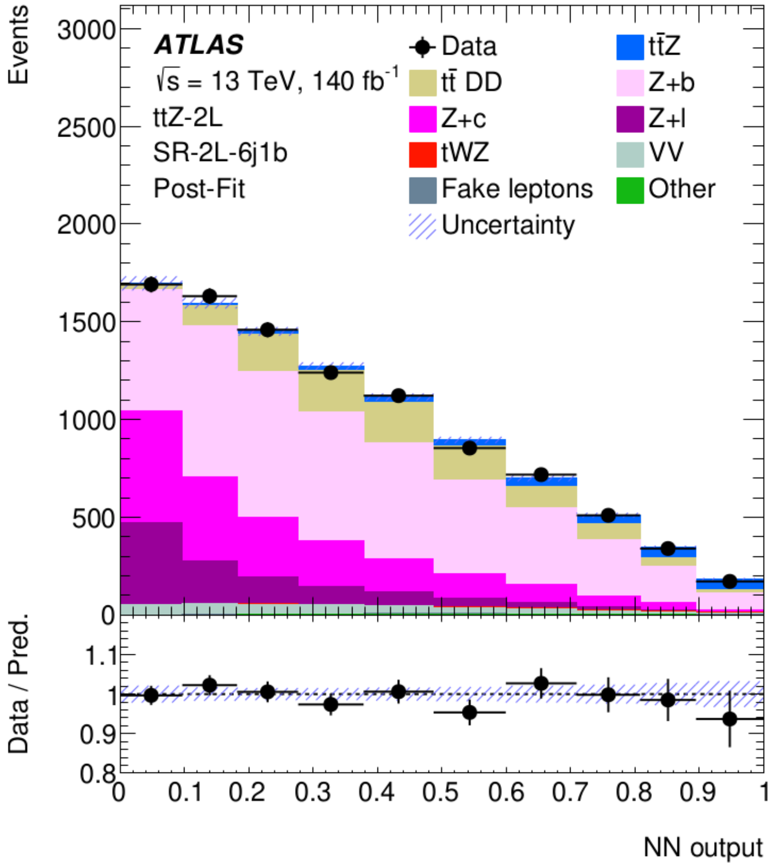


$t\bar{t}Z$

arXiv:2312.04450, accepted by JHEP



- Selection of events with 2L, 3L and 4L
- Events divided in categories based on number of jets, b-jets, lepton flavour and charge
- Neural net (NN) used to separate signal and background in each region
  - Binary in 2L and 4L regions
  - Multiclass in 3L region



$t\bar{t}Z$: Inclusive cross-section

- Using 2L, 3L and 4L channels and performing simultaneous profile-likelihood fit to 8 SR and 4 CR
- $\sigma_{t\bar{t}Z}$ = 0.86 ± 0.04 (stat.) ± 0.04 (syst.) pb
  - Precision of 6.5%, 35% improvement to previous measurement

    EPJC 81 (2021) 737
  - Systematic component reduced by 50%
  - Leading uncertainties:
    - Background normalisations, jets and missing transverse energy
- Measurement in agreement with NLO+NNLL+EW

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

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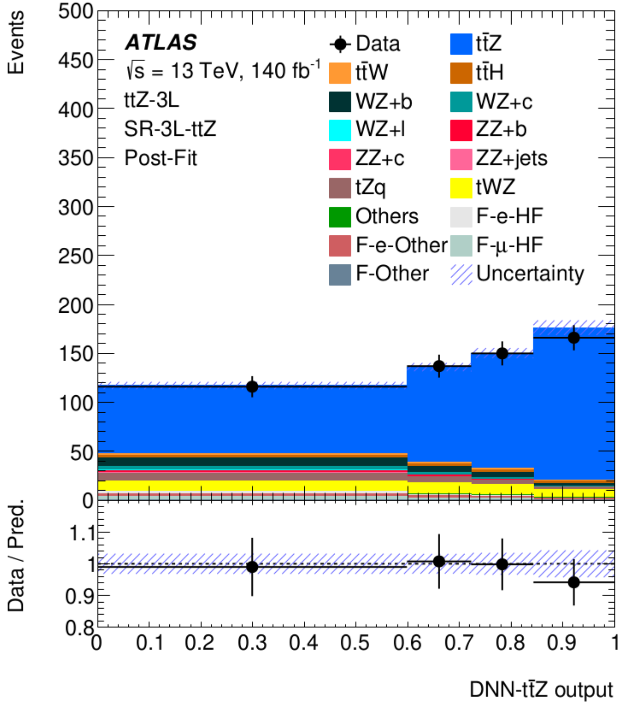
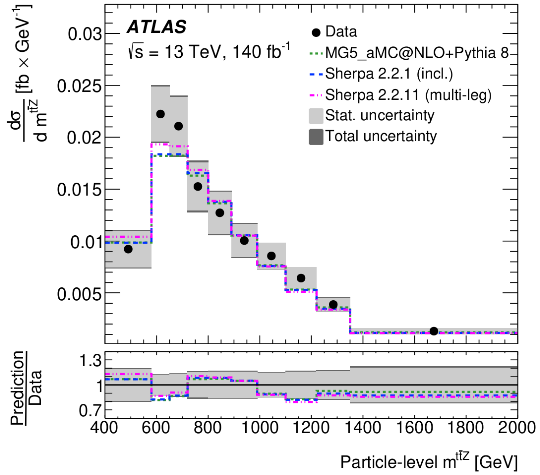
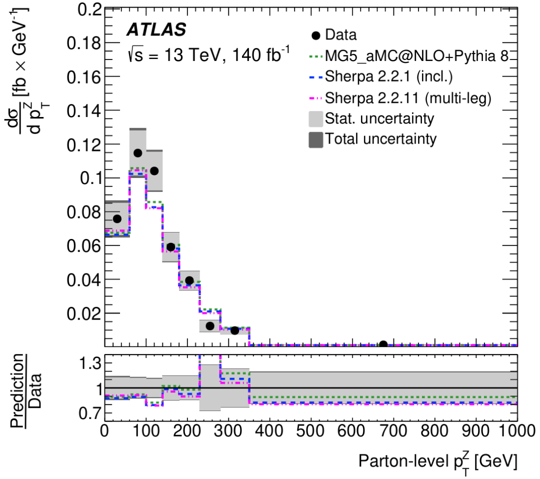


