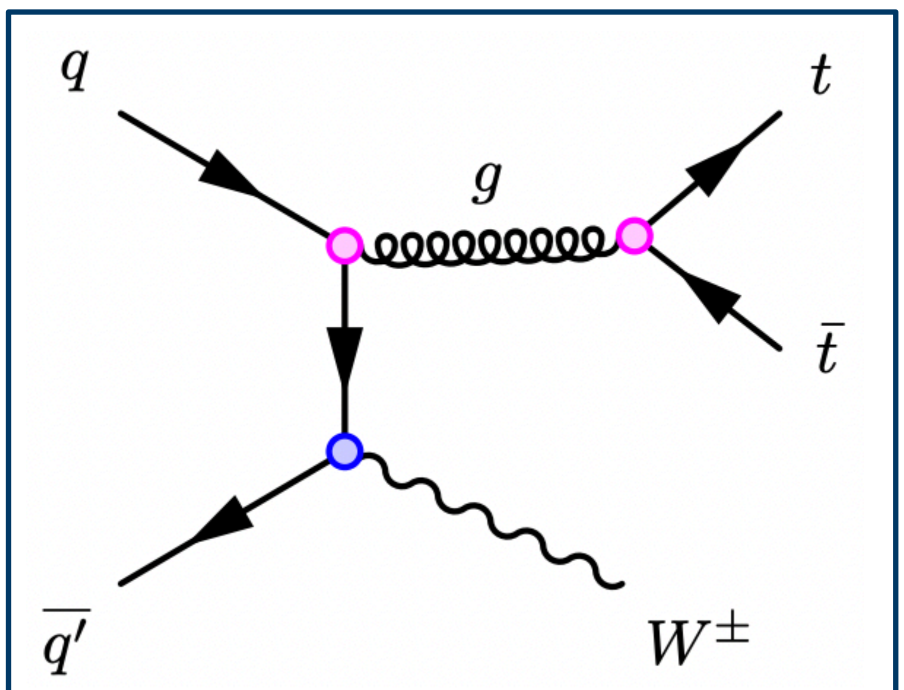
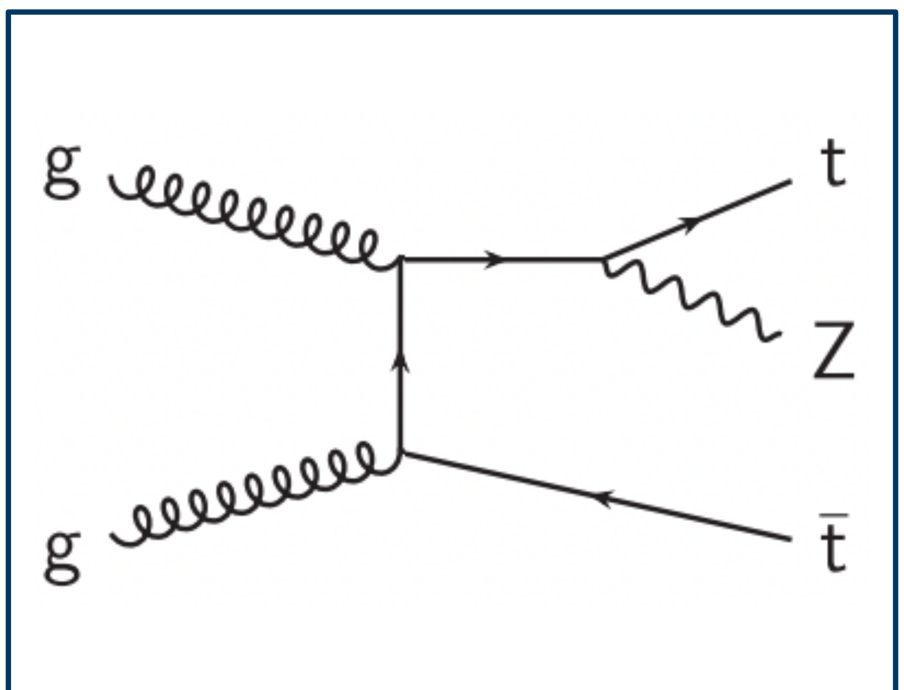
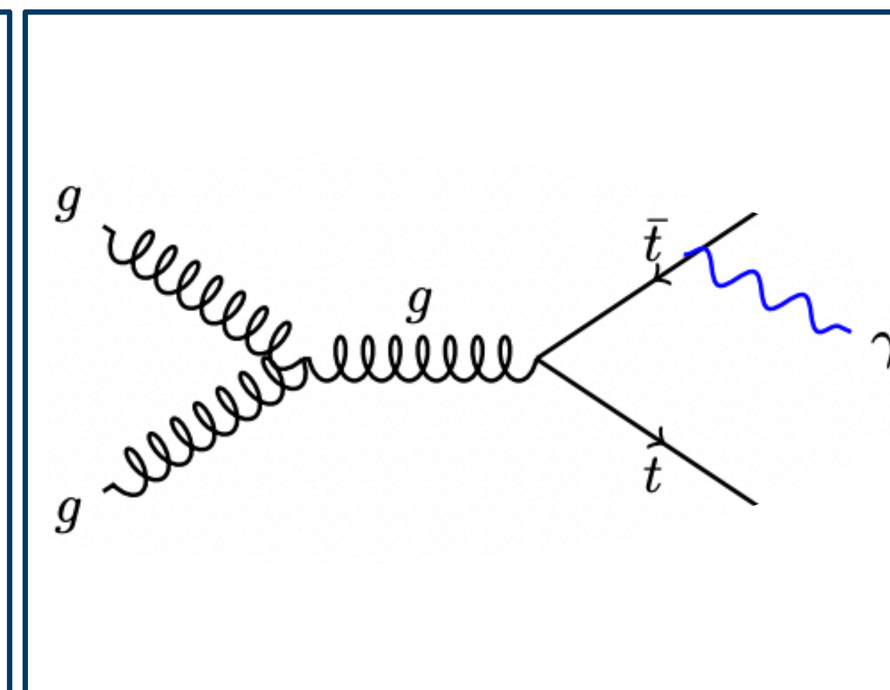
ttW/ttZ/ttγ Measurements (ATLAS+CMS)

Jonathan Jamieson, University of Glasgow
on behalf of the ATLAS and CMS collaborations

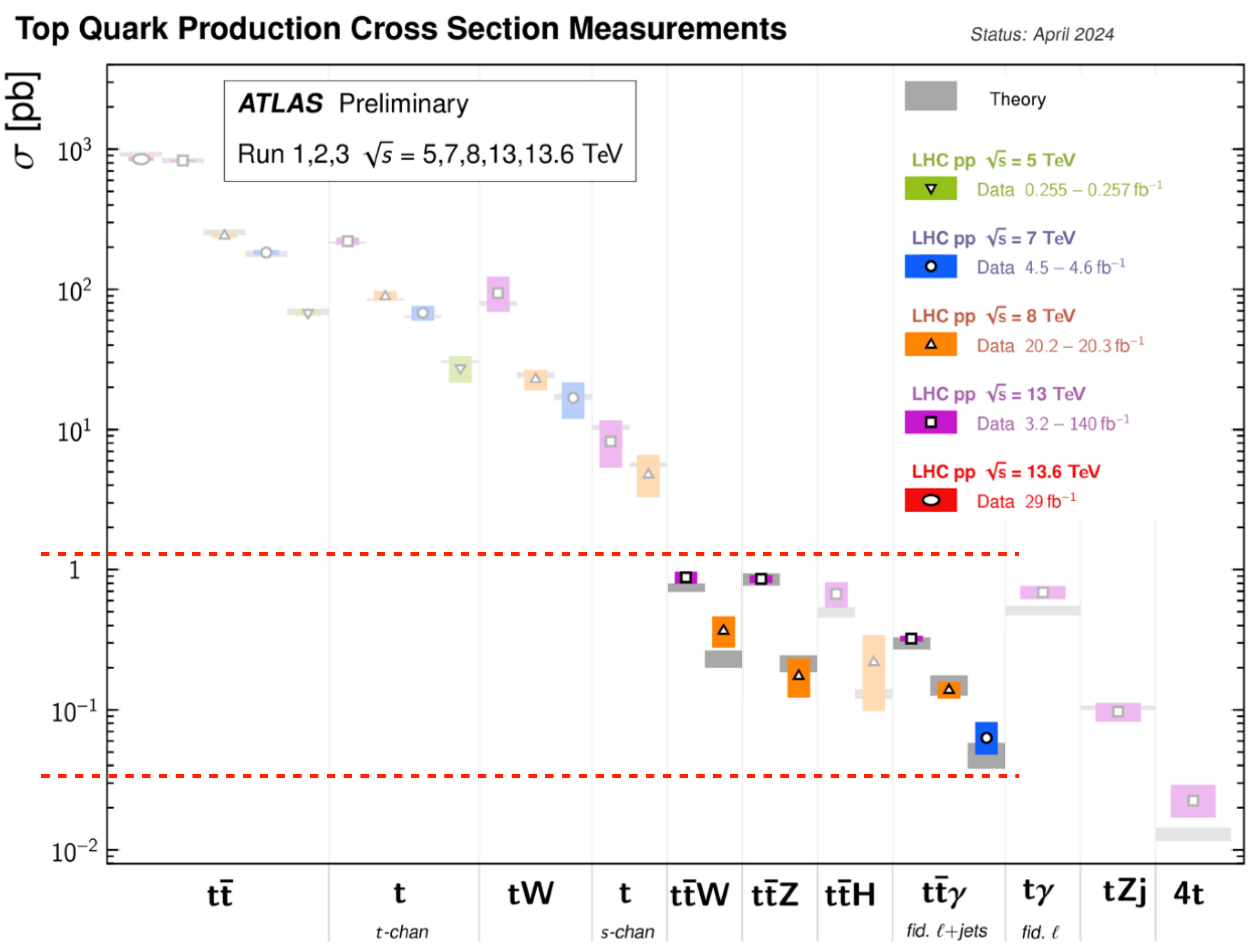






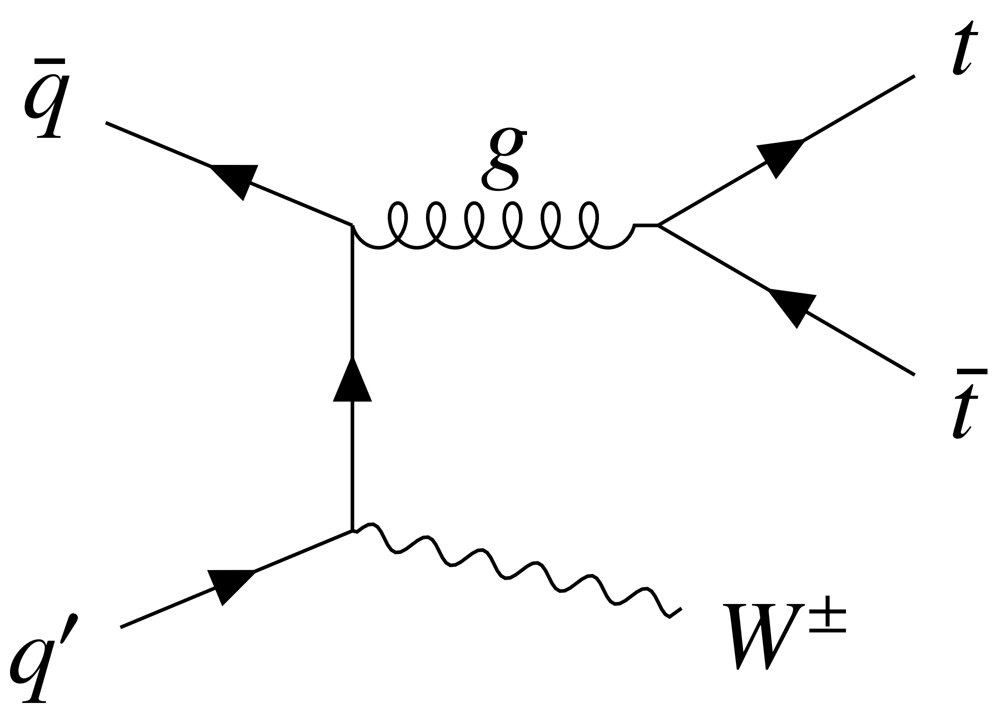
We are moving towards the era of precision rare processes

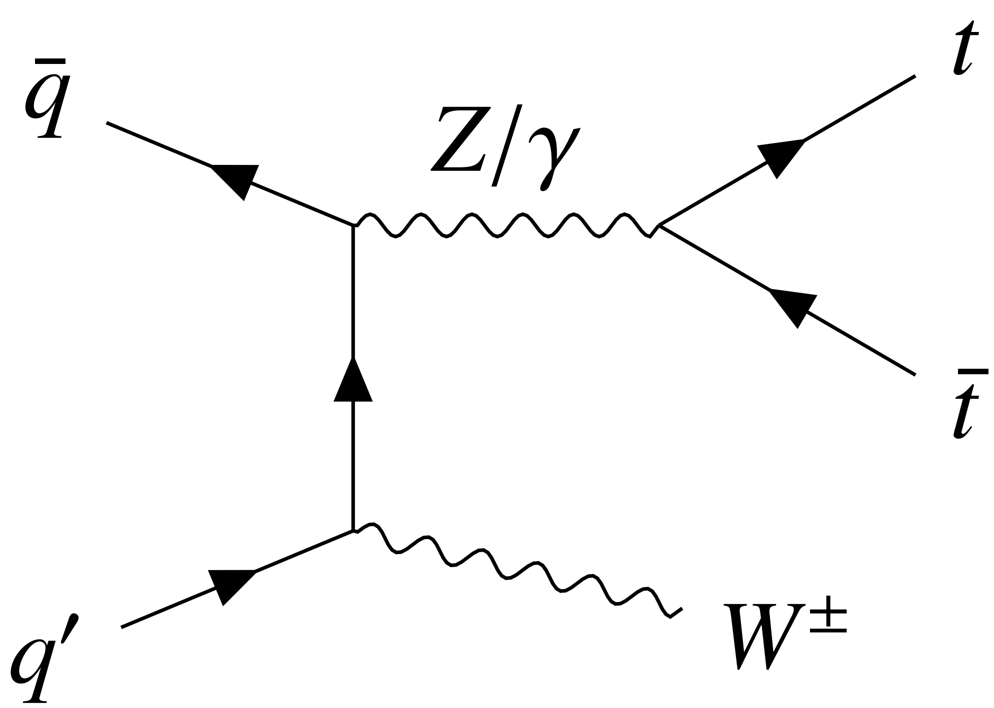
- **Multiple rare $t\bar{t}X$ processes accessible** at the LHC
- Unresolved **tensions exist with SM predictions**
- Window into top-quark **EWK couplings**
- Highly **sensitive to EFT operators**
- **Important backgrounds** for SM/BSM processes
- **Increasingly precise measurements** with growing LHC datasets



