Top + X measurements with ATLAS

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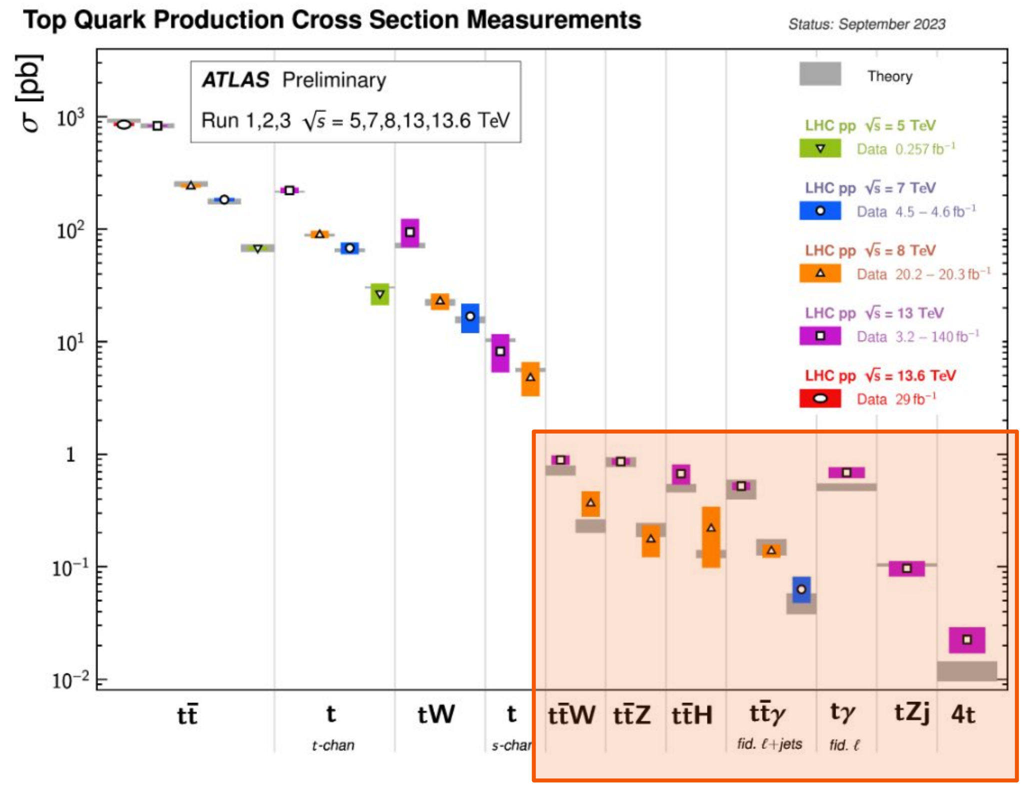
Why top + X?

Some of the heaviest final states we can produce at the LHC!

- ★ Rare processes
- ★ Probe top quark couplings
- ★ Background to BSM searches and other top processes
- ★ Sensitive to effective field theory parameters
- ★ Develop experimental techniques for statistically-limited measurements



Top + X measurements with ATLAS

A few recent highlights

$t\bar{t}Z$

NEW

arXiv:2312.04450

$t\bar{t}W$

NEW

arXiv:2401.05299

$t\bar{t}\gamma$

NEW

arXiv:2403.09452

$t\gamma$

arXiv:2302.01283

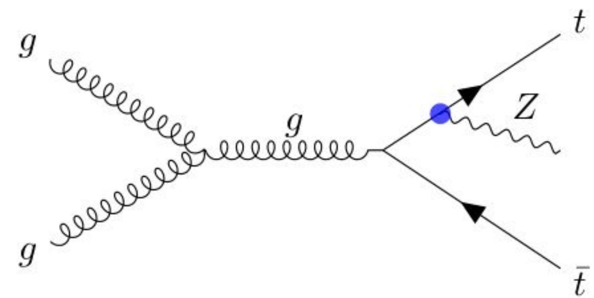
Top + X strategy

There are common elements to many ATLAS Top + X measurements:

- ★ Focus on **leptonic final states** which have less background
  - ○ Typically use **multivariate analysis** to maximise measurement sensitivity (signal/background separation)
- ★ **Inclusive cross-sections**: Profile likelihood fit
- ★ **Differential cross-sections**: Unfolding, taking detector effects into account to measure cross-sections at particle- or parton-level
- ★ Common treatment of systematic uncertainties
- ★ Provide **likelihoods** on HEPData for reinterpretations/future combinations