$t\bar{t}Z$: Differential cross-sections

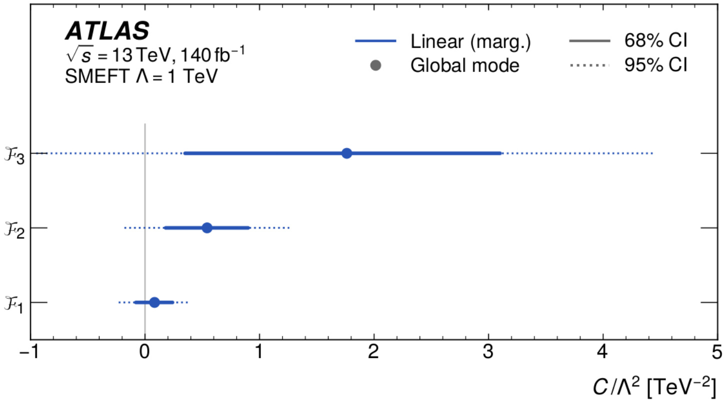
- 3L and 4L channels unfolded using profile-likelihood
- 17 observables unfolded, sensitive to EFT operators and MC modelling
- Tikhonov regularisation in variables including reconstructed top quarks
- Measurement of absolute and normalised distributions on particle and parton level
- No shape difference between measurement and predictions
- Measurements statistically limited (30%)
- Likelihoods available in the HEPdata record

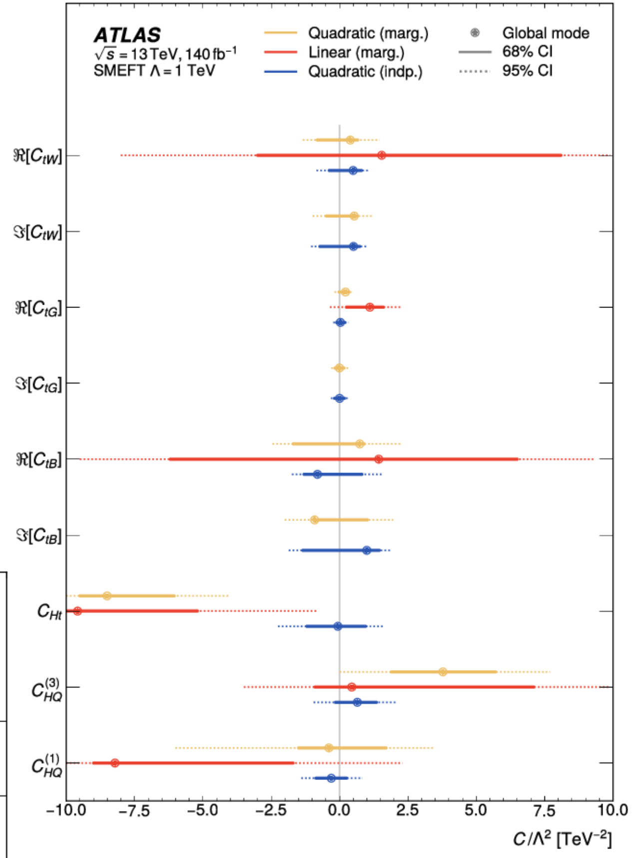




$t\bar{t}Z$: Spin correlation and SMEFT interpretation

- Spin correlations
  - $O = f_{SM} O_{spin-on} + (1 - f_{SM}) O_{spin-off}$
  - f_{SM}=1.20 ± 0.63 (stat.) ± 0.25 (syst.)=1.20 ± 0.68
  - Disfavour no-spin hypothesis by 1.8 σ
- 20 SMEFT operators in Warsaw basis taken into account
  - Relevant operators are of dimension-6 $\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i^{(6)}$
    - Cut-off scale Λ, Wilson coefficient C_i
  - Modelled with SMEFTsim 3.0
  - Fits performed with linear and quadratic parametrisation
  - Fit in rotated base based on Fisher information matrix