ATL-PHYS-PUB-2024-006

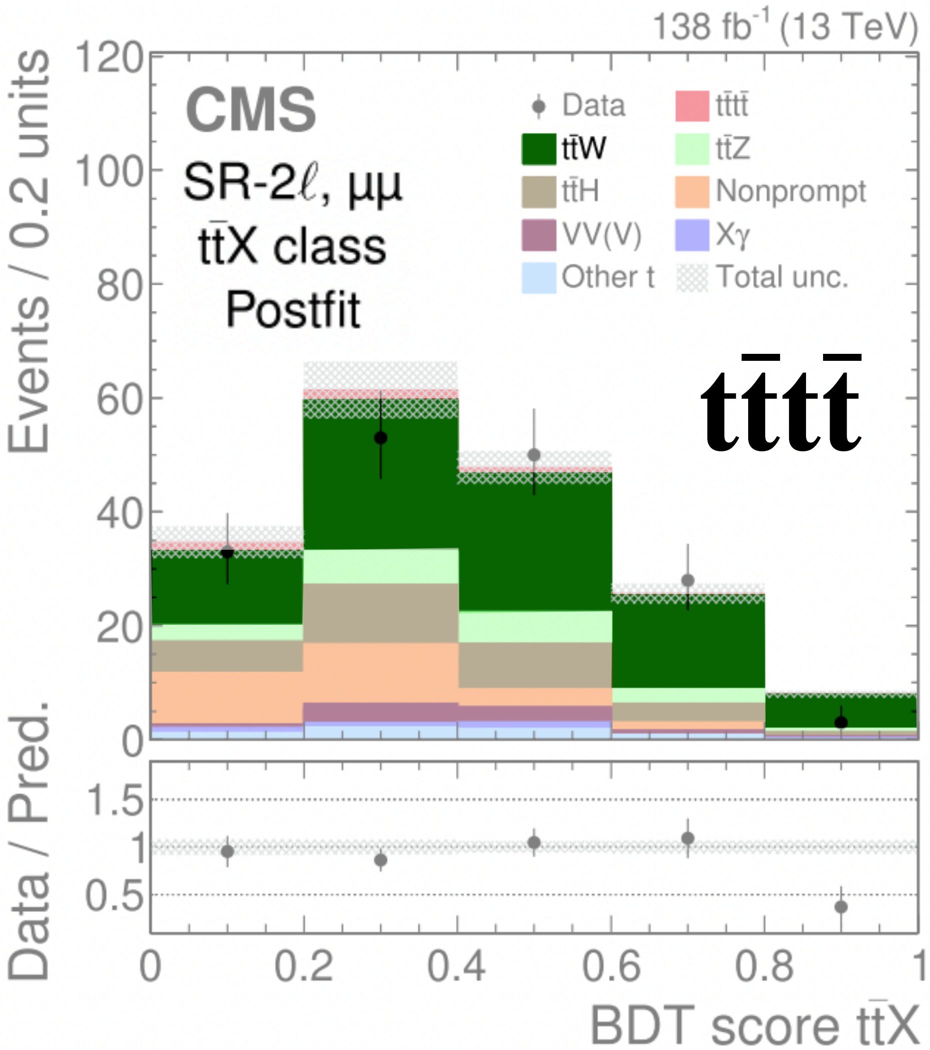
$t\bar{t}W$





$t\bar{t}W$ cross-section motivation

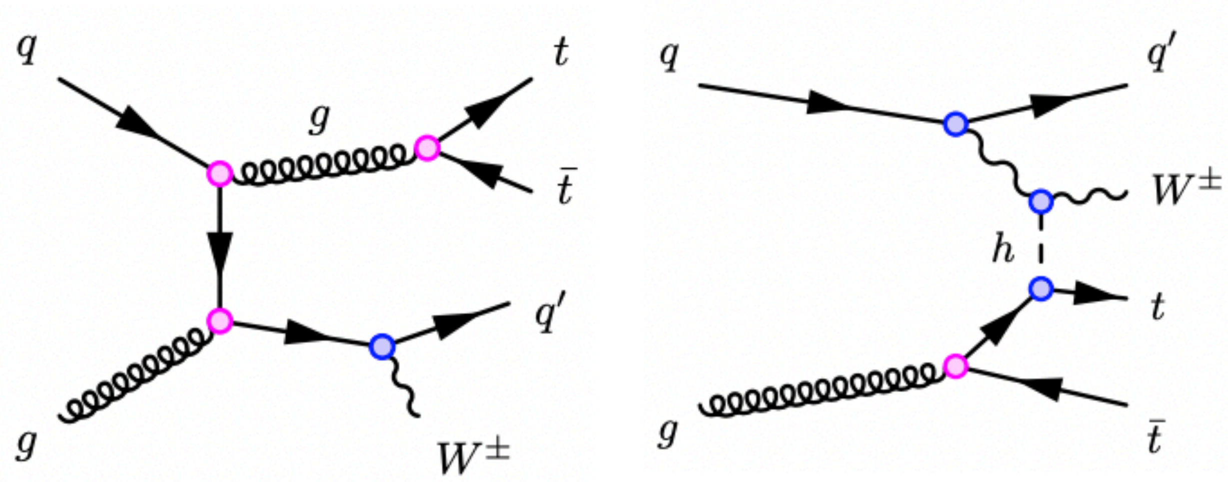
- Important background to SM/BSM processes ($\mathbf{t\bar{t}t\bar{t}}$, $t\bar{t}H$, SS dilepton)



Phys. Lett. B 847 (2023) 138290

- Previous results show tension with SM but systematics limited

- Very sensitive to higher order **QCD**/**EWK** corrections



$t\bar{t}W$ cross-section measurements

$t\bar{t}W$ common strategy

- 2 lepton (same-sign) + 3 lepton (1 opposite-sign) channels
- Combined likelihood fit with targeted background-rich control regions
- Inclusive cross-section + W^+/W^- cross-section ratio

- JHEP 07 (2023) 219

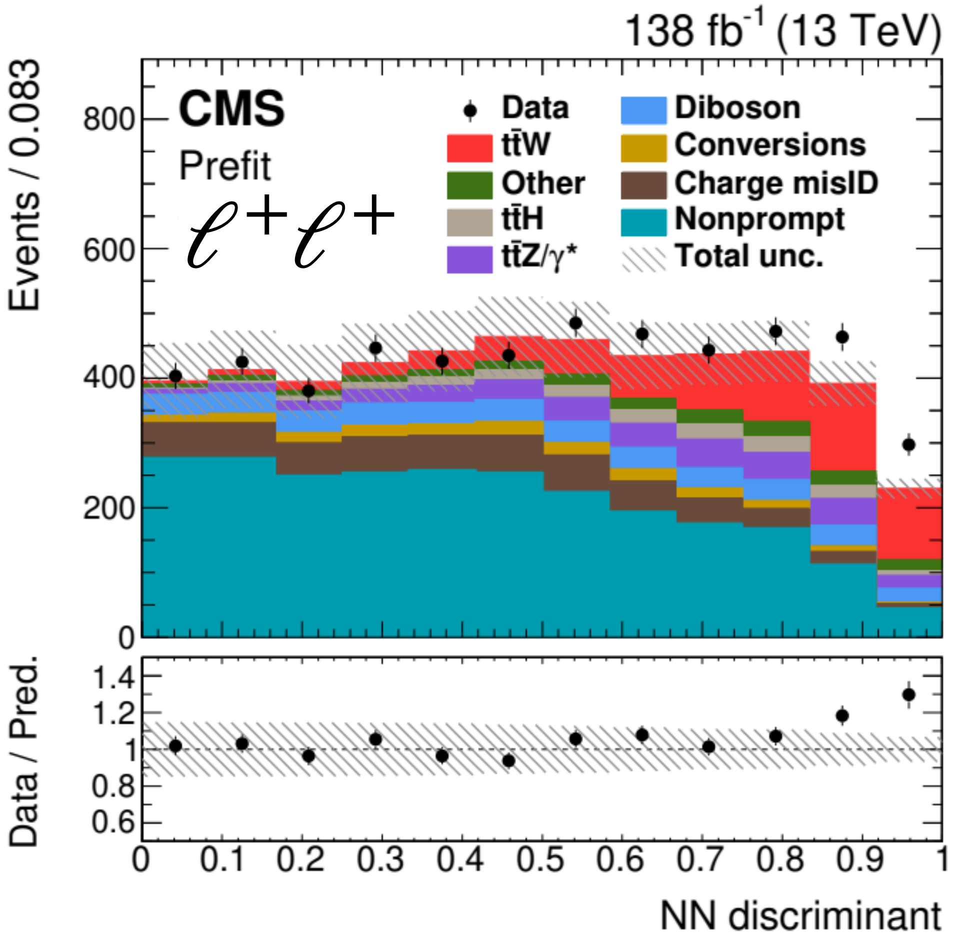
- arXiv:2401.05299
(accepted by JHEP)

- Neural network fit for 2-lepton signal extraction
- Dedicated data control regions to improve background estimates

- Significant reduction in non-prompt backgrounds
- First differential $t\bar{t}W$ cross-section measurement in ATLAS
- Comparison to NNLO prediction

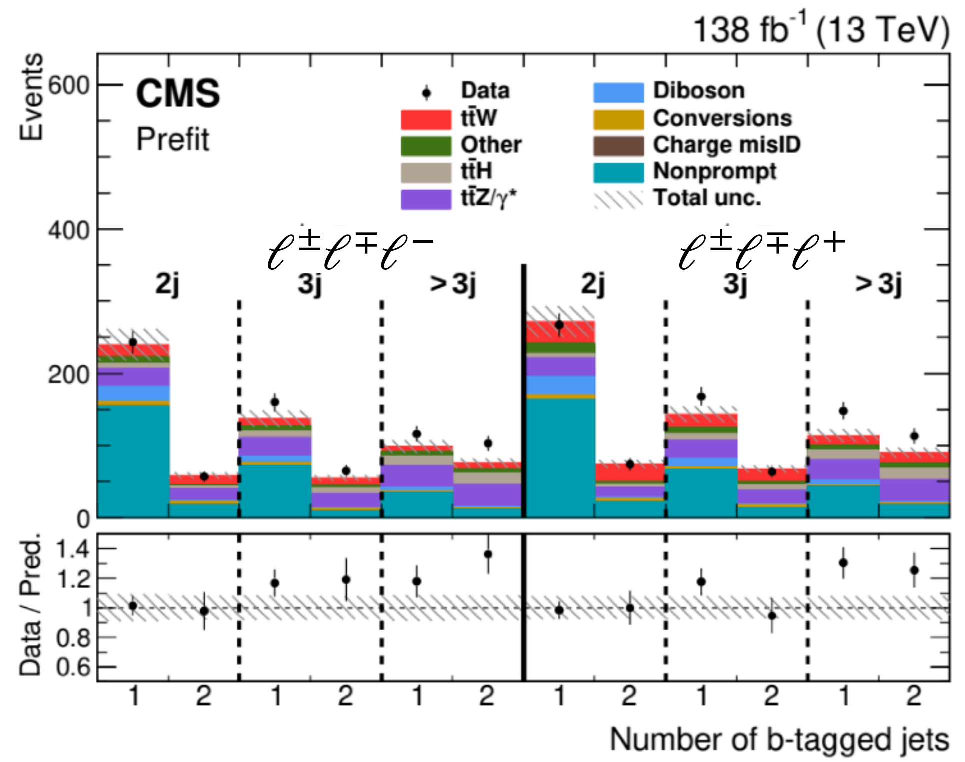
JHEP 07 (2023) 219

- Neural network event classification in 2ℓ same-sign channel



- Separate $t\bar{t}W$, $t\bar{t}Z + t\bar{t}H$, $t\bar{t}\gamma^*$, and non-prompt

- Split 3ℓ channel by lepton charge sum, N_{jets}, and $N_{b\text{-jets}}$



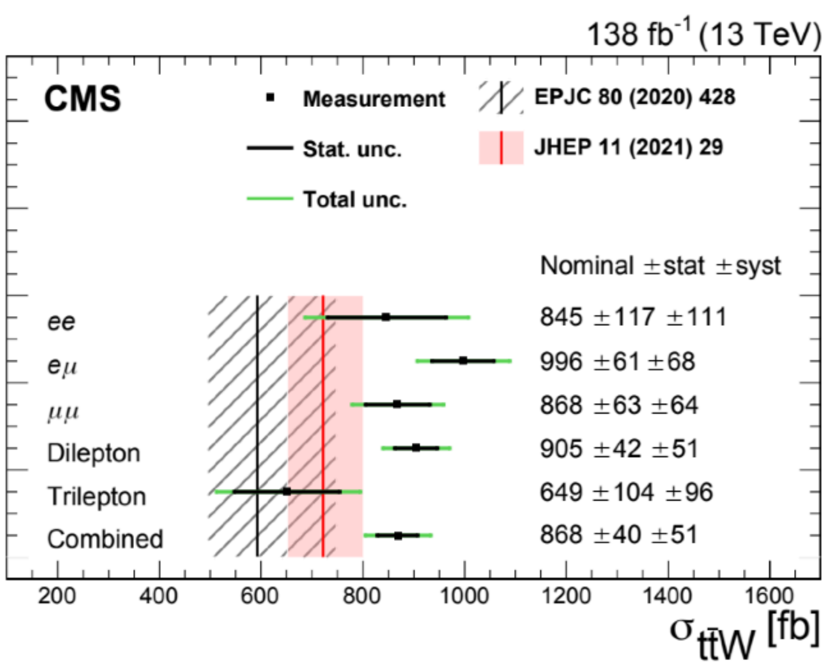
- Fit $m(3\ell)$ for each subcategory in final fit

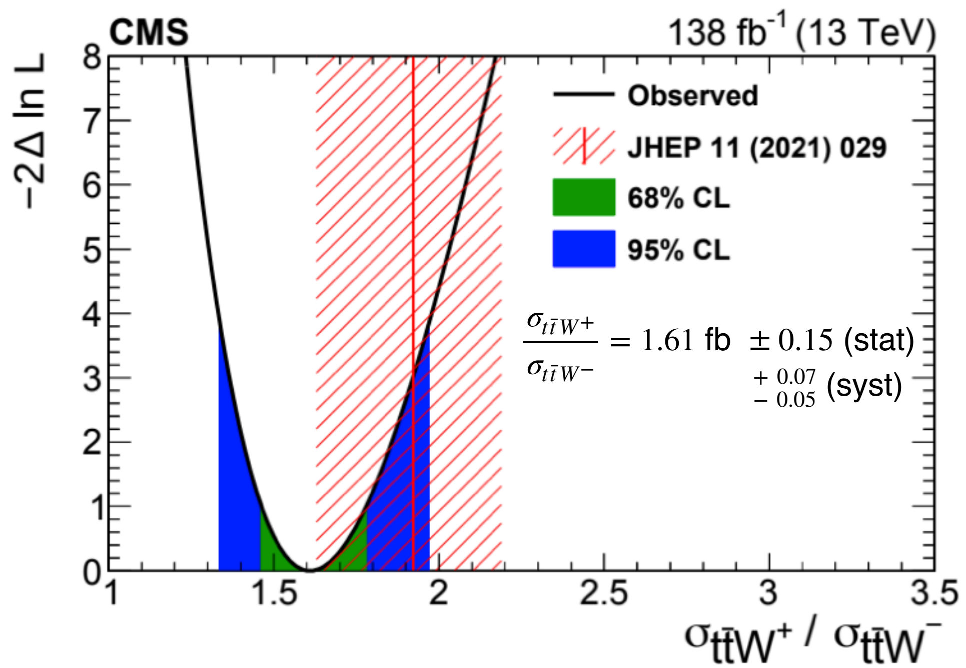
$t\bar{t}W$ inclusive cross-section

JHEP 07 (2023) 219

- **Significantly reduced uncertainties** w.r.t previous measurement (~7.5% total uncertainty)
- Dominant uncertainty: **$t\bar{t}H$ normalisation**
- Cross-sections are consistent with SM but tension remains

$$\sigma_{t\bar{t}W} = 868 \pm 40\ \text{(stat)} \pm 51\ \text{(syst) fb}$$





Source	Uncertainty [%]
Experimental uncertainties	
Integrated luminosity	1.9
b tagging efficiency	1.6
Trigger efficiency	1.2
Pileup reweighting	1.0
L1 inefficiency	0.7
Jet energy scale	0.6
Jet energy resolution	0.4
Lepton selection efficiency	0.4
Background uncertainties	
$t\bar{t}H$ normalization	2.6
Charge misidentification	1.6
Nonprompt leptons	1.3
VVV normalization	1.2
$t\bar{t}VV$ normalization	1.2
Conversions normalization	0.7
$t\bar{t}\gamma$ normalization	0.6
ZZ normalization	0.6
Other normalizations	0.5
$t\bar{t}Z$ normalization	0.3
WZ normalization	0.2
tZq normalization	0.2
tHq normalization	0.2
Modeling uncertainties	
$t\bar{t}W$ scale	1.8
$t\bar{t}W$ color reconnection	1.0
ISR & FSR scale for $t\bar{t}W$	0.8
$t\bar{t}\gamma$ scale	0.4
VVV scale	0.3
$t\bar{t}H$ scale	0.2
Conversions	0.2
Simulation statistical uncertainty	1.8
Total systematic uncertainty	5.8

$t\bar{t}W$ cross-section measurements

$t\bar{t}W$ common strategy

- 2 lepton (same-sign) + 3 lepton (1 opposite-sign) channels
- Combined likelihood fit with targeted background-rich control regions
- Inclusive cross-section + W^{+}/W^{-} cross-section ratio

- JHEP 07 (2023) 219

CMS

- arXiv:2401.05299
(accepted by JHEP)