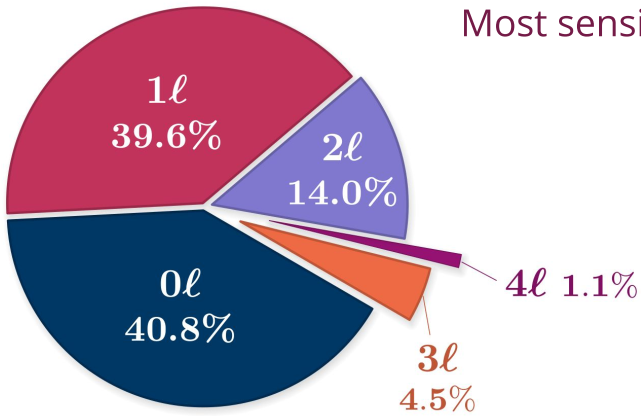
ttZ

arXiv:2312.04450



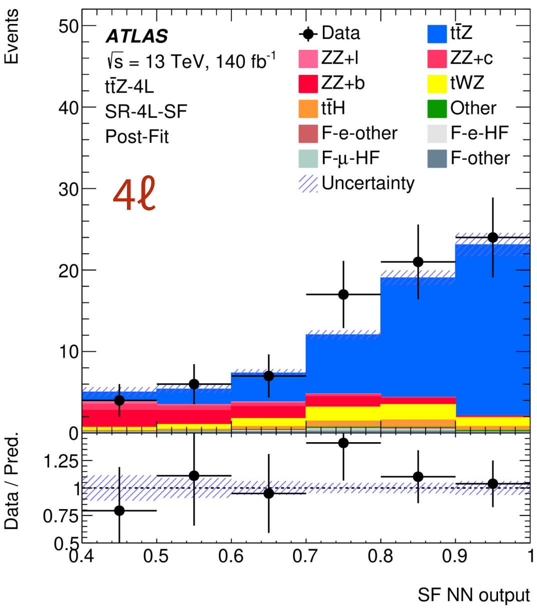
ttZ inclusive cross-section

arXiv:2312.04450



Most sensitive in 2, 3 and 4 lepton (e,μ) channels

- Selected on number of leptons, jets, b-jets, E_T^{miss}
- Neural networks (NNs) used to separate signal in each channel from background
- 8/4 signal/control regions
- Profile likelihood fit based on NN output



Inclusive cross-section:

Combination (2ℓ, 3ℓ & 4ℓ)	0.86 ± 0.05 pb = 0.86 ± 0.04 (stat.) ± 0.04 (syst.) pb

Good **agreement with SM** NLO+NNLL prediction: $0.86^{+0.09}_{-0.10}$ pb [arXiv:1812.08622]

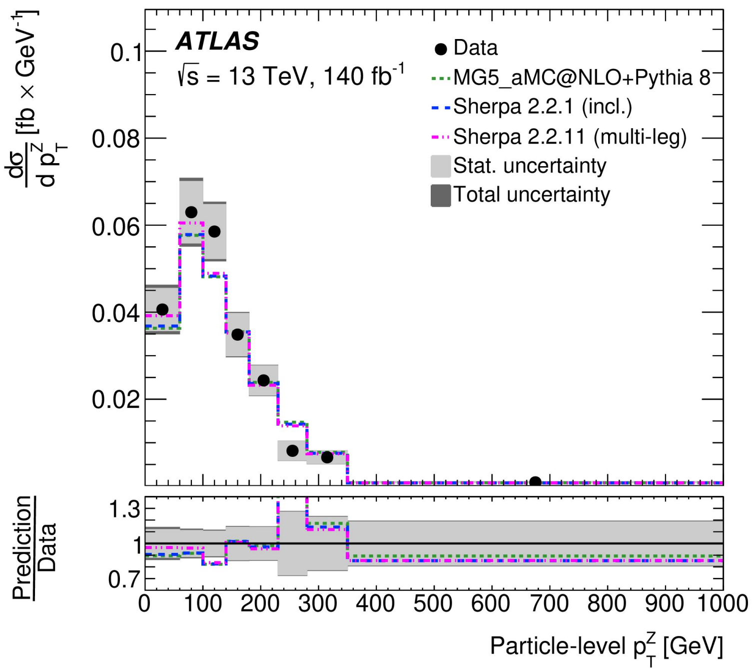
6.5% precision, 35% improvement on previous ATLAS measurement on the same dataset! [arXiv:2103.12603]

ttZ differential cross-section

arXiv:2312.04450

Differential cross-section measurements particle- and parton-level

- Profile likelihood unfolding method
- 17 observables in multiple channels: 3ℓ, 4ℓ and 3ℓ + 4ℓ combination
- Generally, good agreement with NLO predictions
- Measurements are **statistically-limited**
    - Background normalisation and ttZ modelling are important systematic uncertainties
- Looking forward to Run 3, with improvement in precision for “free”



ttZ spin correlations

arXiv:2312.04450

Presence of the Z boson modifies the SM expectations for spin correlations between the two top-quarks: attempt to measure this effect **at detector-level**