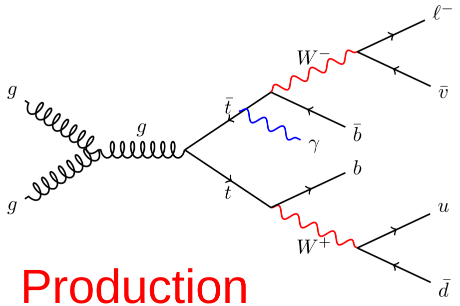
ATLAS EXPERIMENT

$t\bar{t}\gamma$

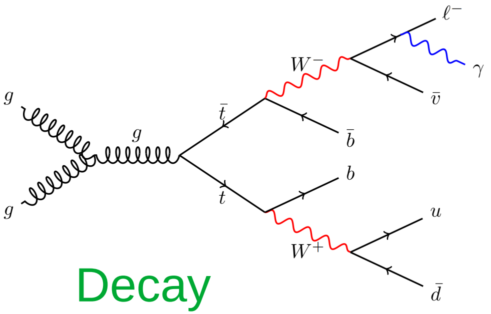
arXiv:2403.09452

Universität Siegen

- Measuring $t\bar{t}\gamma$ production for the first time
  - Production: Photon emitted from ISR or off-shell top quark
  - Photons from decay products treated as background
  - Sensitive to tγ coupling
- Measuring total cross-section (production+decay)



Production

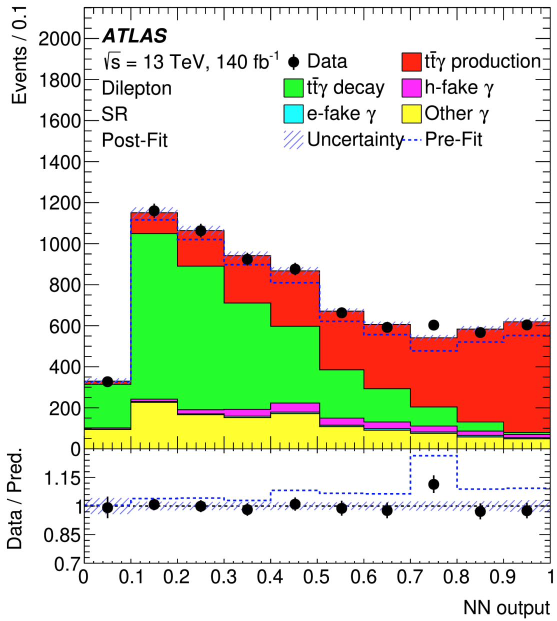


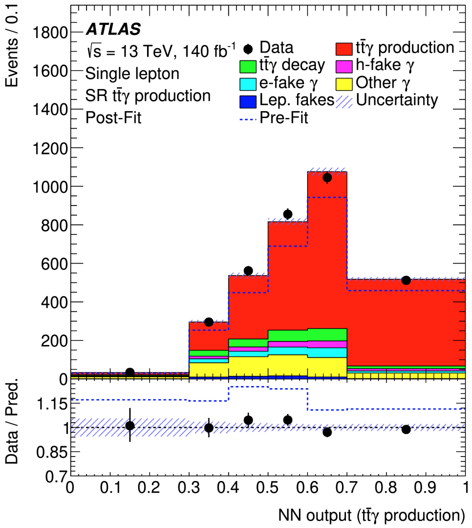
Decay

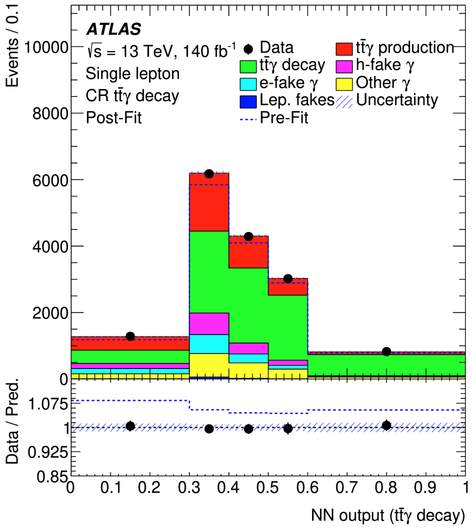
- Measurement in single-lepton and dilepton channels
- NNs to separate signal and background
  - Multiclass in single-lepton, binary in dilepton channel
- Events with misidentified photons (electrons or hadrons) estimated with data-driven methods
  - e→γ by electrons normalised by comparison of data and MC Z→ e^+e^-
  - h→γ by hadrons estimated using fake enriched control regions

$t\bar{t}\gamma$: Inclusive cross-section

- Measured for $t\bar{t}\gamma$ production and total $t\bar{t}\gamma$ (production+decay) in fiducial phase space
- $\sigma_{t\bar{t}\gamma,\ \mathrm{production}}$ = 322 ± 5 (stat) ± 15 (syst) fb (5.2%)
  - MC: 299 ± 31 fb (scale+PDF) (MadGraph5_aMC@NLO)
  - Observed cross-section in agreement with prediction
  - Sensitivity systematically limited by $t\bar{t}\gamma$ modelling, normalisation of $t\bar{t}\gamma$ decay, jet and b-tagging uncertainty