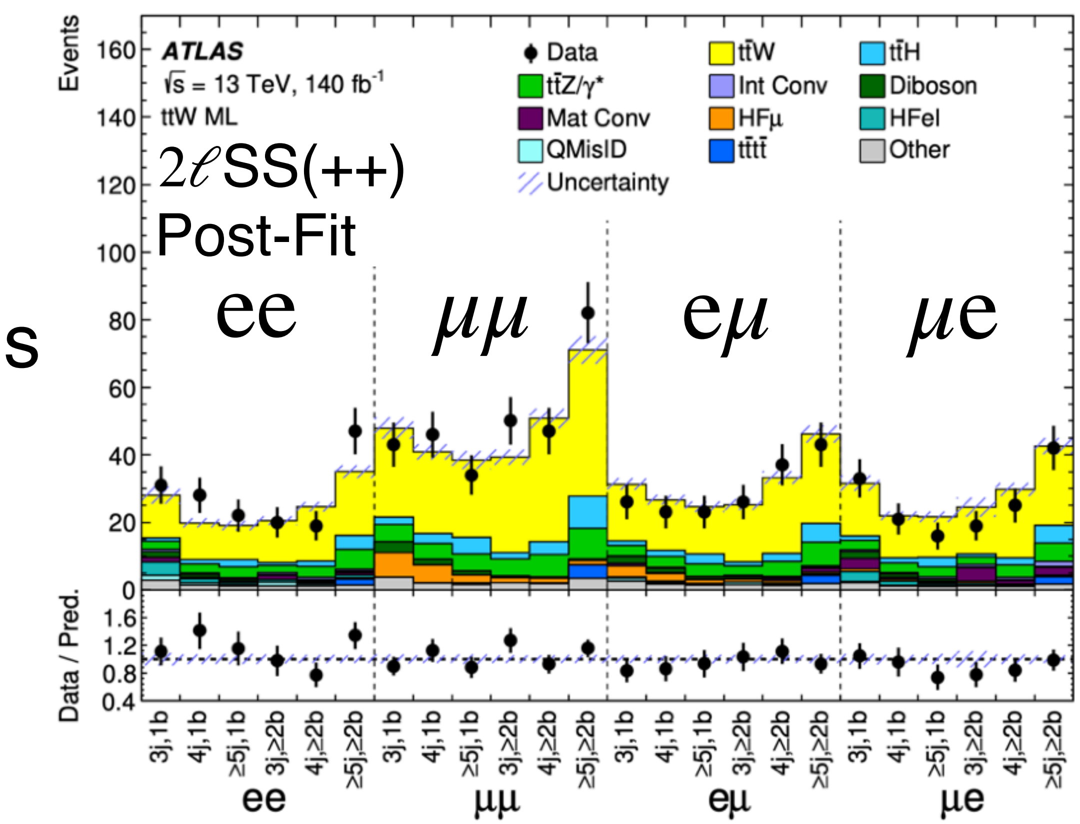
ATLAS EXPERIMENT

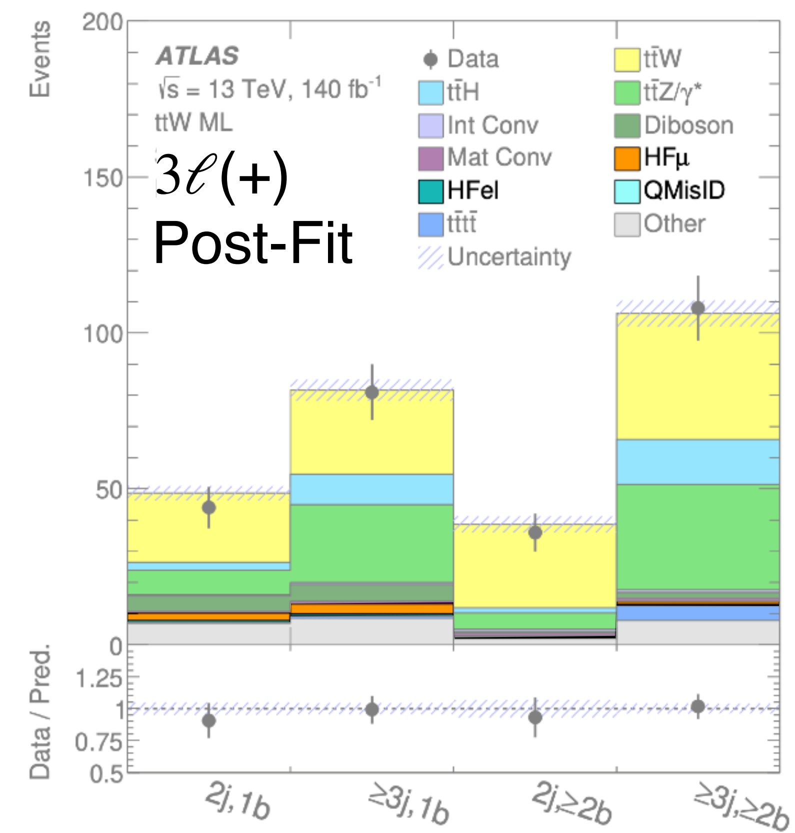
- Neural network fit for 2-lepton signal extraction
- Dedicated data control regions to improve background estimates

- Significant reduction in non-prompt backgrounds
- First differential $t\bar{t}W$ cross-section measurement in ATLAS
- Comparison to NNLO prediction

arXiv:2401.05299 ATLAS EXPERIMENT

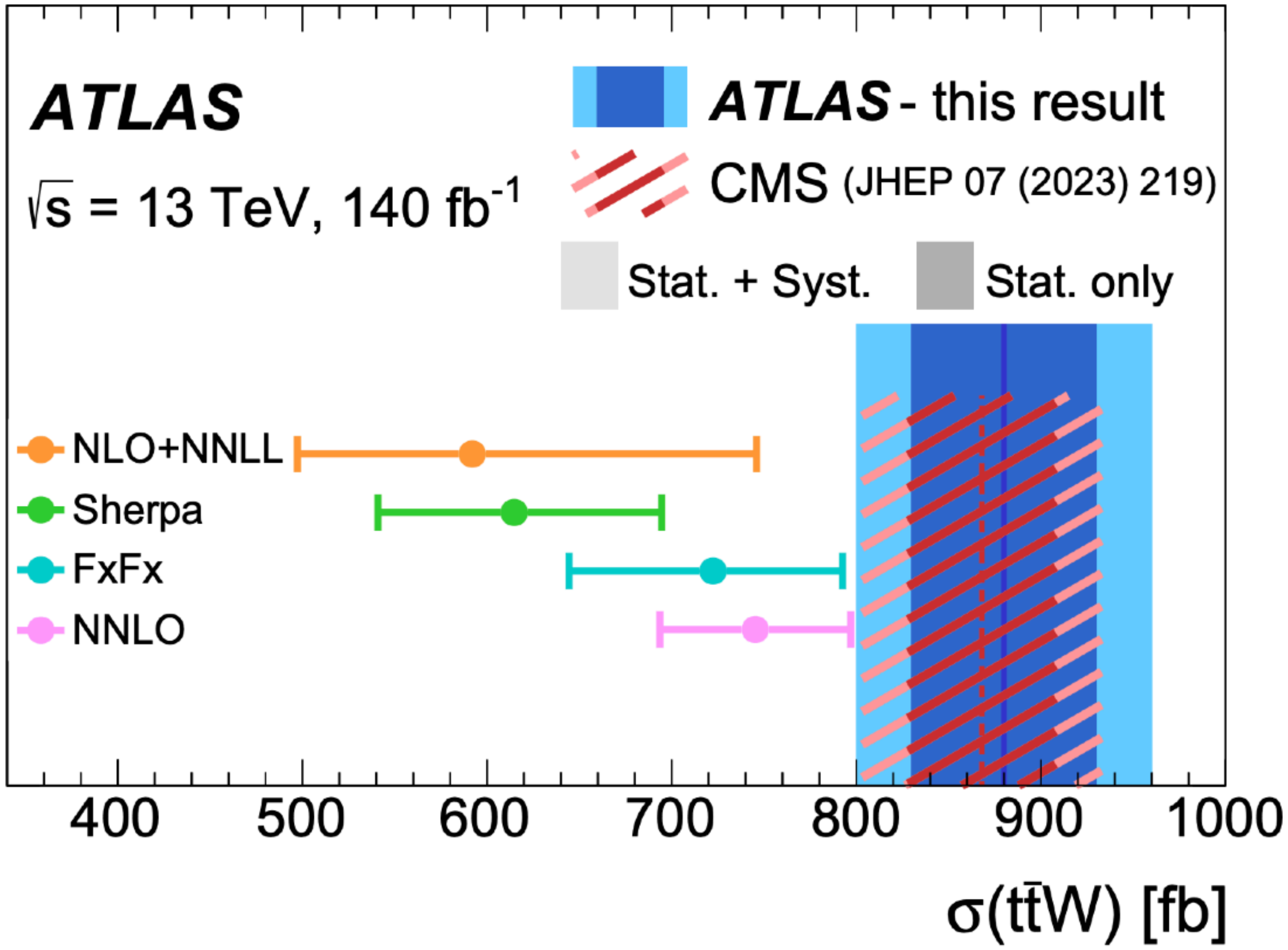
- Combined fit: 48 ($2\ell SS$) + 8 (3ℓ) signal regions and 10 background-enriched control regions
- Split channels by lepton charge sum, lepton flavour, N_{jets}, and $N_{b\text{-jets}}$
- Additional dedicated BDTs for lepton isolation and incorrect electron charge assignment
- **Significant reduction in non-prompt lepton background from heavy flavour decays** w.r.t CMS





arXiv:2401.05299 ATLAS EXPERIMENT

- Inclusive XS compared to CMS and stat-of-the-art NNLO prediction: Rev. Lett. 131, 231901 (2023)
- Dominant uncertainty: $t\bar{t}W$ modelling (different treatment w.r.t CMS)
- Experimental results in good agreement



- **Tension with SM prediction remains** $(\sim 1.6\sigma)$

$$\sigma_{t\bar{t}W}^{CMS} = 868 \pm 40 \text{ (stat)} \pm 51 \text{ (syst) fb}$$

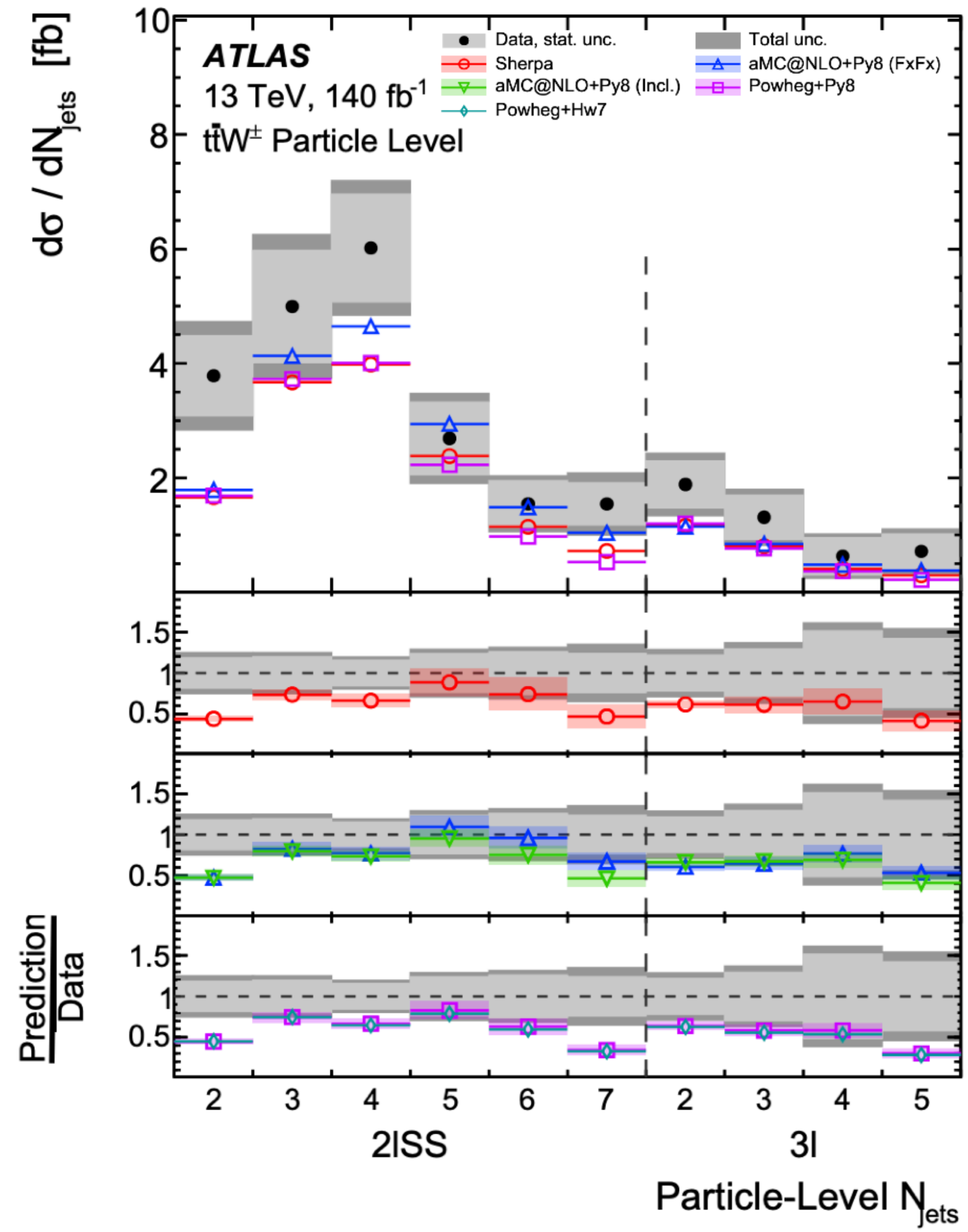
$$\sigma_{t\bar{t}W}^{ATLAS} = 880 \pm 50 \text{ (stat)} \pm 70 \text{ (syst) fb}$$

$$\sigma_{\text{NNLO(QCD)+NLO(EWK)}} = 745 \pm 50 \text{ (scale)} \pm 13 \text{ (2-loop approx.)} \pm 19 \text{ (PDF}, \alpha_s\text{) fb}$$

$t\bar{t}W$ differential cross-section

arXiv:2401.05299

- **First differential cross-section measurement in $t\bar{t}W$** final state in ATLAS!
- Combined fit: 2 ($2\ell SS$) + 6 (3ℓ) signal regions, using profile likelihood unfolding
- Differential in $\mathbf{N_{jets}}$, $\mathbf{H_T}$, and **angular variables**
- Measurements **statistically limited**
- Overall excess in differential observables **consistent with inclusive cross-section**



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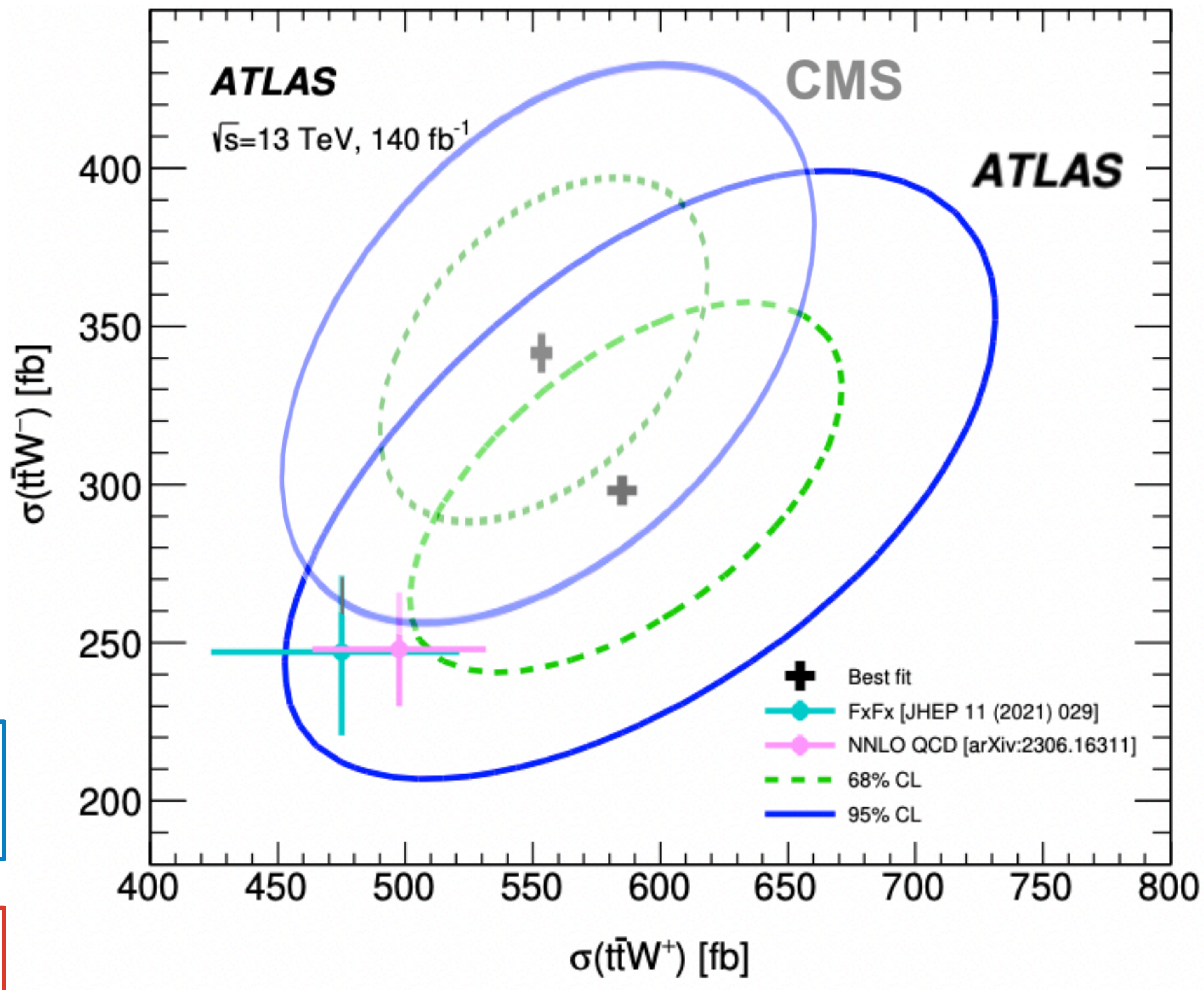
arXiv:2401.05299