$\cos\varphi$

$\cos\theta_r^+ \cdot \cos\theta_r^-$

$\cos\theta_k^+ \cdot \cos\theta_k^-$

$\cos\theta_n^+ \cdot \cos\theta_n^-$

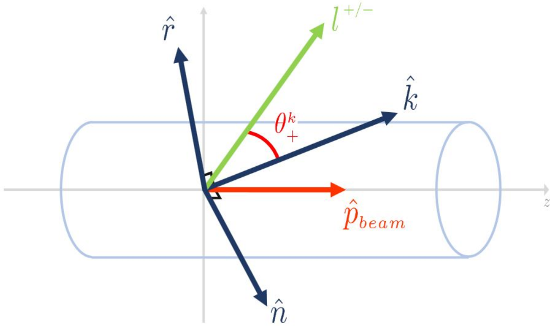
$\cos\theta_r^+ \cdot \cos\theta_k^- + \cos\theta_r^- \cdot \cos\theta_k^+$

$\cos\theta_r^+$

$\cos\theta_r^-$

$\cos\theta_k^+$

$\cos\theta_k^-$



- 9 angular observables used to measure the $t\bar{t}$ spin correlations
- Construct MC templates with/without SM spin correlations

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

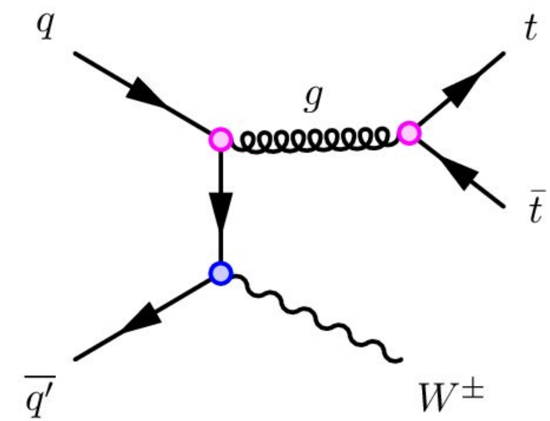
- For each angular observable, extract f_{SM} then combine in χ^2 fit