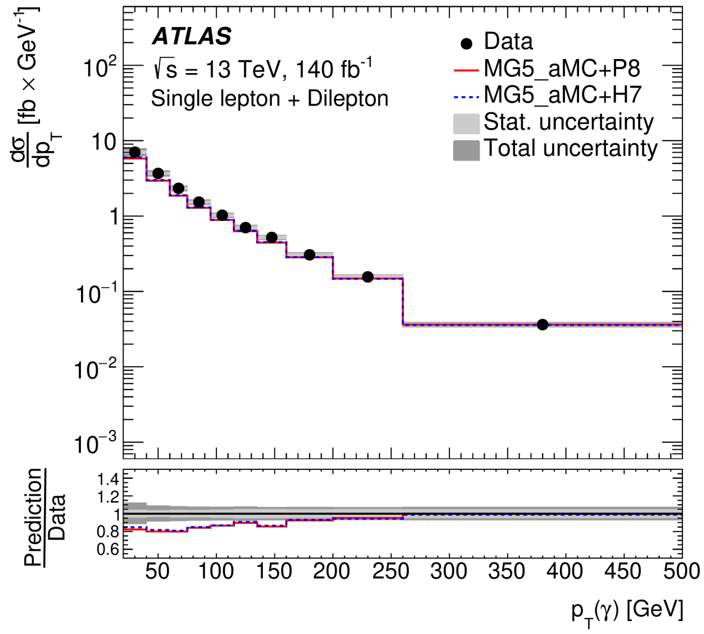


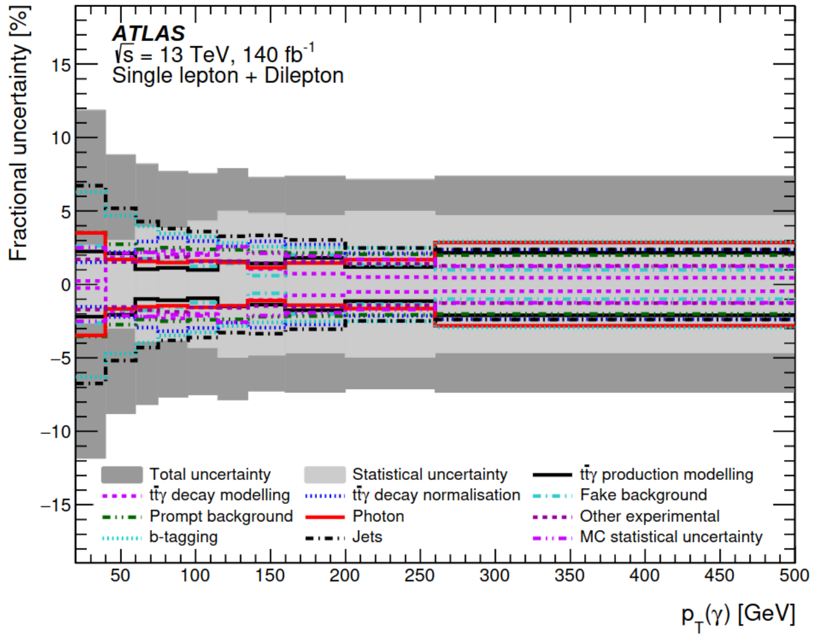




$t\bar{t}\gamma$: Differential measurement

- Normalised and absolute cross-section at particle level
  - Measured production and production+decay in both channels
  - Observables: $p_T(\gamma)$, $\eta(\gamma)$, angular variables among photons and jets or leptons
  - Expected to be sensitive to top-photon coupling