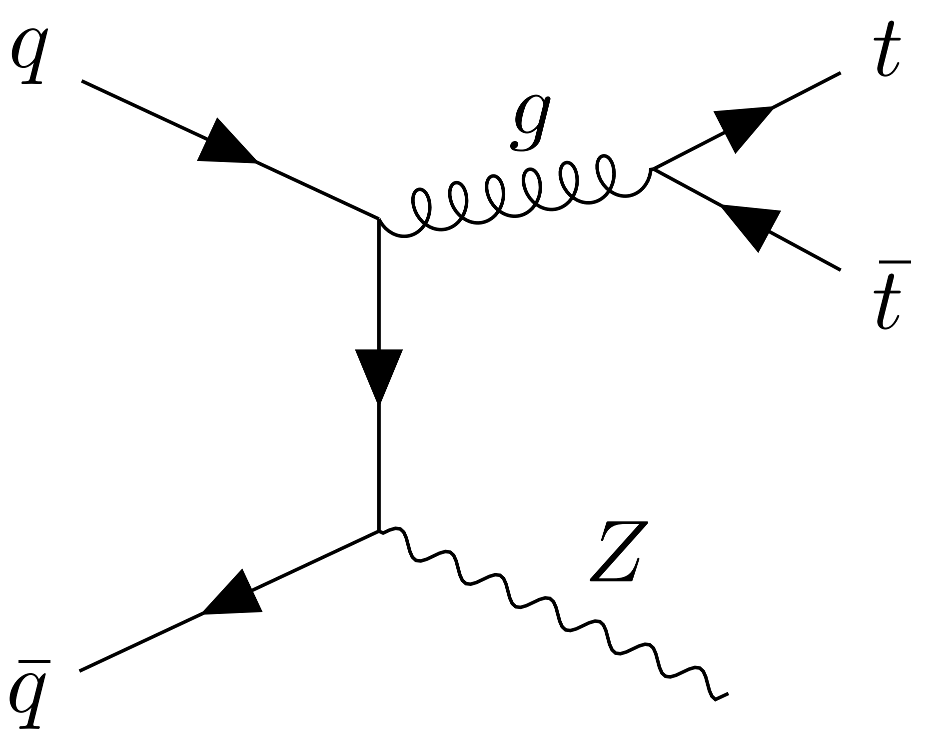
- Both experiments **measure $\sigma(t\bar{t}W^+)$ and $\sigma(t\bar{t}W^-)$ separately**
- Can extract **relative charge asymmetry**
- Measurements consistent with NNLO SM prediction
- CMS measures smaller central value

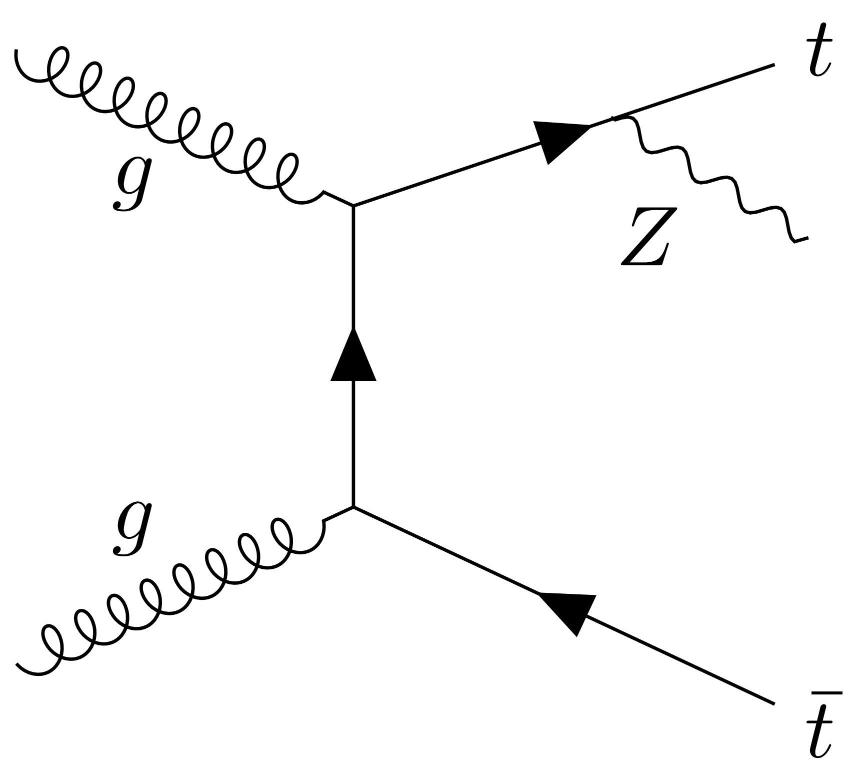


$A_C^{\text{rel}}(\text{ATLAS}) = 0.33 \pm 0.05\ (\text{stat}) \pm 0.02\ (\text{syst})$

$A_C^{\text{rel}}(\text{CMS}) = 0.23 \pm 0.03\ (\text{stat}) \pm 0.03\ (\text{syst})$

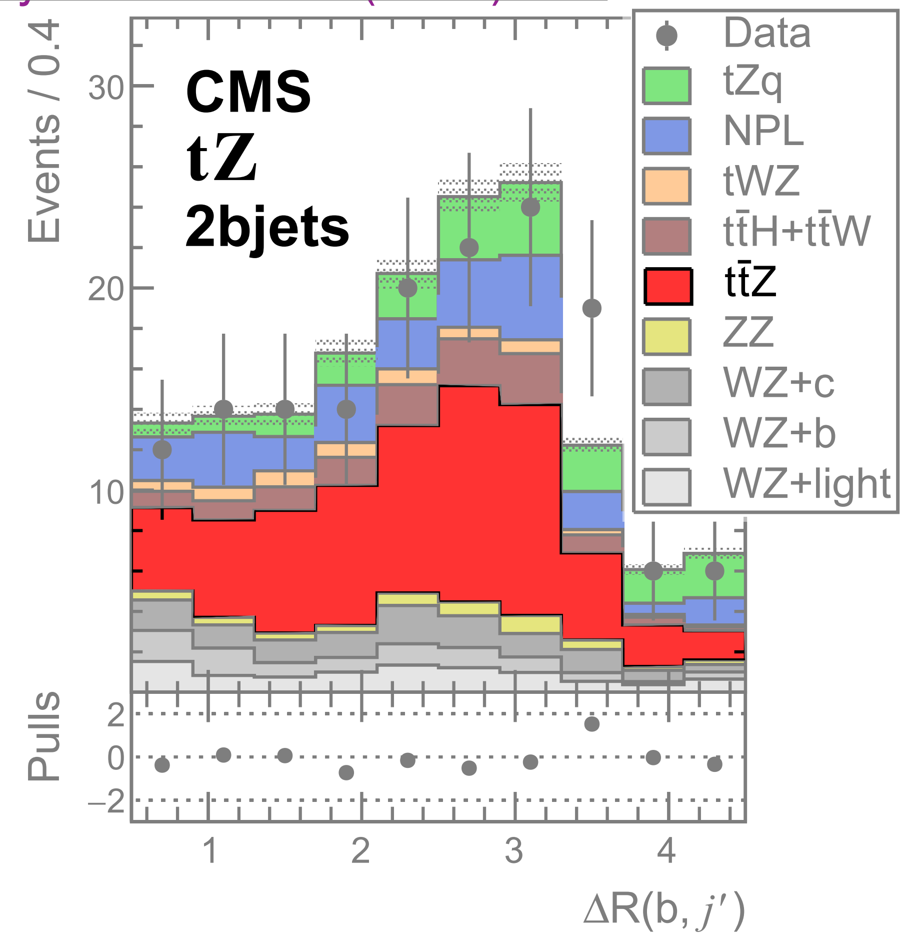
$t\bar{t}Z$



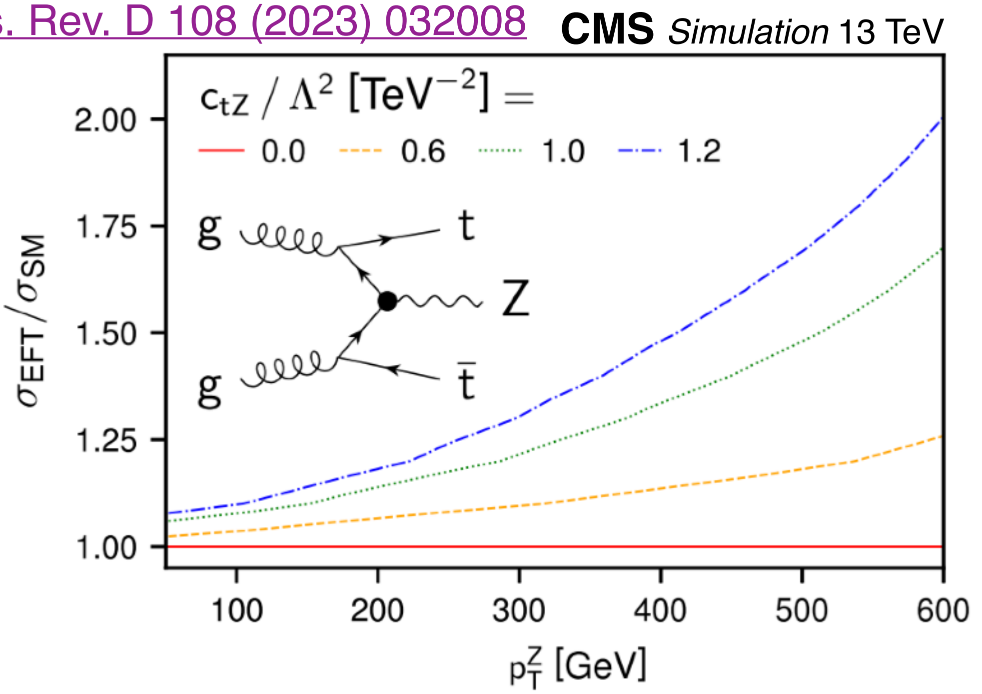


- Important background to SM/BSM processes ($t\bar{t}t\bar{t}$, $t\bar{t}H$, $\mathbf{tZ}$, SS trilepton)
- Constrain EWK parameters and BSM models through tZ coupling
- Sensitive to spin correlation and EFT operators

Phys. Lett. B 779 (2018) 358



Phys. Rev. D 108 (2023) 032008



$t\bar{t}Z$ cross-section measurements

$t\bar{t}Z$ common strategy

- Target 2/3/4 lepton channels
- Combined likelihood fit with targeted background-rich control regions
- EFT interpretation targeting tZ and 4-quark operators

- CMS-PAS-TOP-23-004
- Phys. Rev. D 108 (2023) 032008

- arXiv:2312.04450 (submitted to JHEP)

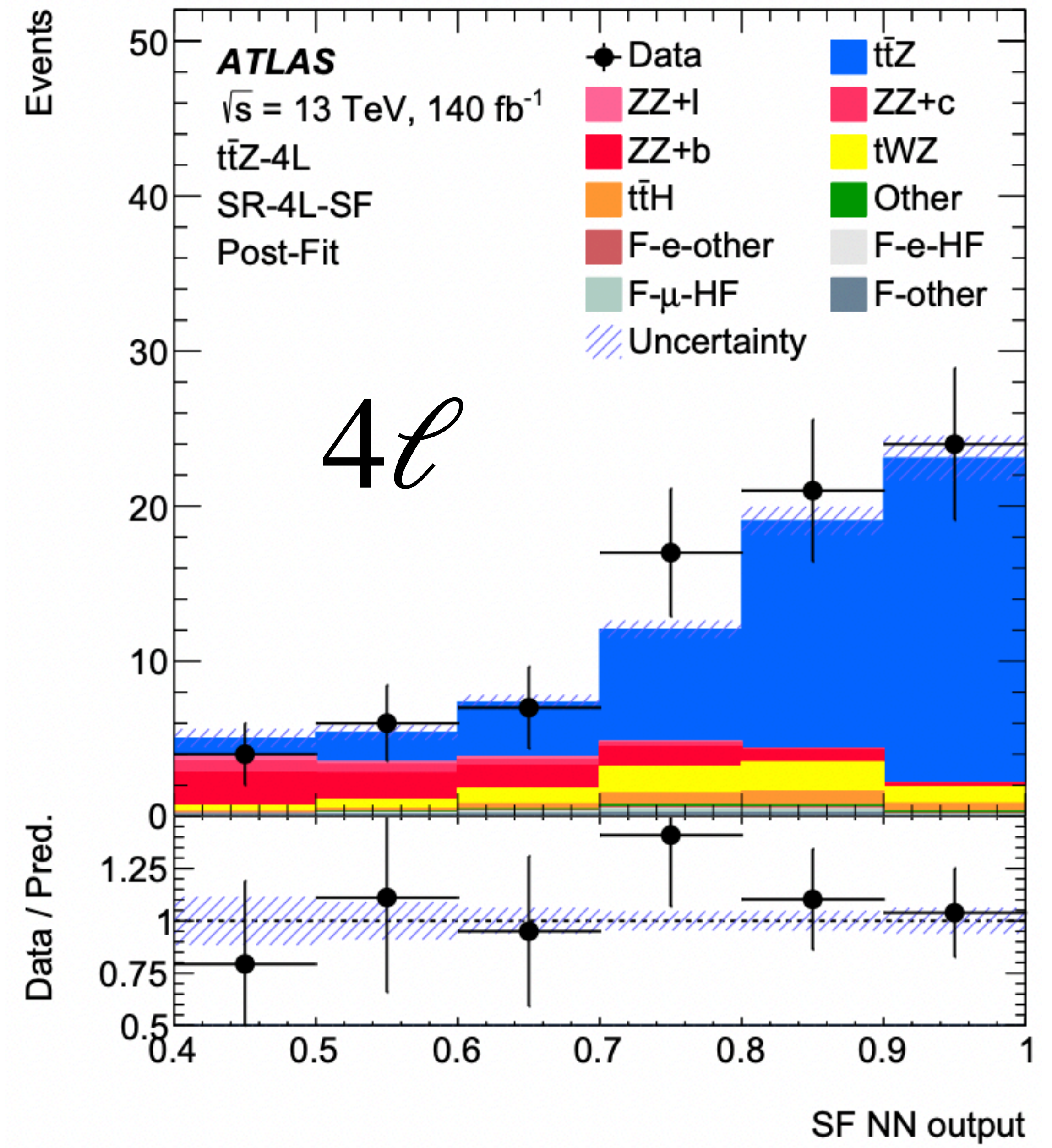
- $t\bar{t}Z + t\bar{t}H$ EFT fits in boosted events
- $t\bar{t}Z$, tWZ, tZq simultaneous cross-section measurement

- Multiple differential observables
- EFT interpretation using differential variables
- Measure effect on $t\bar{t}$ spin correlation

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

[arXiv:2312.04450](https://arxiv.org/abs/2312.04450) ATLAS EXPERIMENT

- Target 2,3, and 4 lepton (e, μ) channels, low statistics but high sensitivity
- Select events based on: N_ℓ, N_j, N_b, E_T^{miss}
- Separate signal from background using Neural networks
- Profile likelihood fit based on NN output (8 SR + 4 CR)
- Fit each channel separately and combined
- Good agreement with SM prediction **(6.5% precision!)**
- Dominant uncertainty: **Background normalisation, jets**



$$\sigma_{t\bar{t}Z}^{comb.} = 860 \pm 40 \text{ (stat)} \pm 40 \text{ (syst) fb}$$

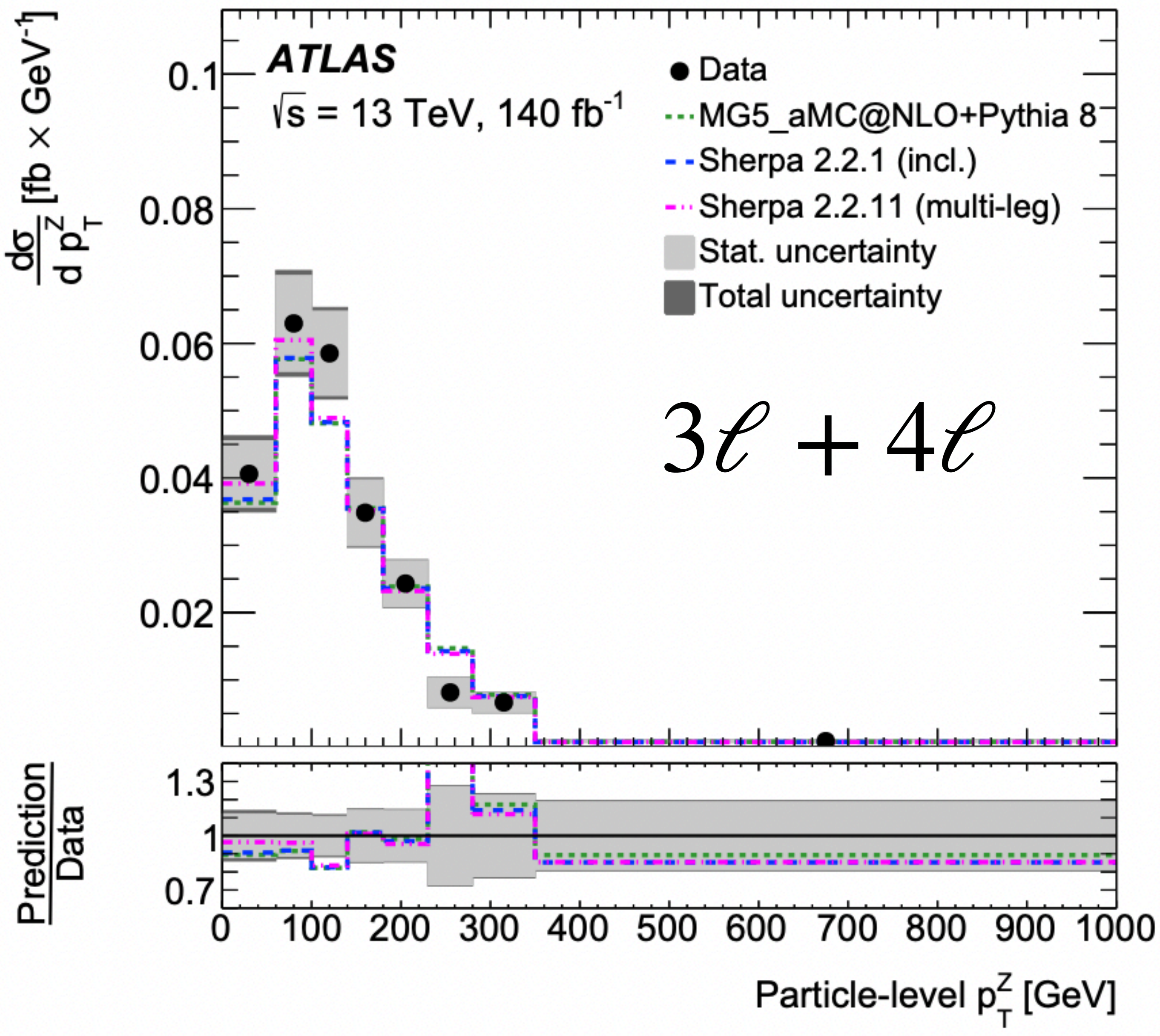
$$\sigma_{t\bar{t}Z}^{NLO+NNLL} = 863^{+73}_{-85} \text{ (scale)} \pm 28 \text{ (PDF}, \alpha_s\text{) fb}$$