➡ **Spin-off hypothesis disfavoured at 1.8σ level**

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

ttW

arXiv:2401.05299

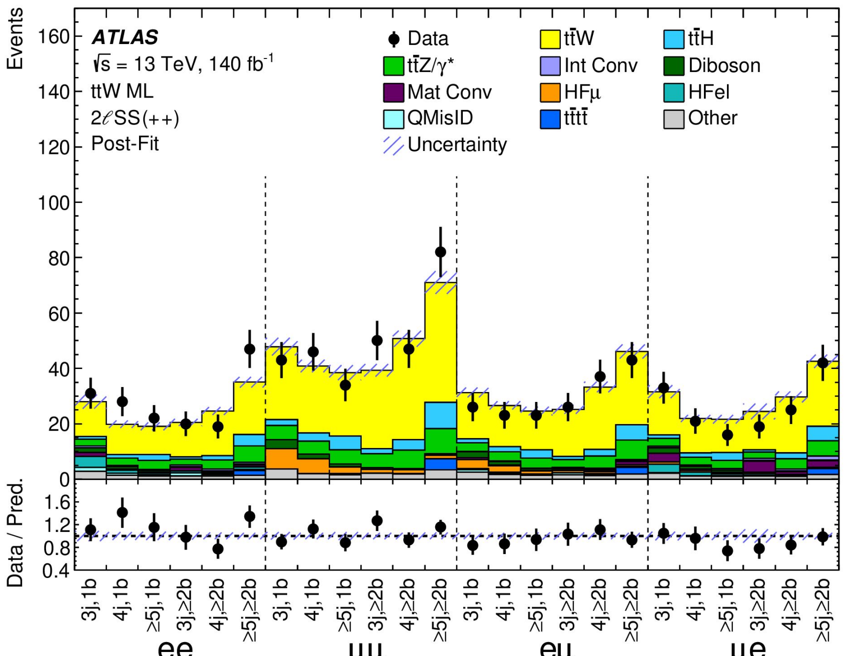


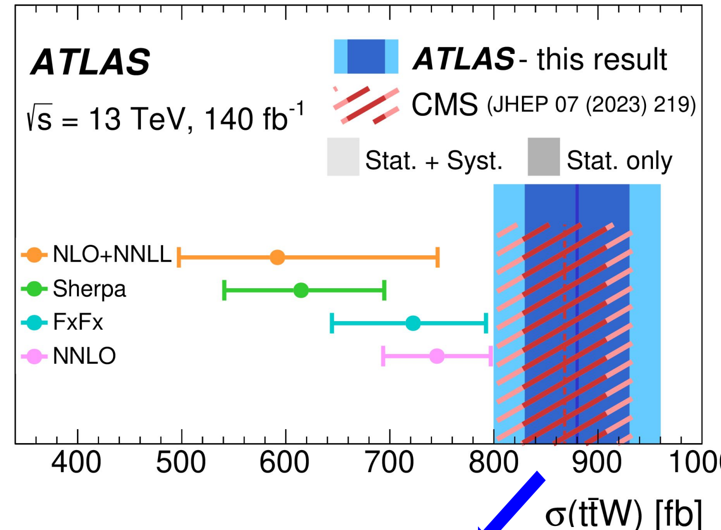
ttW inclusive cross-section

arXiv:2401.05299

Inclusive cross-section profile likelihood fit in

- 2 same-sign or 3 isolated leptons (2ℓSS/3ℓ) channels
- 48 (2ℓSS) + 8 (3ℓ) signal regions and 10 control regions





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

10% precision, some tension with theory:

$$\sigma_{\mathrm{NNLO(QCD)+NLO(EWK)}} = 745 \pm 50\ (\mathrm{scale}) \pm 13\ (\mathrm{PDF})\ \mathrm{fb}$$

[arXiv:2306.16311]

Dominant uncertainty: ttW modelling

ttW differential cross-section

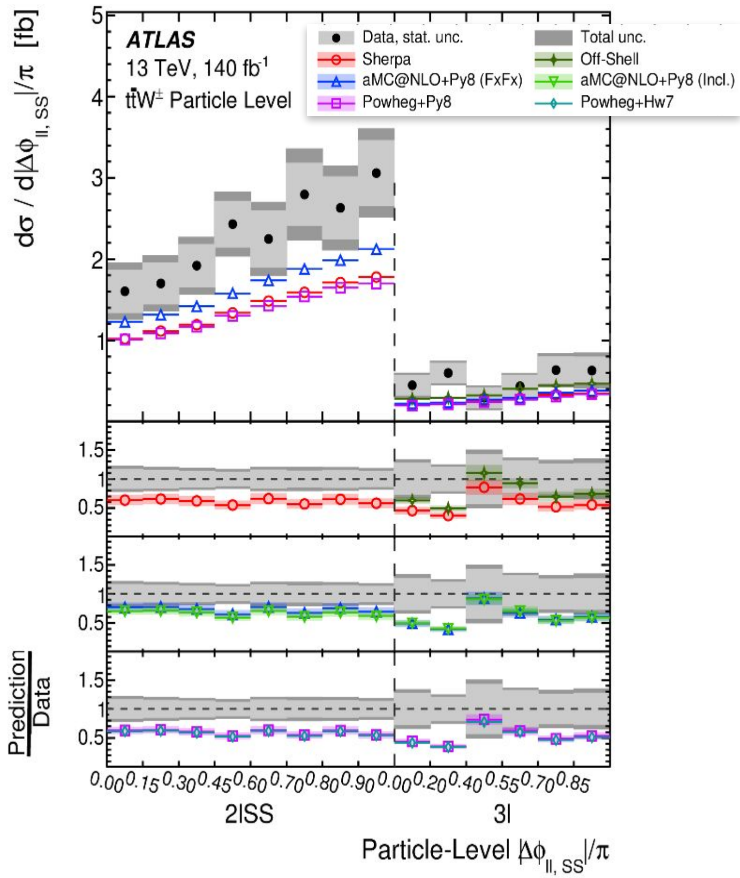
[arXiv:2401.05299]

First differential cross-section measurement of ttW by ATLAS

- 7 observables: angular distances, sum of lepton p_T, jet multiplicity
- 8 signal regions across 2ℓSS and 3ℓ channels
- Profile likelihood unfolding