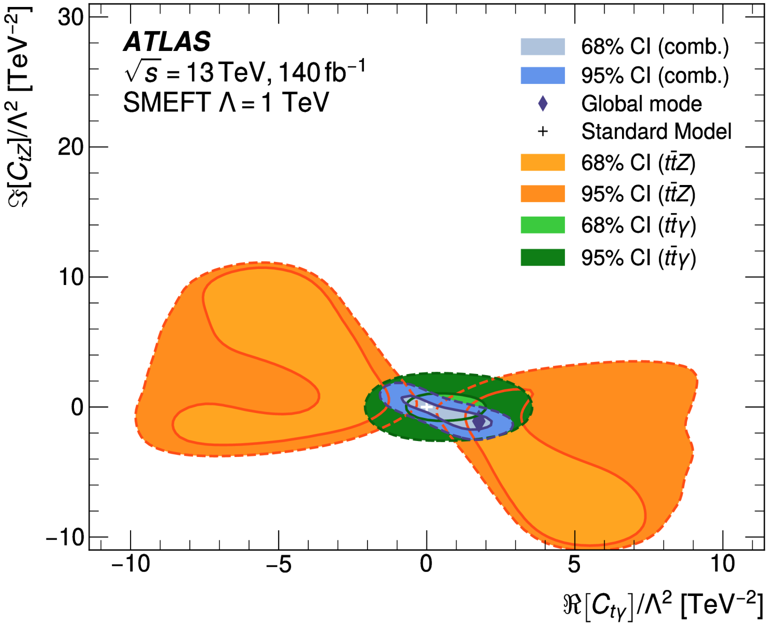


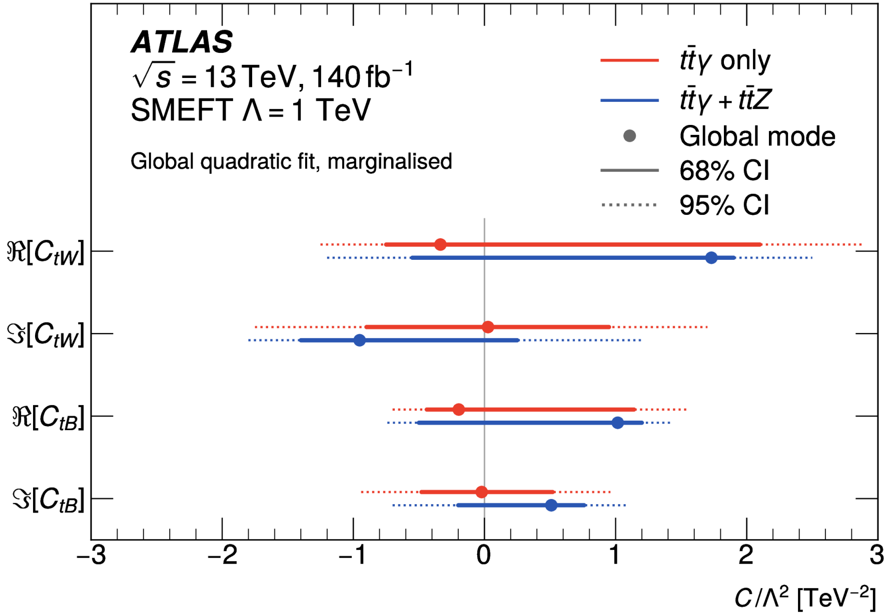


Precision about 10% (absolute) and 5% (normalised)

EFT interpretation: $t\bar{t}\gamma$ and $t\bar{t}Z$ combination

- Operators sensitive to $t\gamma$ coupling are sensitive to tZ coupling as well
  → Combination with $t\bar{t}Z$
- Simultaneous unfolding of transverse momentum of Z and γ as input
  - Same UFO model as $t\bar{t}Z$
- Results available in C_{tB} C_{tW} and C_{tZ} $C_{t\gamma}$ basis

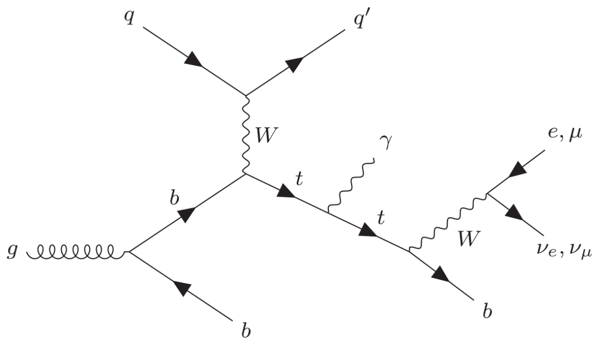




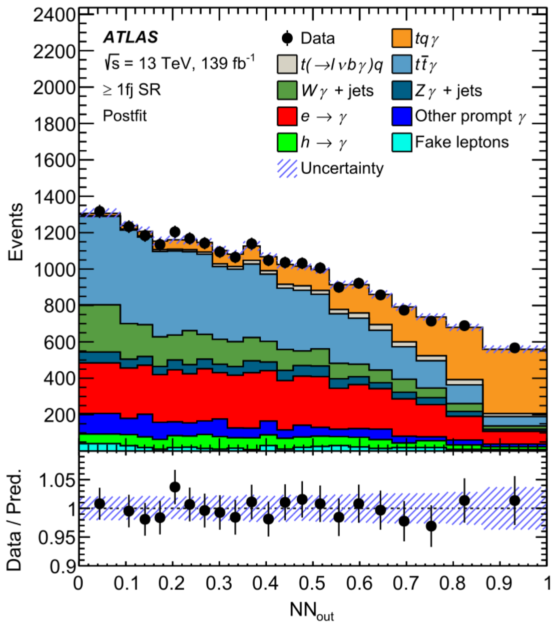
tqγ

PRL 131 (2023) 181901

- Signal region with one photon, one lepton and exactly one b
  - Photon emitted from top quark before decay
  - Cut on m(eγ) to suppress Z background
  - Regions differ by number (0 or 1) of forward jets (2.5<η<4.5)
  - NN trained to separate signal and background