Eur. Phys. J. C 79 (2019) 249

$t\bar{t}Z$ differential cross-section

arXiv:2312.04450 ATLAS EXPERIMENT

- Measure differential cross-sections unfolded to particle- and parton-level
- 17 observables across 3ℓ, 4ℓ and $3\ell + 4\ell$ channels
- Good agreement with NLO predictions across all variables
- Measurements are **statistically limited**
- **Background normalisation and $t\bar{t}Z$ modelling also significant** sources of uncertainty



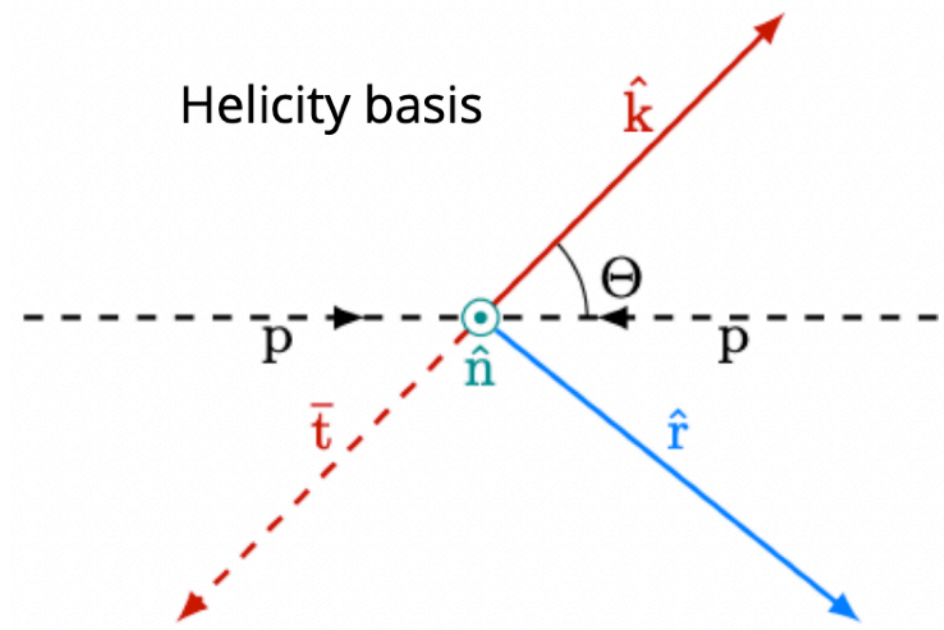
$t\bar{t}Z$ Spin correlation

arXiv:2312.04450 ATLAS EXPERIMENT

- Z-boson in production modifies expected spin correlation between top-quark pair
- **First ever measurement of this effect** at detector-level using template method:

$$O = \mathbf{f}_{\mathrm{SM}} \cdot O_{\text{spin-on}} + (1 - \mathbf{f}_{\mathrm{SM}}) \cdot O_{\text{spin-off}}$$

- 9 angular observables (O) used as spin-sensitive variables
- For each observable **extract scaling factor ($\mathbf{f}_{\mathrm{SM}}$) for spin-on** and **spin-off** templates
- **Spin-off hypothesis rejected at** 1.8σ



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

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

$t\bar{t}Z$ cross-section measurements

$t\bar{t}Z$ common strategy

- Target 2/3/4 lepton channels
- Combined likelihood fit with targeted background-rich control regions
- EFT interpretation targeting tZ and 4-quark operators

- CMS-PAS-TOP-23-004
- Phys. Rev. D 108 (2023) 032008

- arXiv:2312.04450
  (submitted to JHEP)

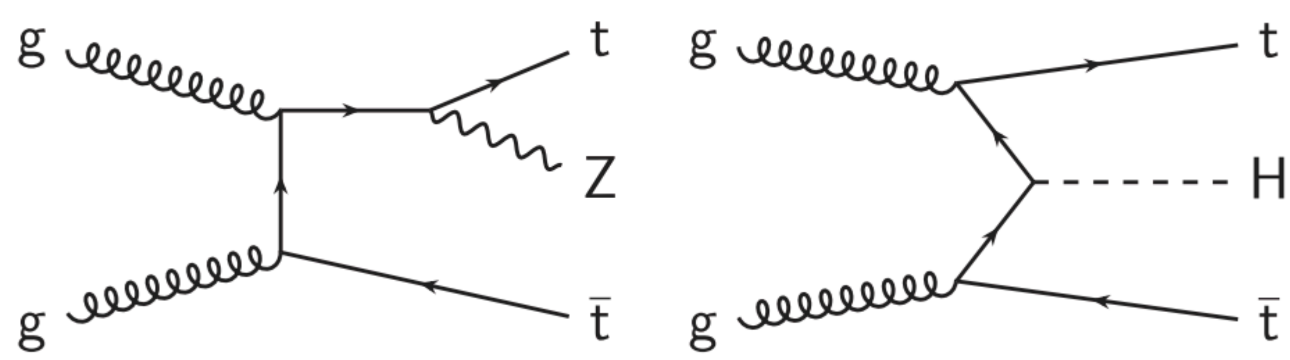
- $t\bar{t}Z + t\bar{t}H$ EFT fits in boosted events
- $t\bar{t}Z$, tWZ, tZq simultaneous cross-section measurement

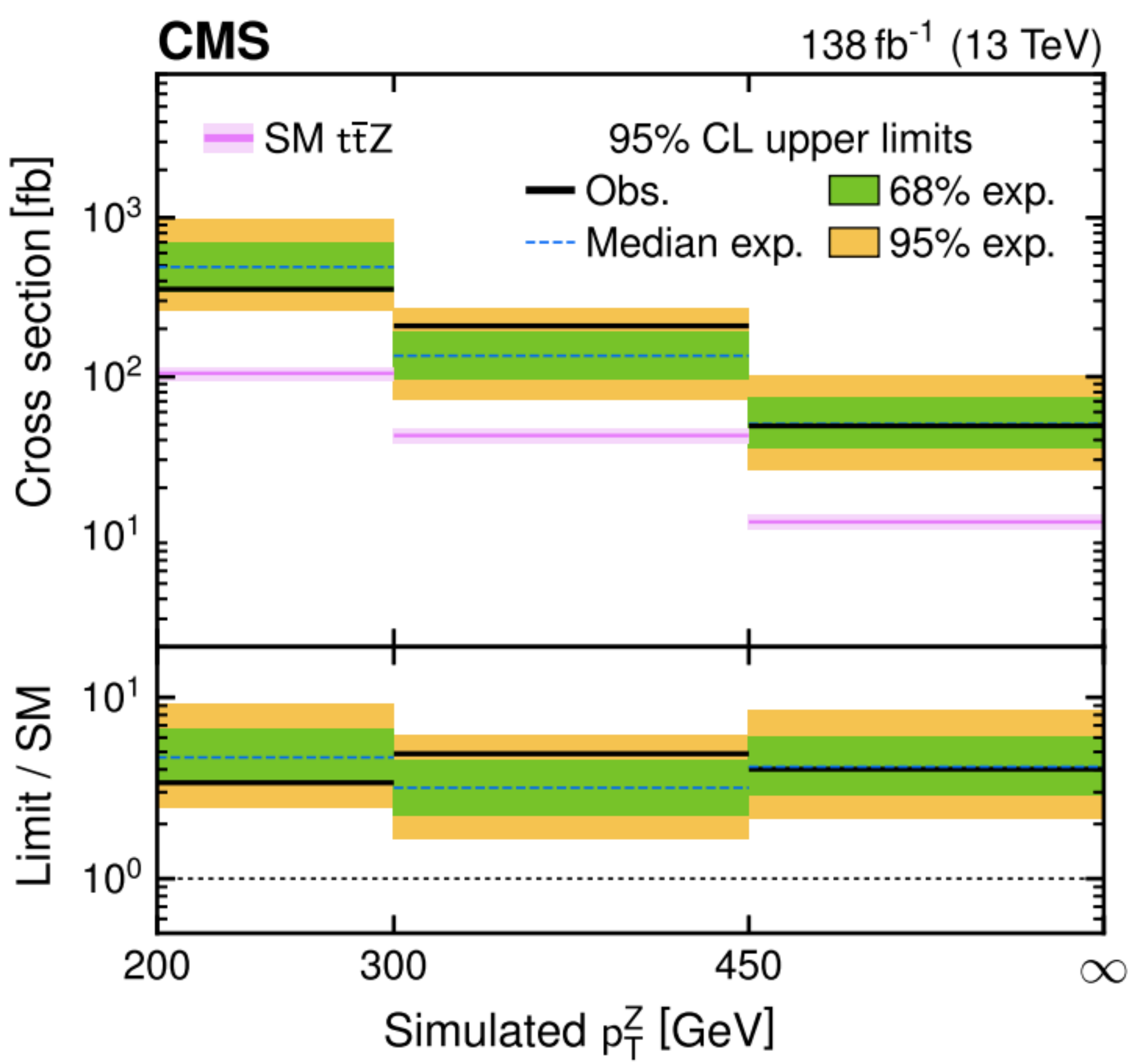
- Multiple differential observables
- EFT interpretation using differential variables
- Measure effect on $t\bar{t}$ spin correlation

$t\bar{t}Z + t\bar{t}H$ Boosted cross-section

Phys. Rev. D 108 (2023) 032008

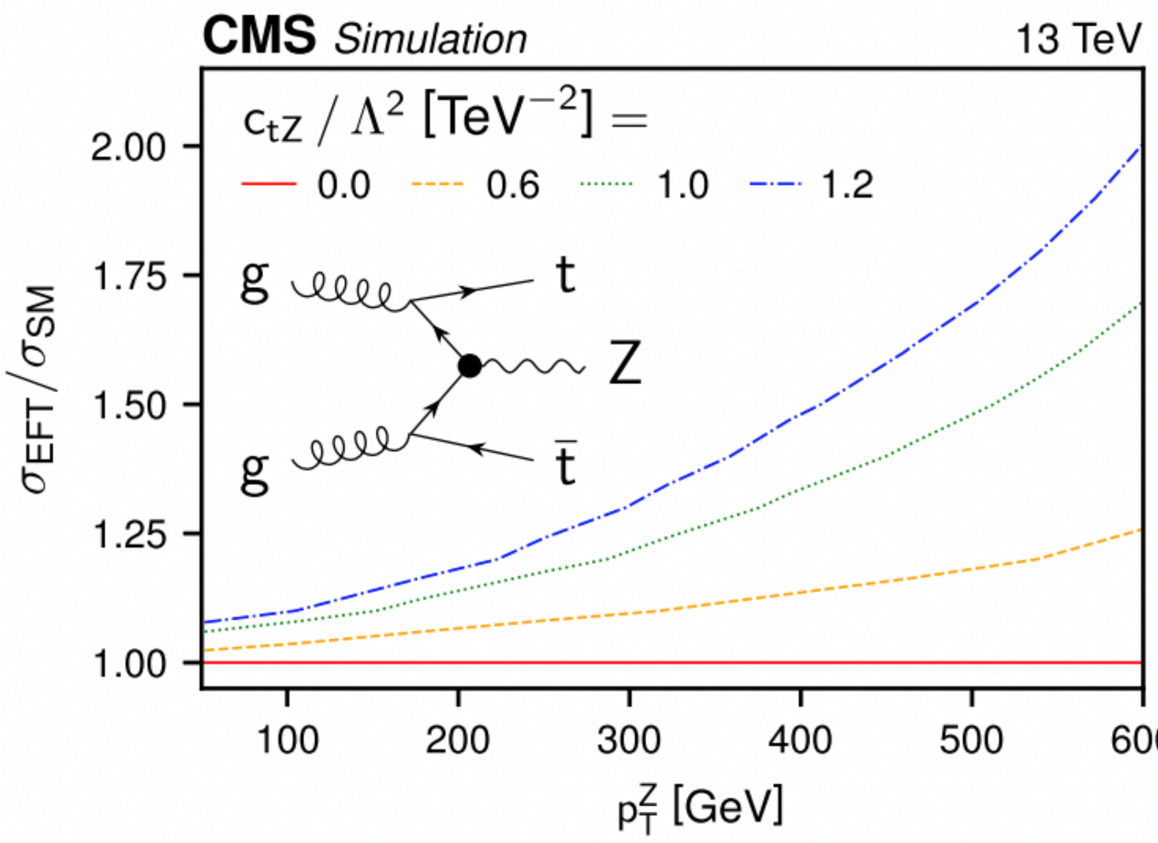
- One lepton (e or μ), One high-p_T jet (H/Z candidate), ≥ 2 b-tagged jets
- **DNN to separate $t\bar{t}Z$, $t\bar{t}H$,** and backgrounds
- Simultaneous profile likelihood fit to event yields in p_T and mass observables, and DNN output
- **Extract 95% upper limits on differential cross-section** for both $p_T(Z)$ and $p_T(H)$
- Measurements **statistically limited**

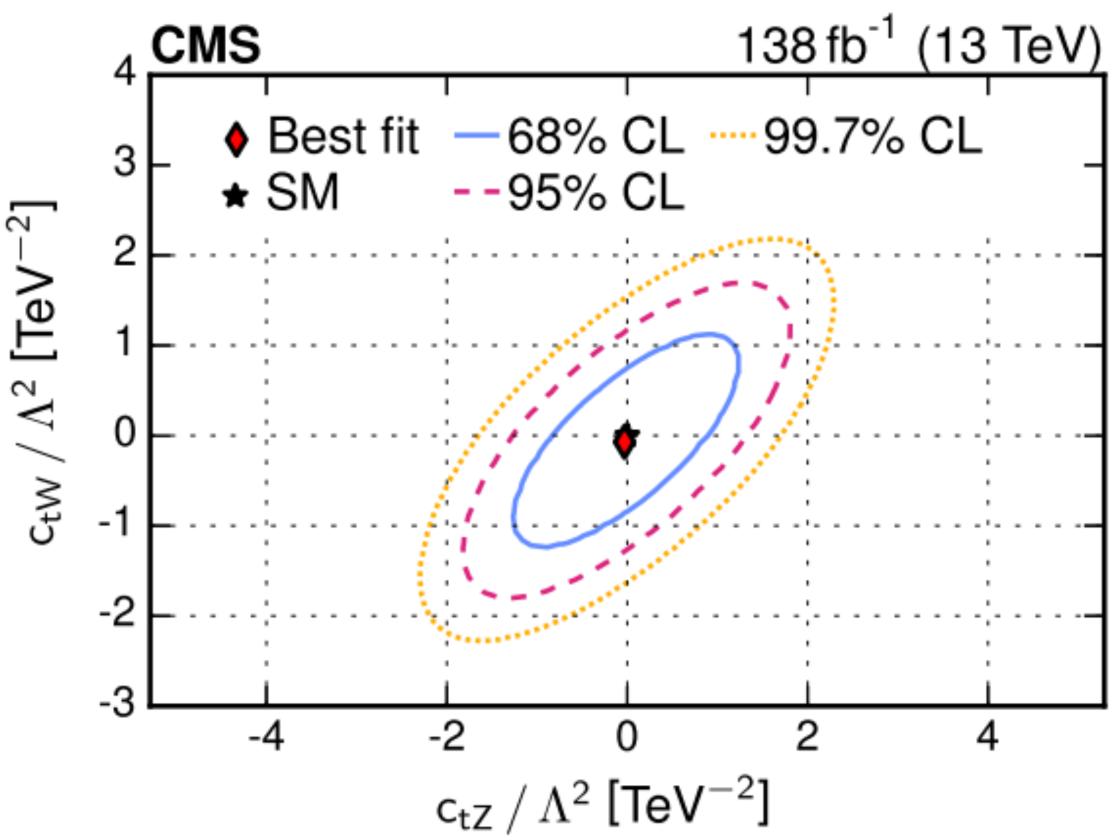




Phys. Rev. D 108 (2023) 032008

- **EFT effects grow strongly with p_T** in both boosted topologies
- **Combined fit to extract EFT limits** on operators sensitive to tV, tH, and 4-quark couplings
- 95% CL limits in agreement with SM
- **EFT limits consistent/competitive** with most stringent existing limits