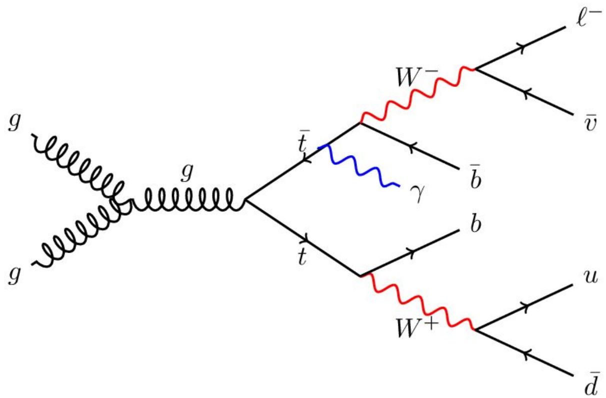
Overall excess in differential results that are consistent with inclusive cross-section result.

Dominant uncertainty: ttW modelling (~10 to 30%)



ttγ

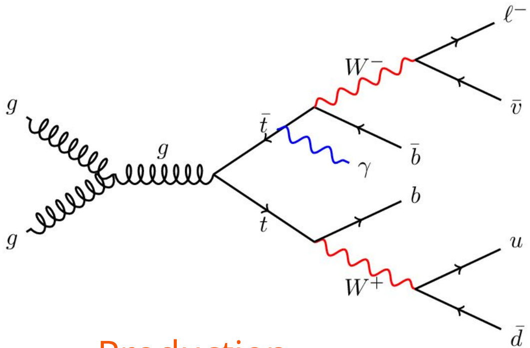
arXiv:2403.09452



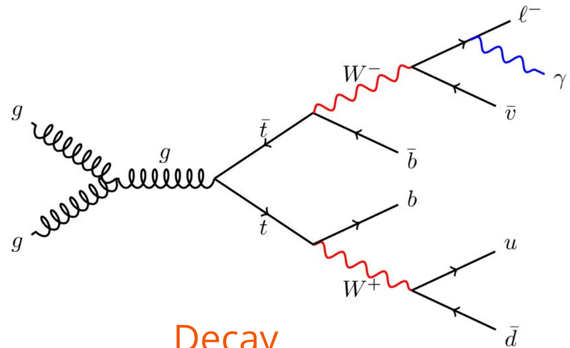
$t\bar{t}\gamma$ inclusive cross-section

arXiv:2403.09452

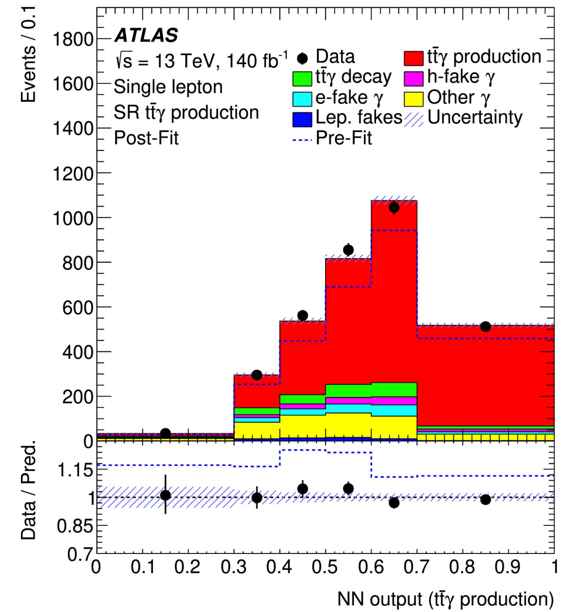
Photon in $t\bar{t}\gamma$ can be radiated from production or decay particles:



Production



Decay



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

- in single-lepton and dilepton channels
- for **production-only** and **total** (regardless of photon origin)

Using neural networks to separate signal/background

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

MadGraph prediction:

$$\sigma_{\text{NLO QCD}} = 299\ ^{+29}_{-30}\ (\text{scale})\ ^{+7}_{-4}\ (\text{PDF})\ \text{fb}$$