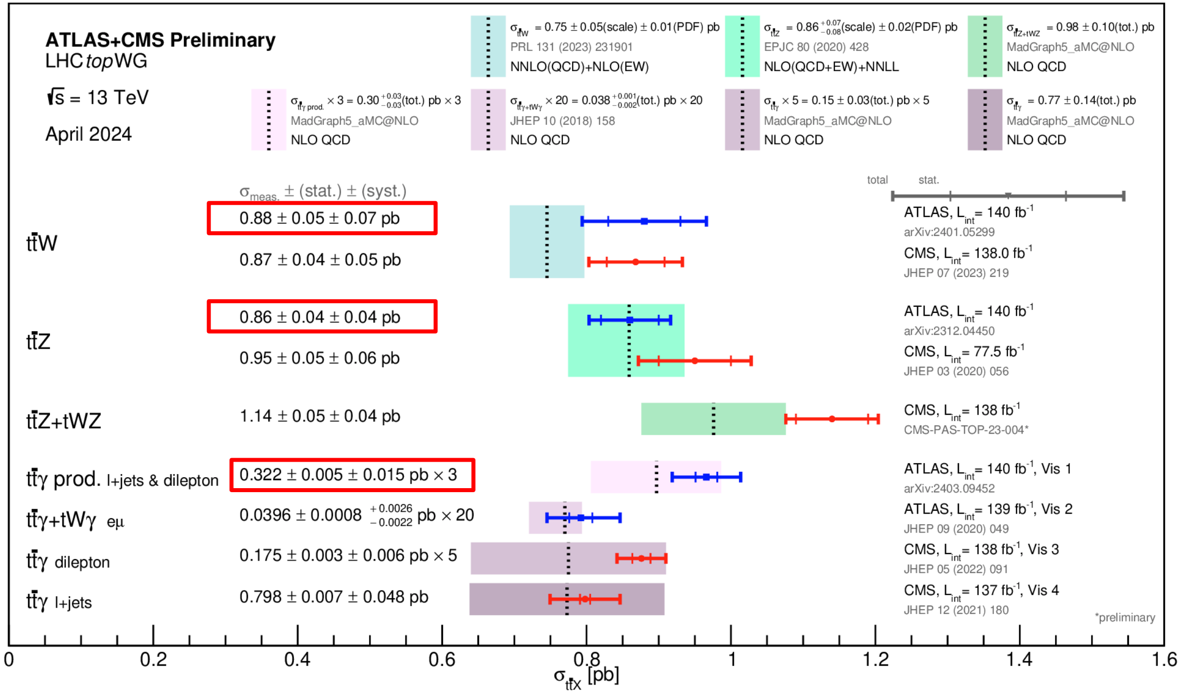


- Main backgrounds
  - $t\bar{t}\gamma$: MC normalised to data in control region
  - Fakes like in $t\bar{t}\gamma$
- Process observed at 9.3σ
  - $\sigma_{tq\gamma} \times B(t \to l\nu b) = 688 \pm 23(\text{stat.})^{+75}_{-71}(\text{syst.})\text{fb}$
  - Compatible with MC prediction $\sigma^{\text{NLO}} = 515^{+36}_{-42}\text{fb}$
  - CMS: evidence with 35fb^{-1} PRL 121 (2018) 221802



Summary

- Precision measurements of top + boson for inclusive cross-section
  - $t\bar{t}Z$: 35% improvement with same dataset
  - $t\bar{t}W$: Better agreement of theory and experimental results
  - $t\bar{t}\gamma$: Separate measurement of production for the first time
  - $tq\gamma$: Observation at 9.3σ
- Differential measurements statistically limited
- Limits on EFT coefficients from $t\bar{t}Z$ and $t\bar{t}\gamma$



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Backup

$t\bar{t}W$

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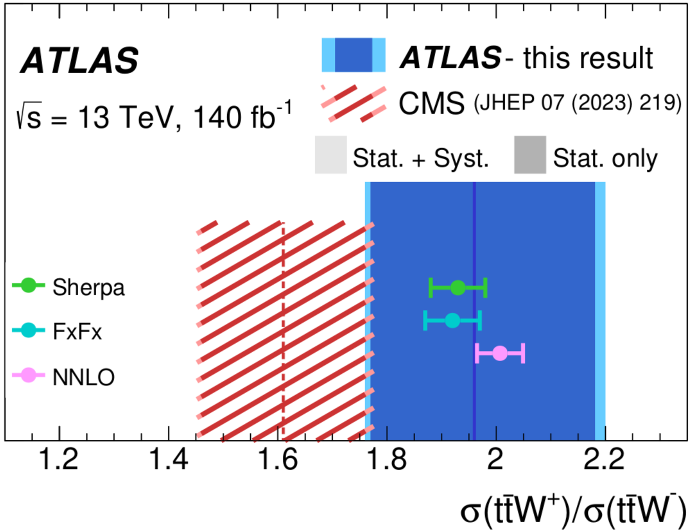

Variable	Definition
N_{jets}	Number of selected jets with $p_{\text{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$
$H_{\text{T}}^{\text{jet}}$	Scalar sum of the transverse momenta of selected jets with $p_{\text{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$
$H_{\text{T}}^{\text{lep}}$	Scalar sum of the transverse momenta of selected leptons
$\Delta R_{\ell b,\text{lead}}$	Angular separation between the leading lepton and the leading b-tagged jet
$\lvert\Delta\phi_{\ell\ell,\text{SS}}\rvert$	Absolute azimuthal separation between the two leptons of the same-sign pair
$\lvert\Delta\eta_{\ell\ell,\text{SS}}\rvert$	Absolute pseudorapidity separation between the two leptons of the same-sign pair