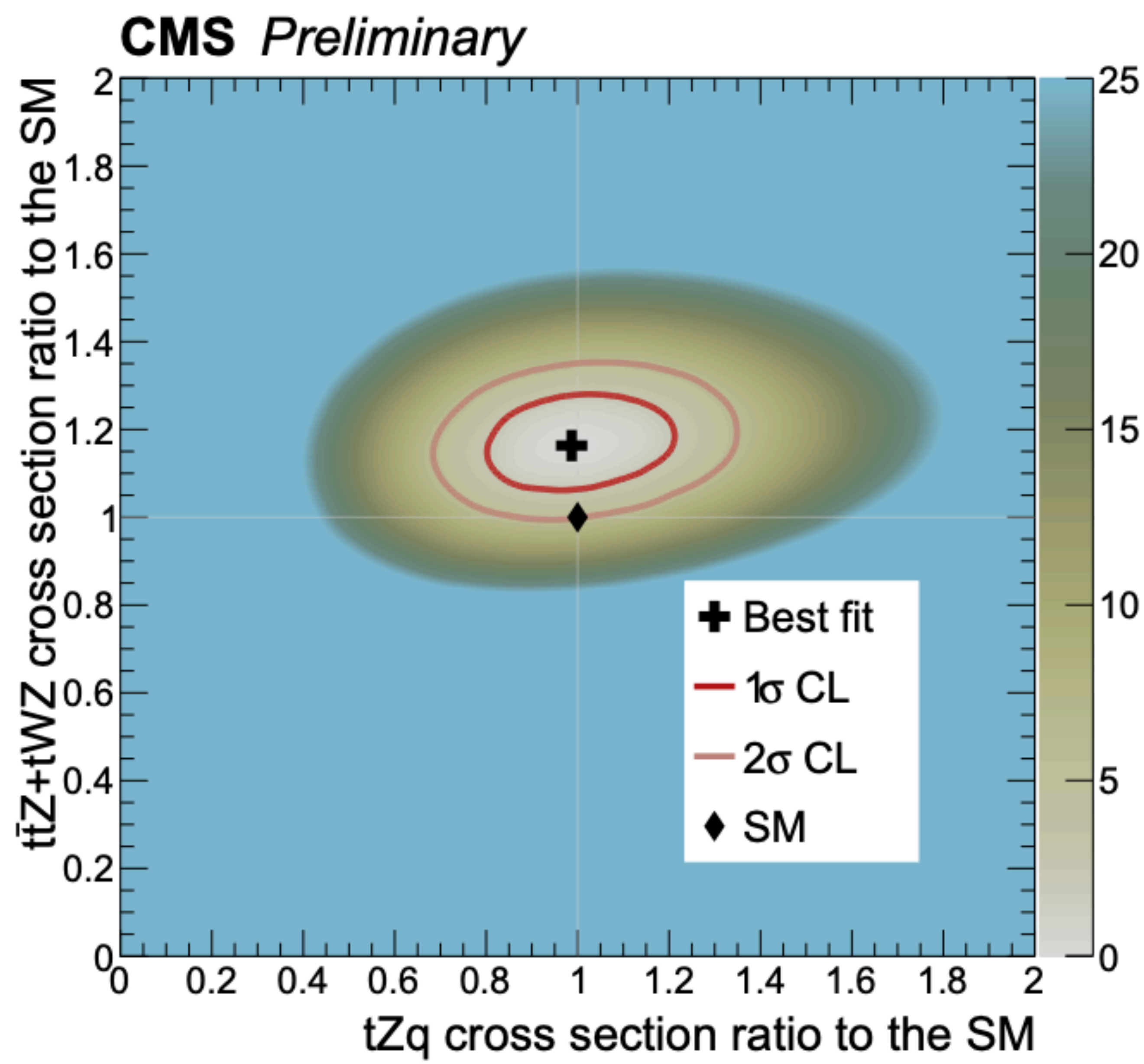




Bonus: Combined $t\bar{t}Z$, tWZ, tZq XS

CMS-PAS-TOP-23-004

- **First simultaneous measurement of $t\bar{t}Z + tWZ$ cross-section!**
- Target 3 lepton channel with Z mass window
- **DNN classifier to split events** into $t\bar{t}Z + tWZ$, tZq, and backgrounds
- **Add 4 lepton channel for inclusive measurement** to enhance $t\bar{t}Z$ signal
- **Combined XS in tension in SM** ($\sim 2\sigma$)

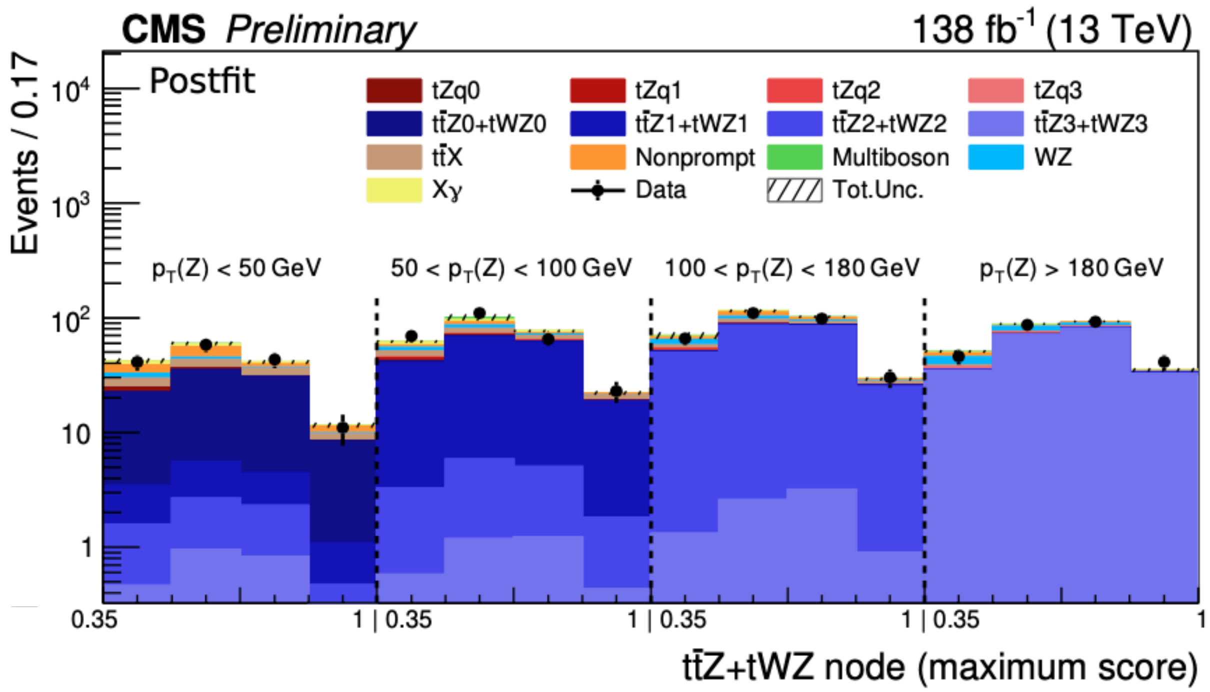


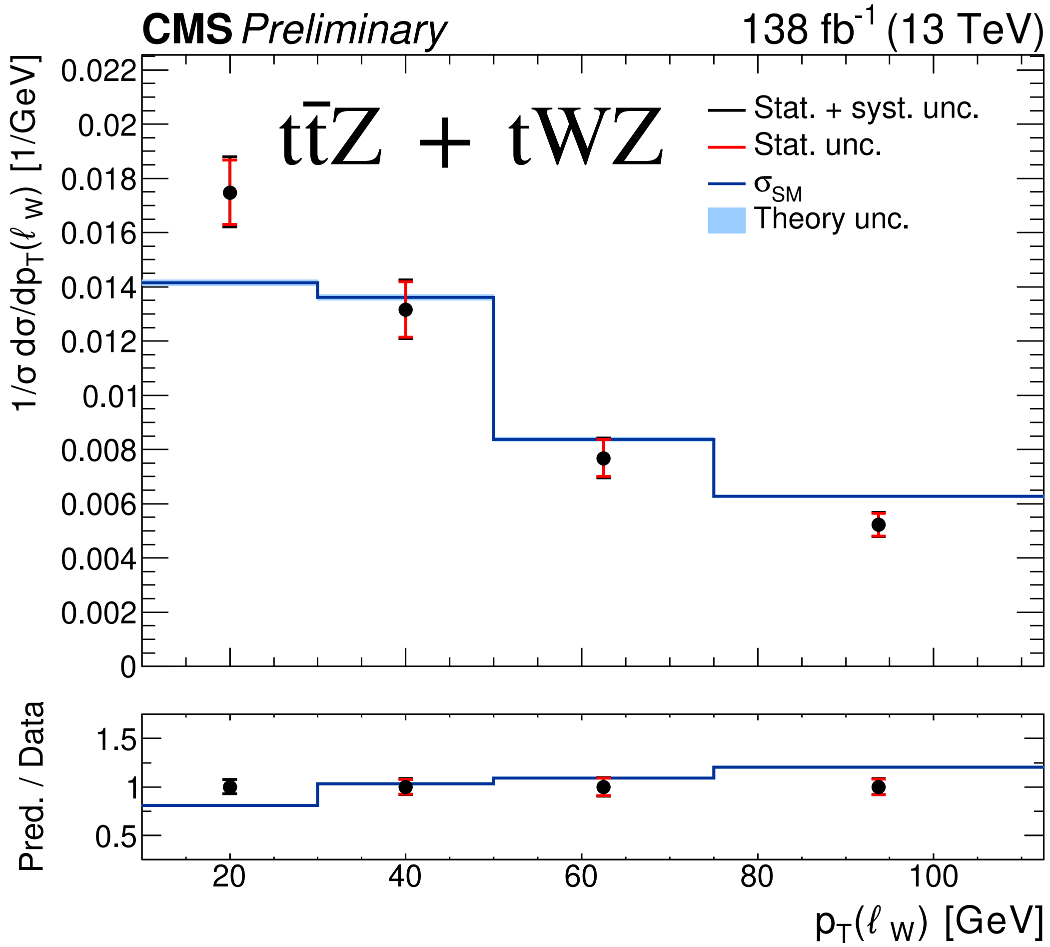
$\sigma_{t\bar{t}Z+tWZ} = 1.14 \pm 0.05$ (stat) $\pm\, 0.04$ (syst) pb

$\sigma_{tZq} = 0.81 \pm 0.07$ (stat) $\pm\, 0.06$ (syst) pb

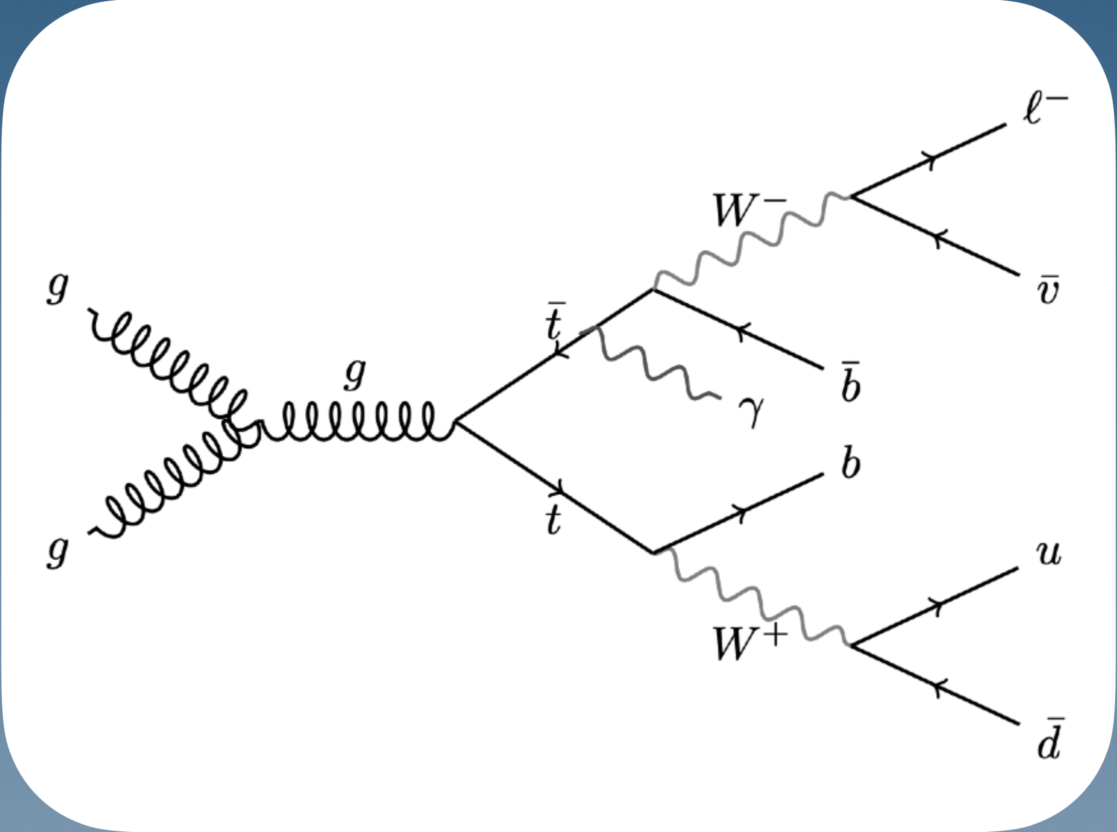
CMS-PAS-TOP-23-004

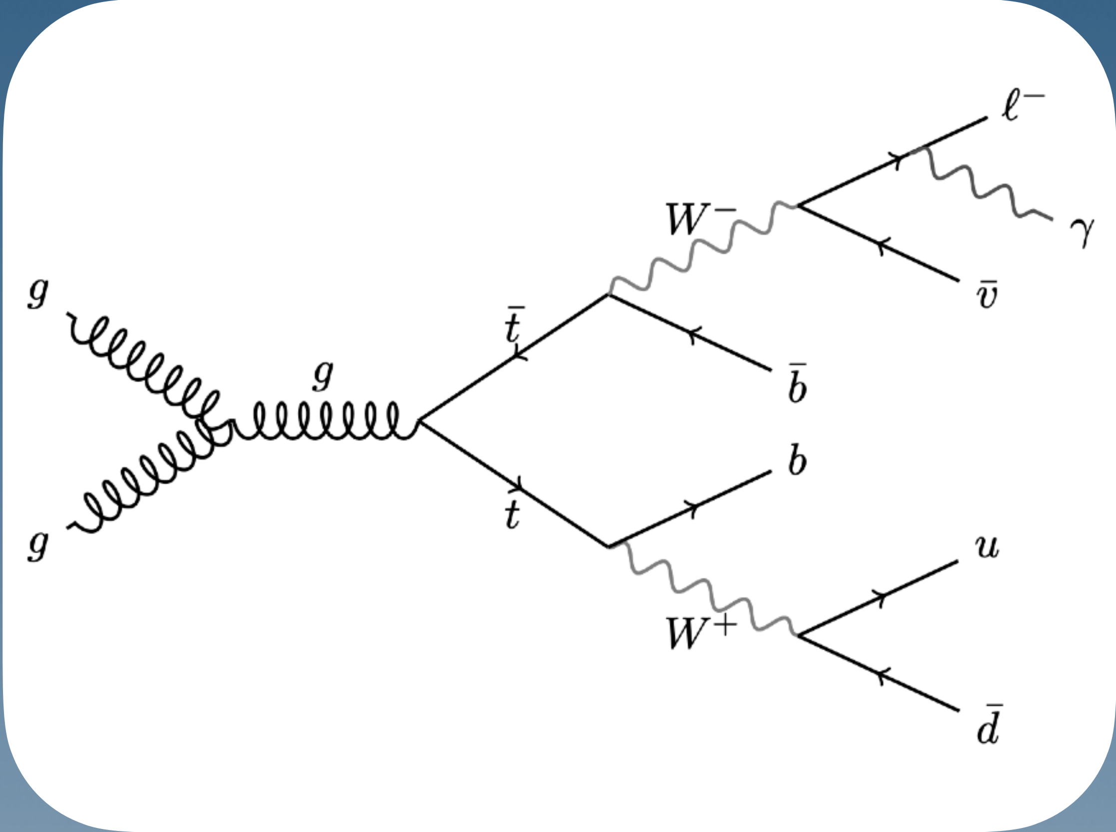
- Measure differential cross-sections at parton-level using profile likelihood unfolding
- Focus on **p_T and angular variables sensitive to EFT and QCD modelling**
- **Fit NN scores across observable bins**, further split signal by generator-level values
- **Increased tension with NLO predictions at low $p_T(\ell_W)$** (Momentum of lepton from W decay)
- Measurements are **statistically limited**