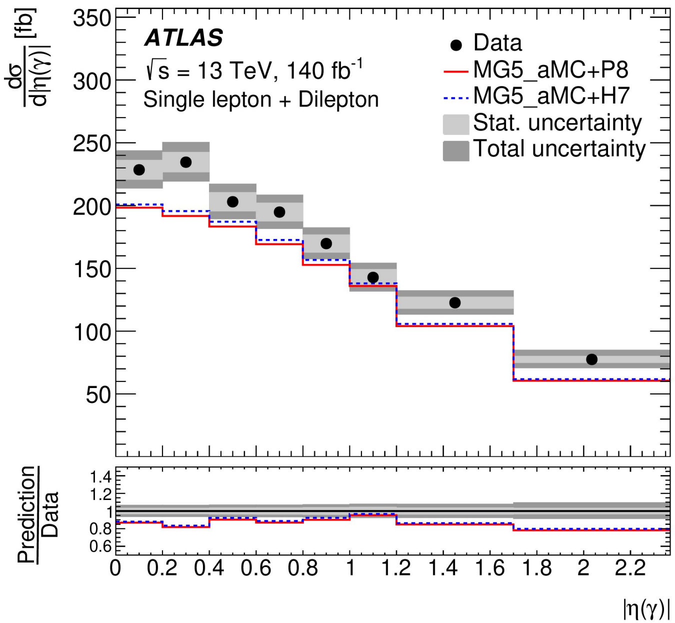
Dominant uncertainties: $t\bar{t}\gamma$ modelling and background normalisation

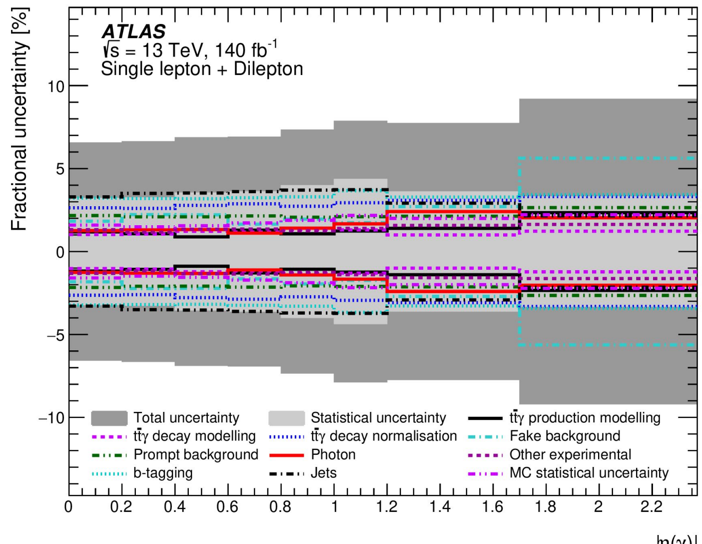
ttγ differential cross-section

arXiv:2403.09452

Differential cross-section measurement in two channels for the following variables:

- Both channels: photon kinematics, angular distances between photon and other reconstructed objects
- Dilepton channel only: sum of the lepton p_T, $\Delta\eta$ and $\Delta\phi$ between leptons
- Generally, **good agreement with SM**





Uncertainties range around 8-10% (absolute) and 5% (normalised)

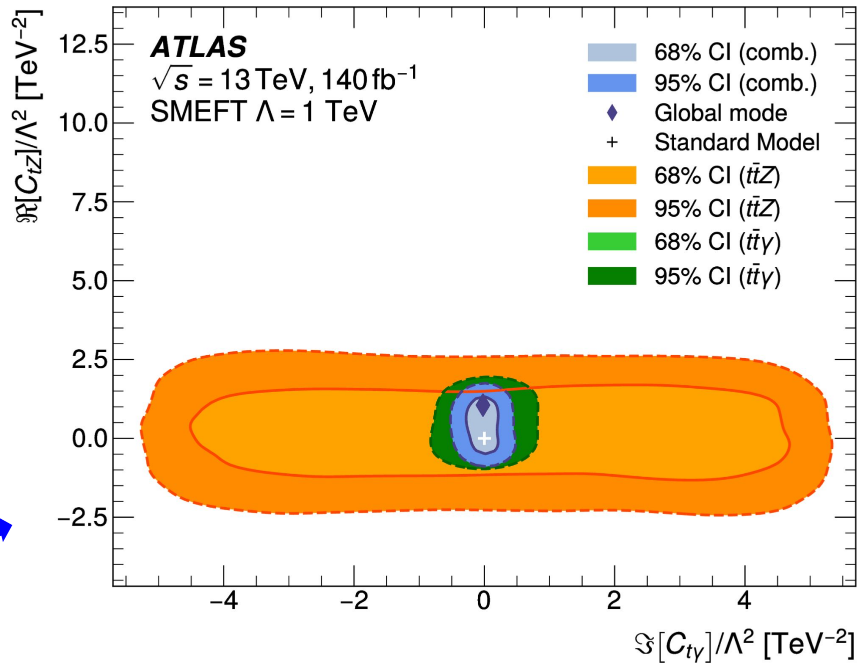
$t\bar{t}\gamma$ + ttZ EFT interpretation