	$\frac{\Delta\sigma(t\bar{t}W)}{\sigma(t\bar{t}W)}$ [%]	$\frac{\Delta\sigma_{\text{fid}}(t\bar{t}W)}{\sigma_{\text{fid}}(t\bar{t}W)}$ [%]	$\frac{\Delta R(t\bar{t}W)}{R(t\bar{t}W)}$ [%]	$\frac{\Delta A_{\text{C}}^{\text{rel}}}{A_{\text{C}}^{\text{rel}}}$ [%]
$t\bar{t}W$ ME modelling	6.0	7.0	0.9	1.3
Prompt-lepton bkg. norm.	3.1	3.1	1.6	2.1
Lepton isolation BDT	2.3	2.3	0.7	1.0
Fakes/VV/$t\bar{t}Z$ norm. (free to vary)	2.3	2.5	1.7	2.4
Non-prompt-lepton bkg. modelling	2.0	2.0	2.4	3.2
Trigger	1.9	1.9	0.5	0.6
MC statistics	1.5	1.6	1.9	2.6
$t\bar{t}W$ PDF	1.5	1.5	2.1	2.8
Jet energy scale	1.3	1.4	1.2	1.7
Prompt-lepton bkg. modelling	1.3	1.3	1.2	1.7
Luminosity	0.9	0.9	0.1	<0.10
Charge Mis-ID	0.7	0.7	0.4	0.6
Jet energy resolution	0.5	0.5	0.6	0.9
Flavour tagging	0.4	0.5	0.5	0.6
$t\bar{t}W$ PS modelling	0.4	0.4	0.29	0.4
$t\bar{t}W$ scale	0.24	<0.10	0.29	0.29
Electron/photon reconstruction	0.21	0.22	0.11	0.13
Muon	0.15	0.17	<0.10	0.2
$E_{\text{T}}^{\text{miss}}$	<0.10	<0.10	0.15	0.21
Pile-up	<0.10	0.11	<0.10	<0.10
Total systematic uncertainty	8	9	5	7
Statistical uncertainty	5	5	10	14
Total	9	11	11	15

tqγ

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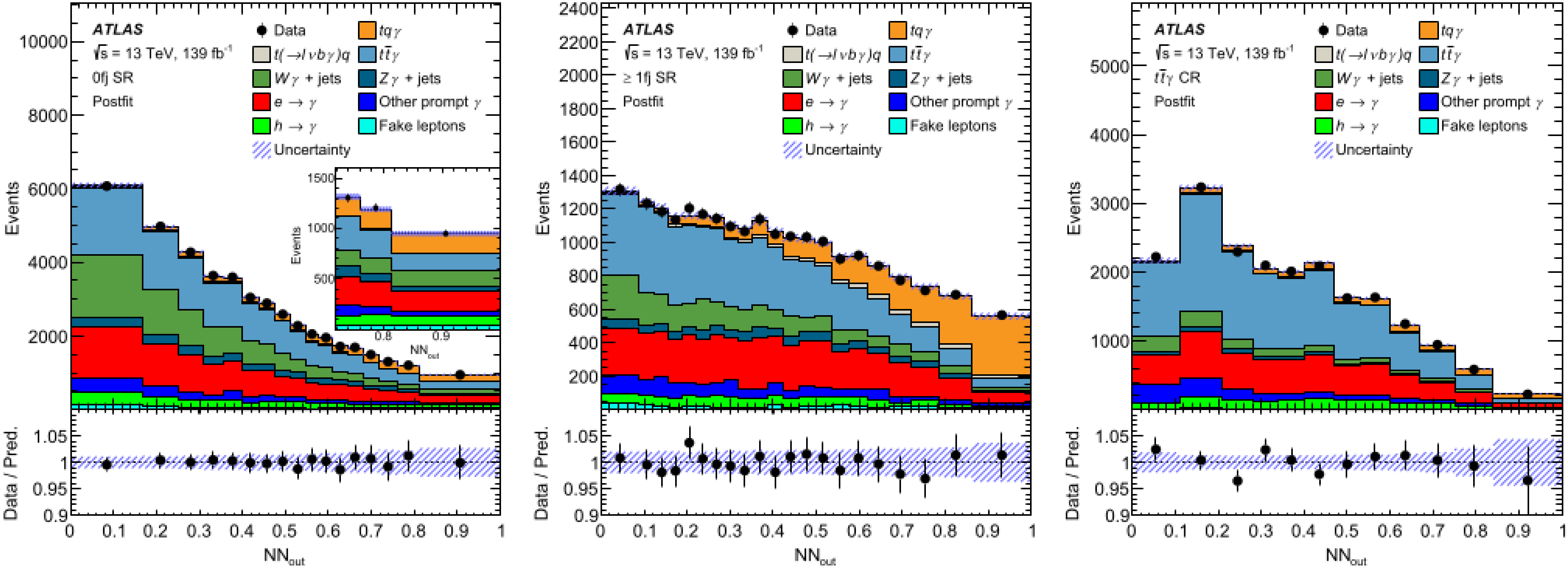