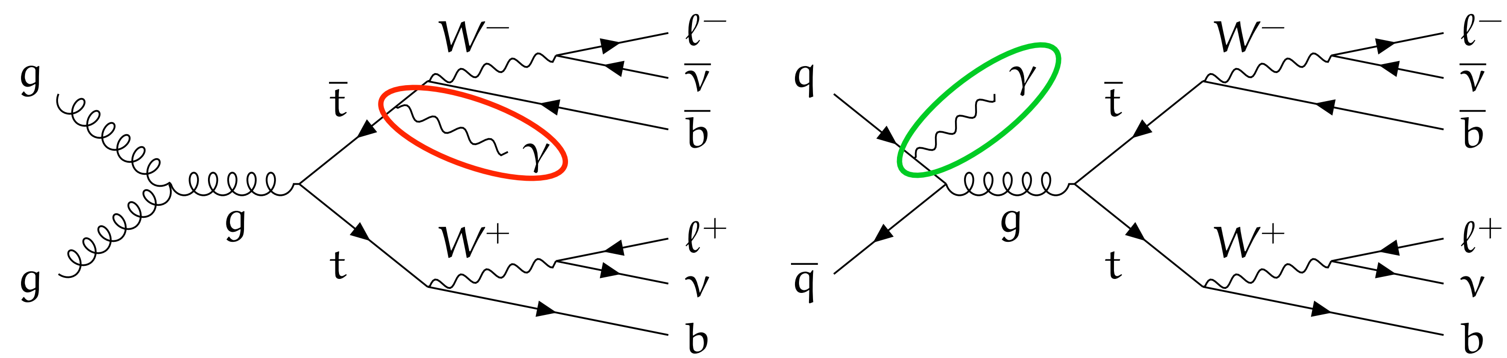


$t\bar{t}\gamma$



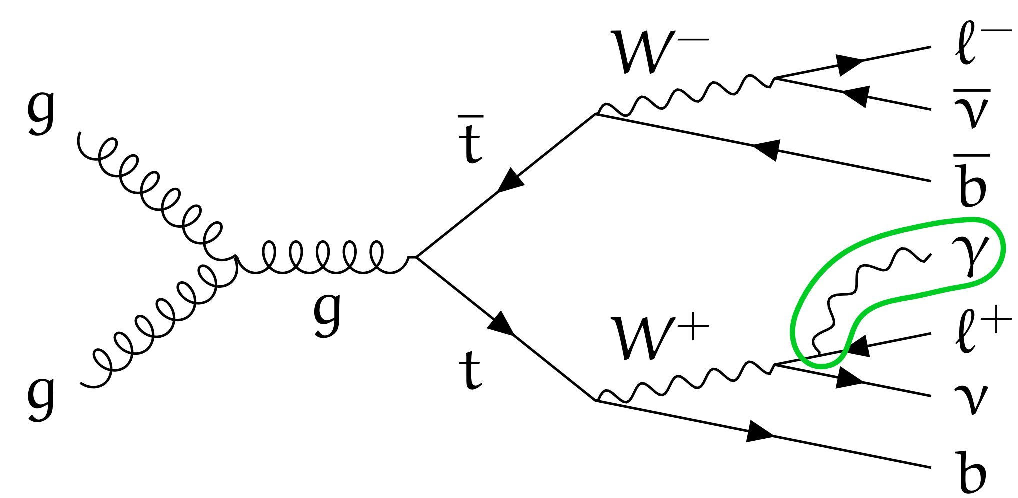


- Direct probe of $t\gamma$ electroweak coupling
- Main background for $tq\gamma$
- Sensitive to EFT operators related to top to anomalous dipole
- Complimentary to $t\bar{t}Z/tWZ$ EFT measurements



$t\bar{t}\gamma$ Production

Photon from **off-shell top-quark decay** or **initial-state radiation**



$t\bar{t}\gamma$ Decay

Photon from **final-state radiation**

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

$t\bar{t}\gamma$ common strategy

- Combined likelihood fit with targeted background-rich control regions
- Fiducial $t\bar{t}\gamma$ cross section measurements at particle-level
- EFT interpretation targeting EWK dipole operators

- JHEP 05 (2022) 091

- Targets events from all production and decay processes
- Combination with single-lepton measurement

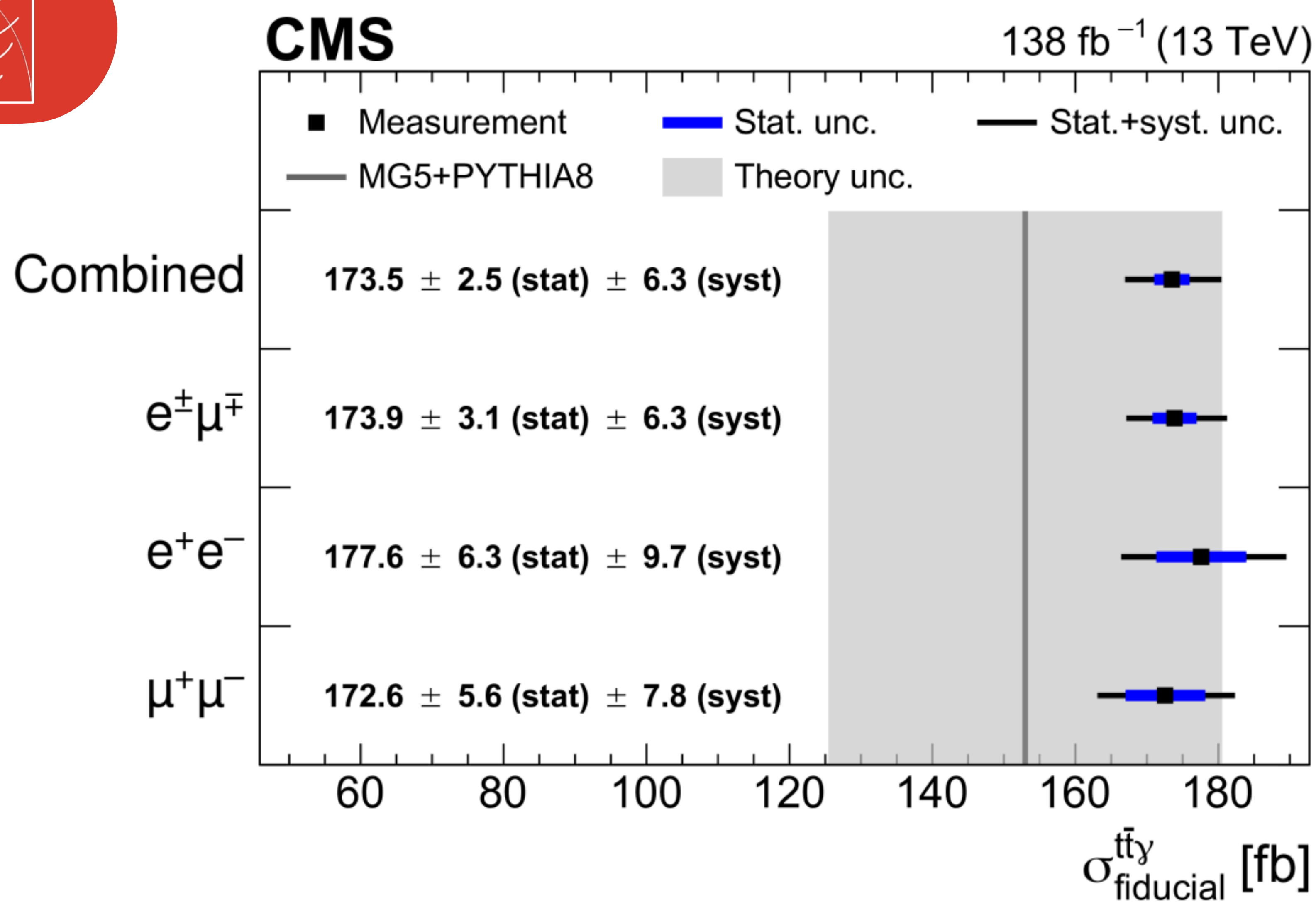
- arXiv:2403.09452 (submitted to JHEP)

- Target $t\bar{t}\gamma$ production only for first time
- Measurements in single-lepton and dilepton channels
- EFT combination with $t\bar{t}Z$

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

JHEP 05 (2022) 091

- 2 OS leptons, 1 photon, ≥1 b-jet
- Combined likelihood fit across 9 photon p_T bins in 3 lepton flavour channels
- Measurement of fiducial cross-sections **in agreement with SM predictions**
- Dominant uncertainties: **Luminosity and signal modelling**



$$\sigma_{\text{fid}}(pp \to t\bar{t}\gamma) = 175.2 \pm 2.5\ \text{(stat)} \pm 6.3\ \text{(syst) fb}$$

$$\sigma_{\text{SM}}^{\text{LO}\ (2\to7)}(pp \to t\bar{t}\gamma) = 155 \pm 27\ \text{fb}$$ (Normalised using NLO K-factor)

MadGraph5_aMC@NLO **(LO production+decay)**

$t\bar{t}\gamma$ common strategy

- Combined likelihood fit with targeted background-rich control regions
- Fiducial measurement to capture contributions from production and decay processes
- EFT interpretation targeting EWK dipole operators

CMS

- JHEP 05 (2022) 091

- Targets events from all production and decay processes
- Combination with single-lepton measurement

ATLAS

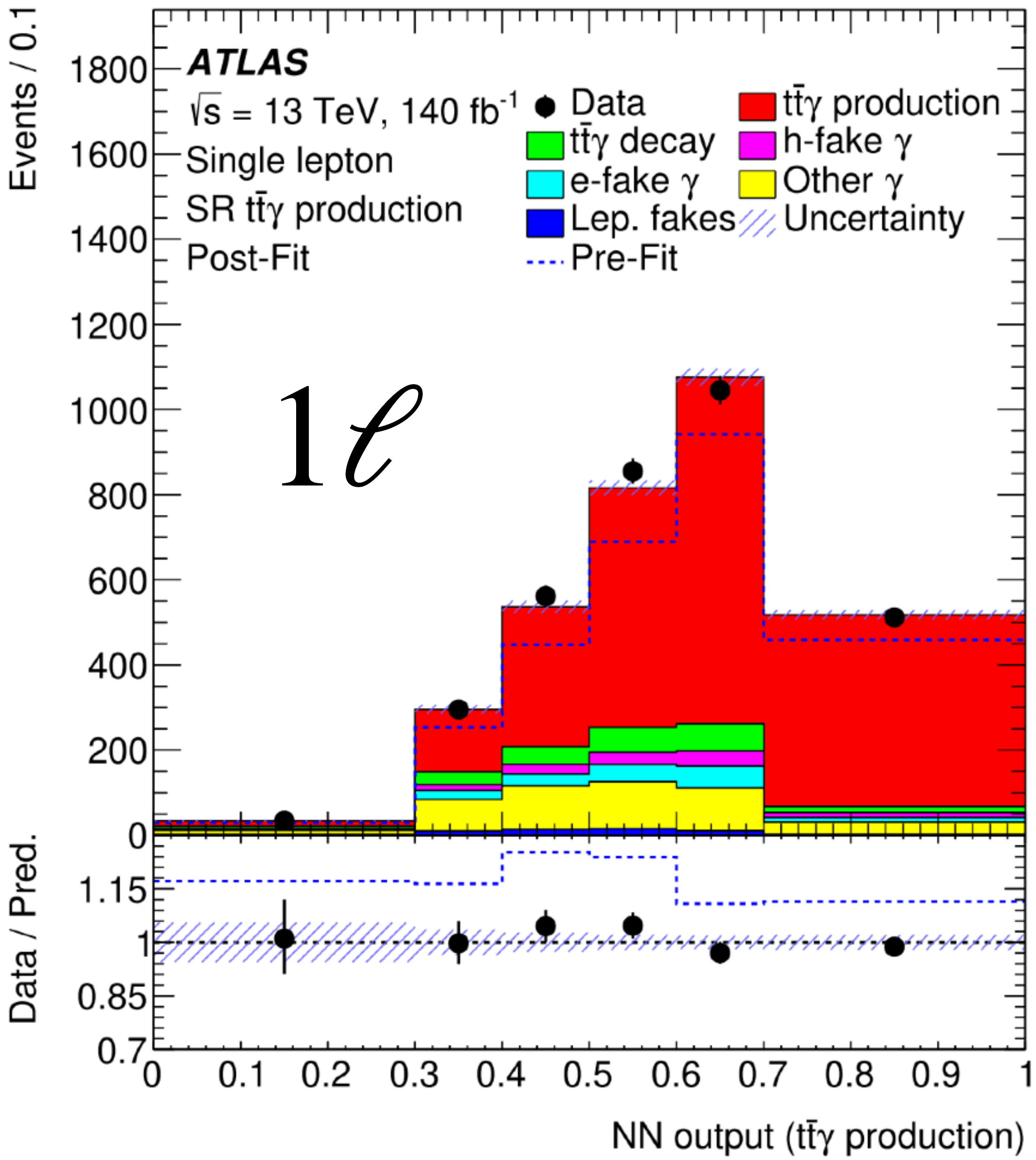
- arXiv:2403.09452
  (submitted to JHEP)

- Target $t\bar{t}\gamma$ production only for first time
- Measurements in single-lepton and dilepton channels
- EFT combination with $t\bar{t}Z$

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

arXiv:2403.09452

- Single-lepton and dilepton opposite-sign channels
- Target **$t\bar{t}\gamma$ production-only** processes to enhance $t\gamma$ coupling
- Single-lepton: **4-class NN** to separate: $t\bar{t}\gamma$ production, $t\bar{t}\gamma$ decay, fake-photon, and prompt-photon backgrounds
- Dilepton: **Binary NN** to separate signal from background
- Combined fit in single-lepton channel over 1 signal region and 3 control-regions from NN output and NN output in dilepton channel
- Dominant uncertainties: **Signal modelling**, **background normalisation**



$$\sigma_{\text{fid}}(t\bar{t}\gamma\,\text{production}) = 322 \pm 5\ \text{(stat)} \pm 15\ \text{(syst) fb}$$

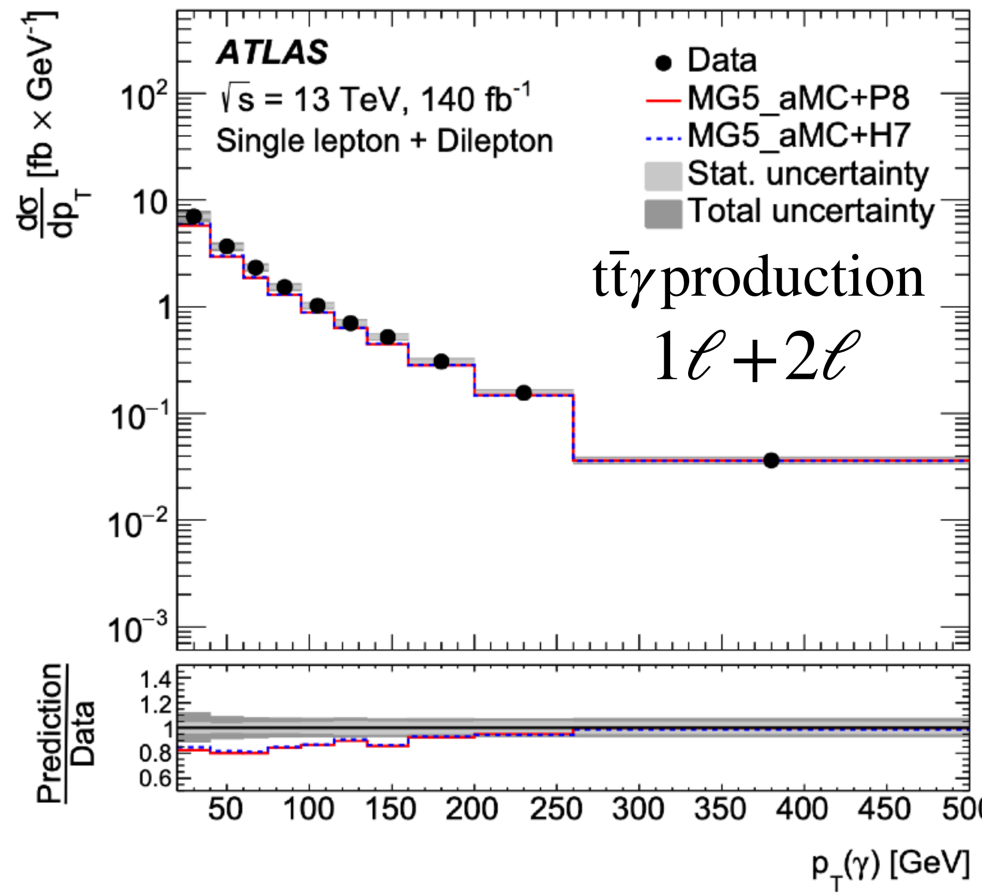
$$\sigma_{\text{SM}}^{\text{NLO }(2\to3)}(t\bar{t}\gamma\,\text{production}) = 299^{+29}_{-30}\ \text{(scale)}^{+7}_{-4}\ \text{(PDF) fb}$$