arXiv:2403.09452

Combined effective field theory interpretation with ttZ and ttγ events

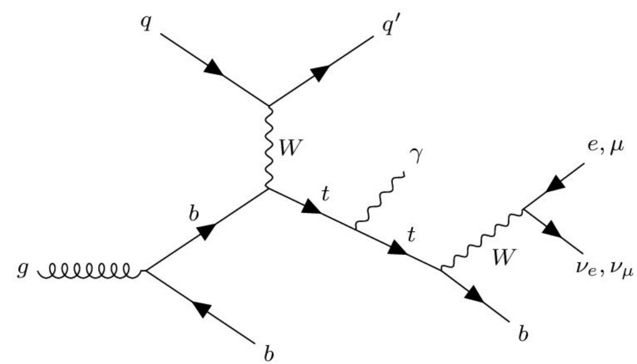
$$\sigma = \sigma_{\rm SM} + \sum_i \frac{C_i}{\Lambda^2}\sigma_i + \sum_{i,j}\frac{C_i C_j}{\Lambda^4}\sigma_{ij}$$

- tγ and tZ couplings are complementary: simultaneous EFT fit using both $p_T(\gamma)$ and $p_T(Z)$
- Relevant dimension-6 Wilson coefficients: C_{tB} and C_{tW} (real and imaginary parts), change basis to get C_{tZ} and $C_{t\gamma}$
- **Tighter constraints** achieved than individual fits



tγ

arXiv:2302.01283

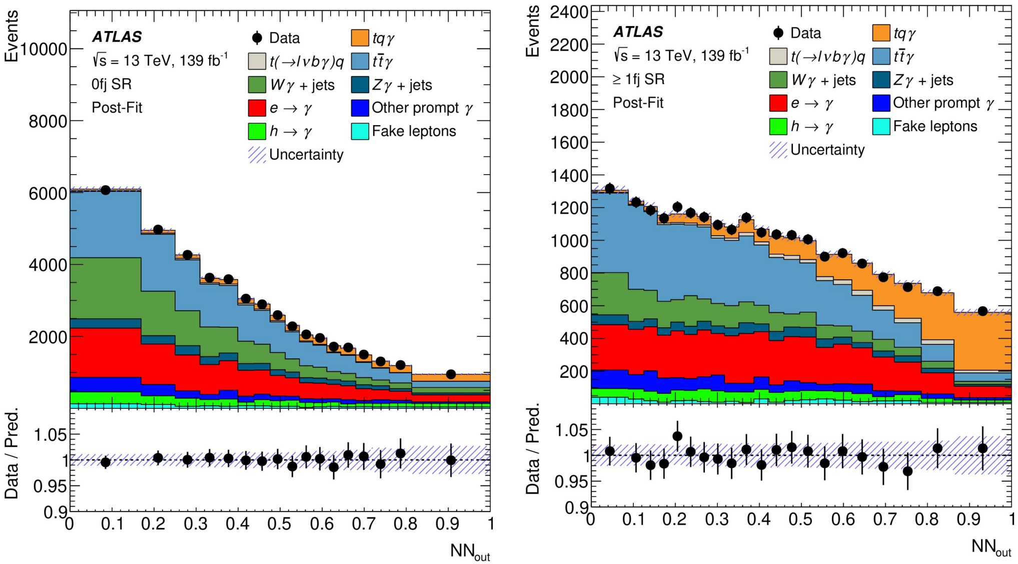


$t\gamma$ observation

[arXiv:2302.01283]

Cross-section measurements of fiducial volumes at particle- and parton-level

- Forward-jets used to define signal regions
- 2 control regions targeting $tt\gamma$ and $W\gamma$
- Data-driven estimate of fake photon processes
- **Neural networks** trained in each signal region to separate signal from the background
- Observed (expected) significance of 9.1 (6.7) σ



Fiducial cross-section measured ~11% precision:

Parton level:

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

$(\sigma^{QCD+EW\ NLO}_{tq\gamma} = 515^{+36}_{-42}\ \text{fb})$

Particle level:

$$\sigma_{tq\gamma} \times BR(t \rightarrow \ell\nu b) + \sigma_{t\rightarrow\ell\nu b\gamma q} = 303 \pm 9(\text{stat})^{+33}_{-32}(\text{syst})\ \text{fb}$$