t$\bar{t}$Z measurement

arXiv:2312.04450

- Previous measurement:
  - σ=0.99 ± 0.05(stat.) ± 0.08(syst.) pb

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

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

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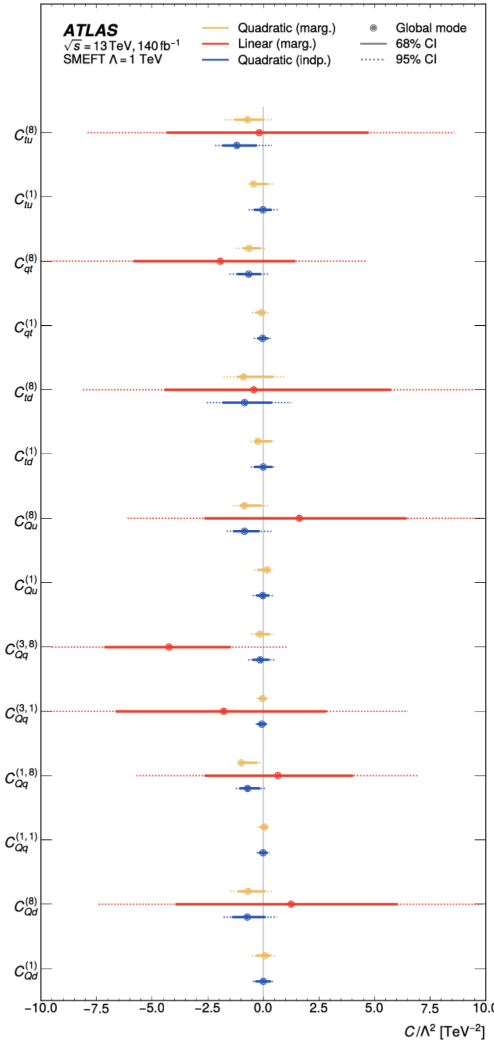
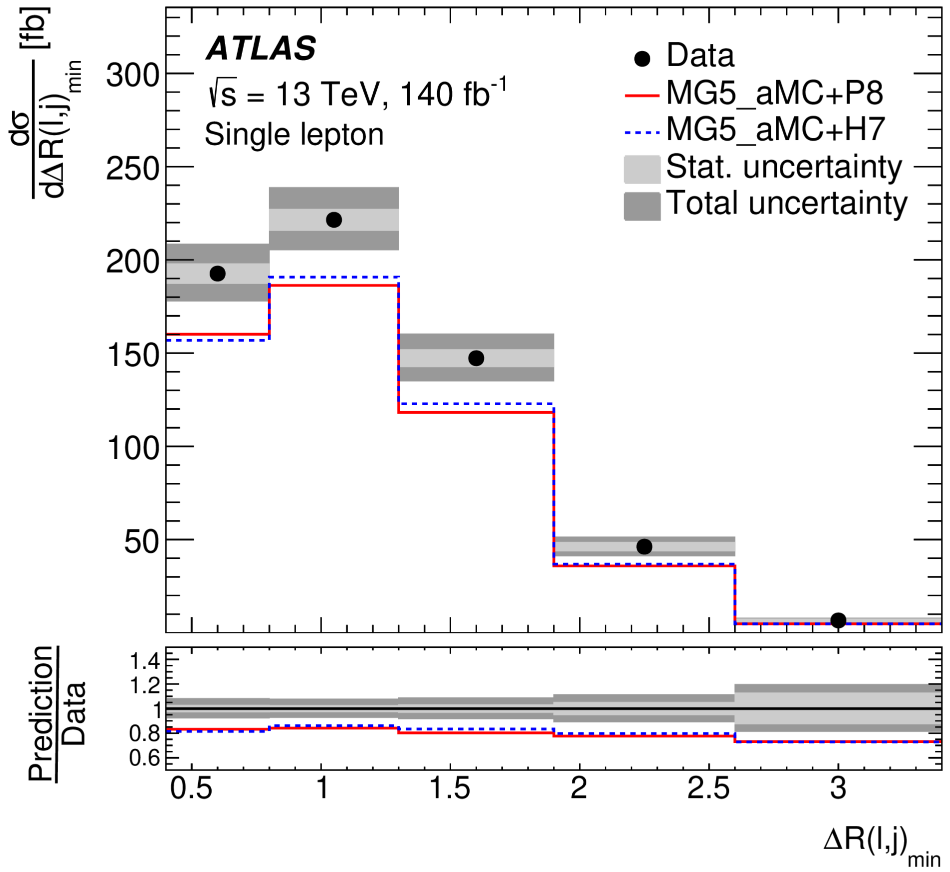


Uncertainty Category	$\Delta\sigma_{t\bar{t}Z}/\sigma_{t\bar{t}Z}$ [%]
Background normalisations	2.0
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	1.9
b-tagging	1.7
$t\bar{t}Z$ μ_{f} and μ_{r} scales	1.6
Leptons	1.6
Z+jets modelling	1.5
tWZ modelling	1.1
$t\bar{t}Z$ showering	1.0
$t\bar{t}Z$ A14 tune	1.0
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

$t\bar{t}\gamma$

arXiv:2403.09452



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

SMEFT

- Standard Model Effective Field Theory (SMEFT) extends SM by new operators
- New operators are required to keep symmetries conserved and build from SM fields
- Relevant operators are of dimension-6 $\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{\mathrm{i}} \frac{\mathrm{C_i}}{\Lambda^2} \mathcal{O}_{\mathrm{i}}^{(6)}$
- Cut-off scale Λ, Wilson coefficient C_i
- Cross-section dependence parametrised as quadratic function of Wilson coefficients
- Both analysis ($t\bar{t}Z$ and $t\bar{t}\gamma$) use SMEFTsim 3.0 UFO model with MadGraph at LO