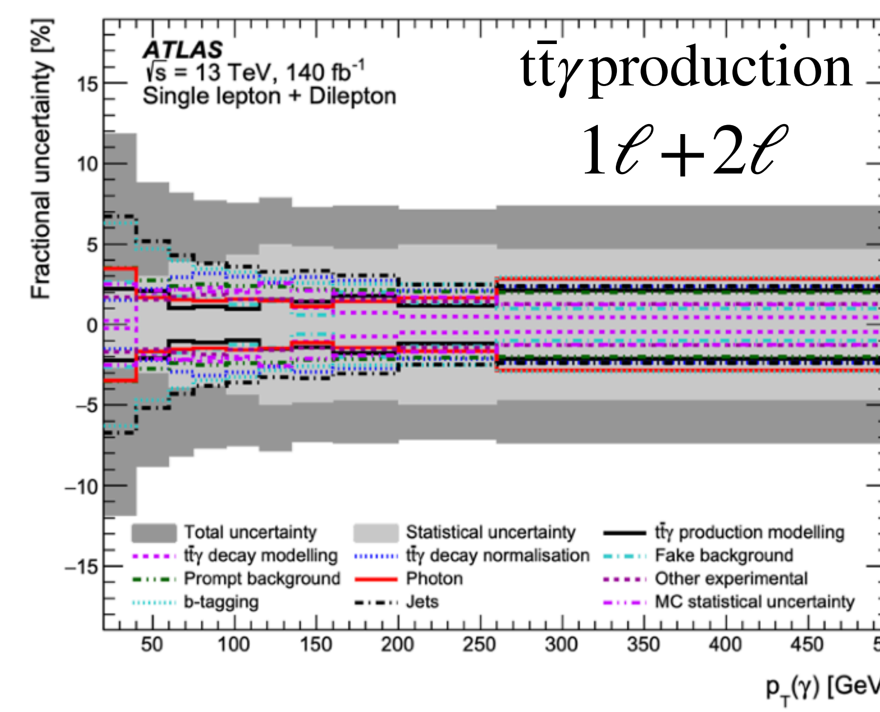
MadGraph5_aMC@NLO **(NLO production only)**

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

arXiv:2403.09452

- Differential cross-sections measured **separately in both channels and combined**
- Profile likelihood unfolding
- Measure XS in terms of kinematics and angular differences of leptons and jets in events
- Generally, **good agreement with SM**
- Reduced uncertainties in normalised fits due to systematic cancellations
- **Statistically limited** in most regions





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

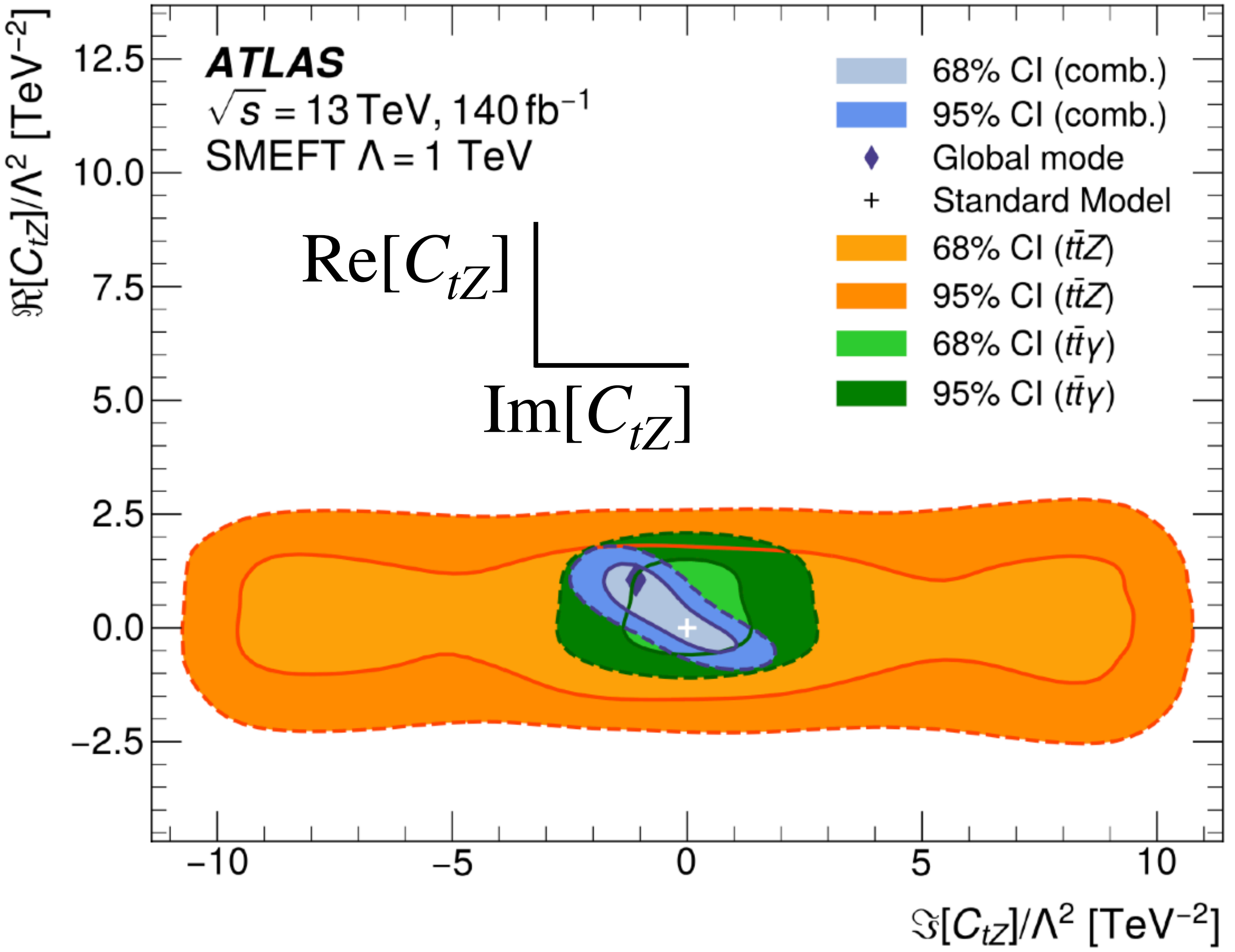
arXiv:2403.09452 ATLAS EXPERIMENT

- EFT interpretation using **photon p_T**
- Limits on **dipole operators C_{tB} and C_{tW}**
- Rotate basis to extract C_{tZ} and $C_{t\gamma}$:

$$C_{tZ} = c_W \cdot C_{tW} - s_W \cdot C_{tB},$$
$$C_{t\gamma} = s_W \cdot C_{tW} + c_W \cdot C_{tB}.$$

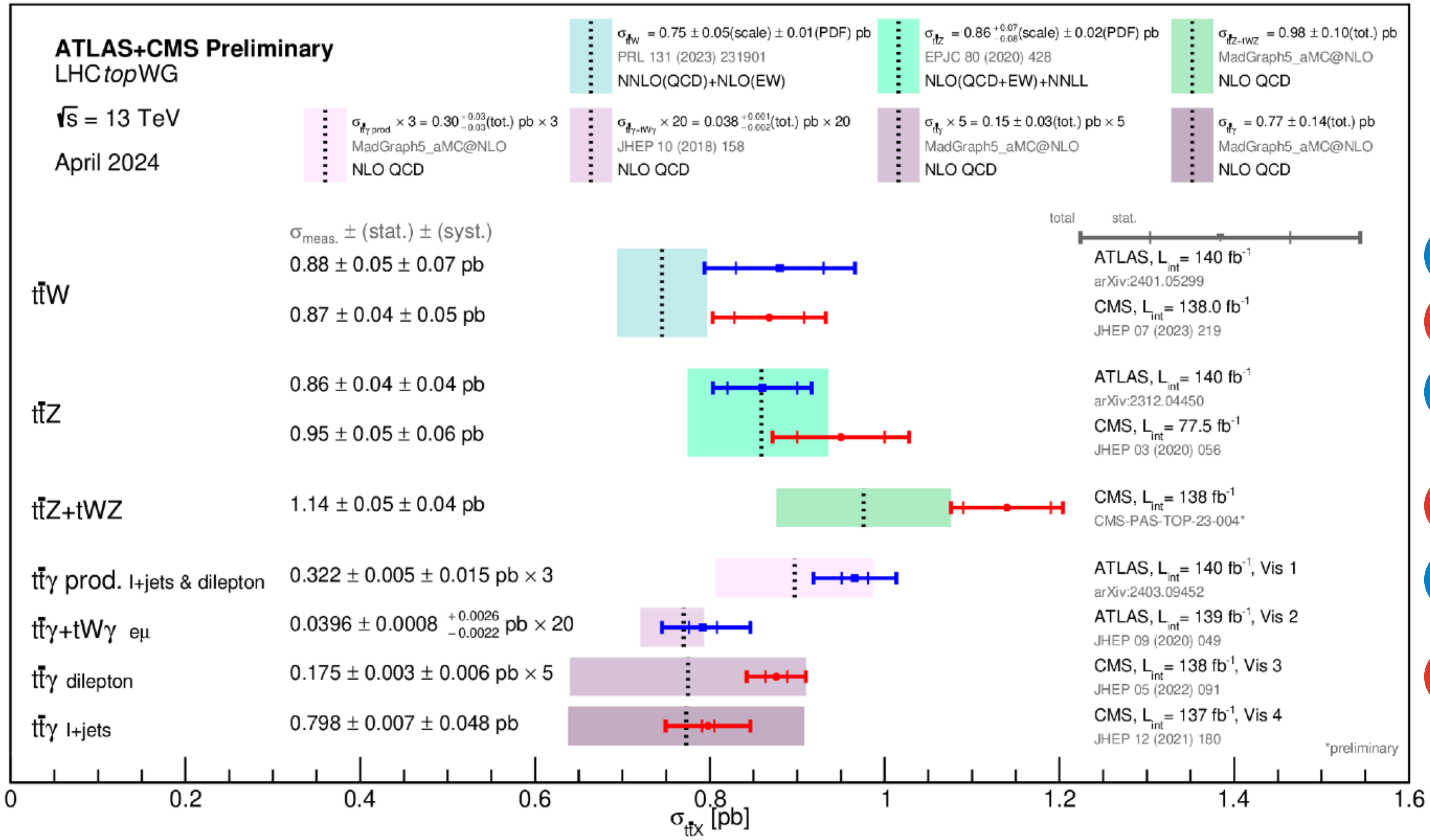
- **EFT fit from simultaneous measurement of photon and Z p_T** (arXiv: 2312.04450)
- Reduces independent limits on C_{tW}
- Combination **resolves degenerate structure** present in separate $t\bar{t}Z$ and $t\bar{t}\gamma$ results

Wilson coefficient		95% CI (obs.) $t\bar{t}\gamma$	95% CI (obs.) $t\bar{t}\gamma + t\bar{t}Z$	Best-fit
$\Re[C_{tW}]$	$O(\Lambda^{-4})$ (marg.)	[−1.2, 2.8]	[−1.2, 2.5]	1.73
	$O(\Lambda^{-4})$ (indep.)	[−0.74, 0.78]	[−0.56, 0.60]	0.01
$\Im[C_{tW}]$	$O(\Lambda^{-4})$ (marg.)	[−1.7, 1.7]	[−1.8, 1.2]	−0.96
	$O(\Lambda^{-4})$ (indep.)	[−0.78, 0.76]	[−0.60, 0.58]	−0.01



Conclusion

- **Wide array of $t\bar{t}X$ processes measured** at both ATLAS and CMS!
  - More data and advanced analysis methods leading to **more precise results!**
- More **stringent limits on new physics** achieved through EFT combinations
  - Thus far bother experiments observe generally good agreement with SM
- Inclusive measurements now largely systematically limited
  - Differential results remain statistically limited **- Expect improvements in Run 3!**



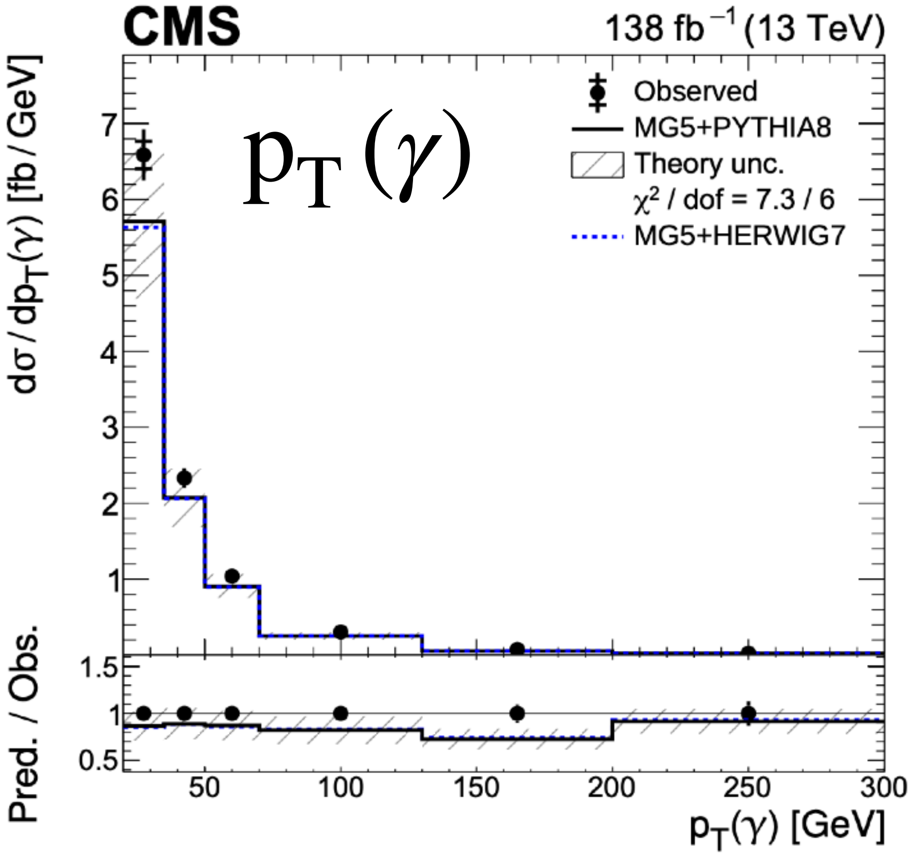
[arXiv:2401.05299](ATLAS)
[JHEP 07 (2023) 219](CMS)
[arXiv:2312.04450](ATLAS)
[CMS-PAS-TOP-23-004](CMS)
[arXiv:2403.09452](ATLAS)
[JHEP 05 (2022) 091](CMS)

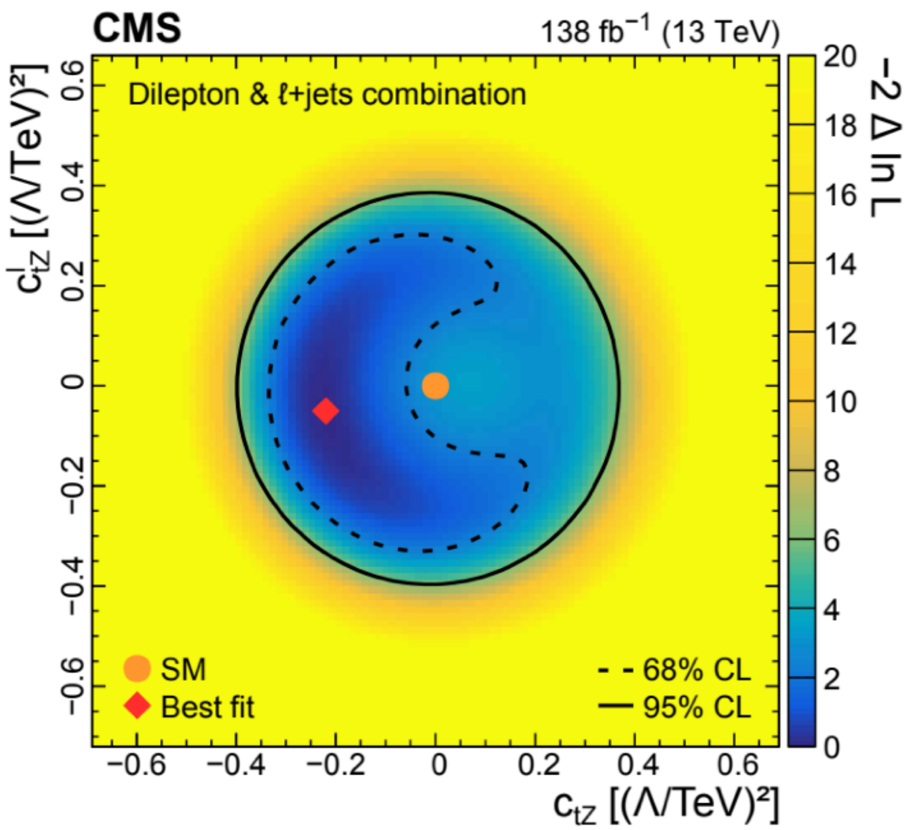
Backup

$t\bar{t}\gamma$ Differential/EFT interpretation

JHEP 05 (2022) 091

- **Differential XS** measured in terms of kinematics and angular differences of leptons and jets in events
- Use matrix inversion without regularisation to unfold
- Generally, **good agreement with SM**
- **Predict smaller angles than measured**, likely due to missing diagrams in LO prediction





- Probe EFT limits on operator affecting **tZ vertex** using **photon p_T distribution**
- Perform combined EFT fit with lepton+jets measurement (JHEP 12 (2021) 180)
- **Most stringent bounds to-date** on C_{tZ} and C^I_{tZ}

$$C_{tZ} \text{ (marg. } 95\%) = [-0.36, 0.31]$$
$$C^I_{tZ} \text{ (marg. } 95\%) = [-0.36, 0.35]$$