$(\sigma^{QCD+EW\ NLO}_{tq\gamma} = 217^{+27}_{-15}\ \text{fb})$

- Agreement with SM at 2.0 (2.1) standard deviations
- Leading systematic uncertainties: $tt\gamma$ and tt modelling, limited background MC statistics

Summary

With more data from Run 2, we are now able to measure Top + X processes precisely

ttZ → ttW → ttγ → tγ

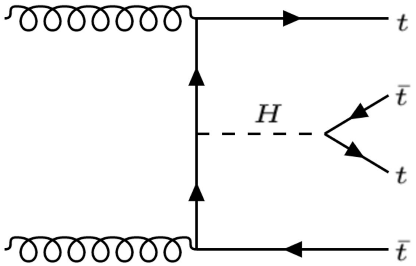
- ★ Precision measurements test the SM and search for new physics effects
- ★ So far, generally observed good agreement with the SM
- ★ Increasingly precise measurements use advanced analysis and statistical methods
- ★ Looking forward to more data in Run 3!

Backup

Multilepton $t\bar{t}t\bar{t}$

arXiv:2303.15061

Inclusive cross-section measurement of four-top-quark production in multilepton final states



- Refined analysis improving upon initial evidence reported in [arXiv:2007.14858]
- Two same-sign or three or more isolated leptons
- GNN used to separate signal and background
  - Data-driven estimate of ttW and fake lepton backgrounds in dedicated control regions
- Irreducible ttt background
- Observed (expected) significance of 6.1 (4.3) standard deviations:

$$\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}\ (\text{stat})\ ^{+4.6}_{-3.4}\ (\text{syst})\ \text{fb} = 22.5^{+6.6}_{-5.5}\ \text{fb}$$

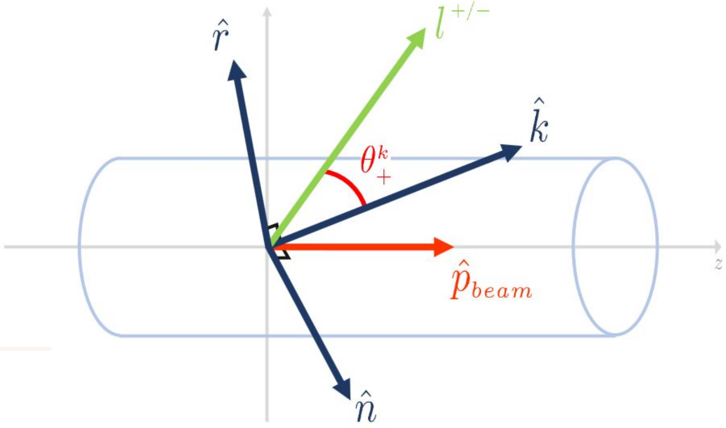
- Consistent with the SM prediction within 1.8 standard deviations → $\sigma_{\text{NLO}} = 12.0 \pm 2.4$ fb [arXiv:1711.02116]
- Limits set on top-quark Yukawa coupling and EFT parameters

ttZ spin correlations

arXiv:2312.04450

Following pheno study in arXiv:2106.09690, we define the helicity (k) axis, transverse (n) axis and r axis in the tt rest frame. The polar angle of the charged lepton or down-type quark from the (anti-)top decay with respect to one of these axes, in the rest frame of its parent (anti-)top quark, is considered as a measure of (anti-)top polarisations and tt spin correlations. Six independent observables can then be defined:

$\cos\theta^{+}_{k}$, $\cos\theta^{-}_{k}$, $\cos\theta^{+}_{n}$, $\cos\theta^{-}_{n}$, $\cos\theta^{+}_{r}$, $\cos\theta^{-}_{r}$



k = direction of top-quark in tt centre-of-mass frame

p = direction of one of the incoming proton beams in the lab frame

$$y = \hat{\mathbf{p}} \cdot \hat{\mathbf{k}}, \quad r = \sqrt{1 - y^2},$$

$$\hat{\mathbf{r}} = \frac{\text{sign}(y)}{r}\left(\hat{\mathbf{p}} - y\hat{\mathbf{k}}\right), \quad \hat{\mathbf{n}} = \frac{\text{sign}(y)}{r}\left(\hat{\mathbf{p}} \times \hat{\mathbf{k}}\right)$$

ttW EWK corrections

QCD

EWK