# Associated production of $tX$ and $t\bar{t} + X$, including their EFT interpretation

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On behalf of the ATLAS Collaboration

SM@LHC2025, Durham
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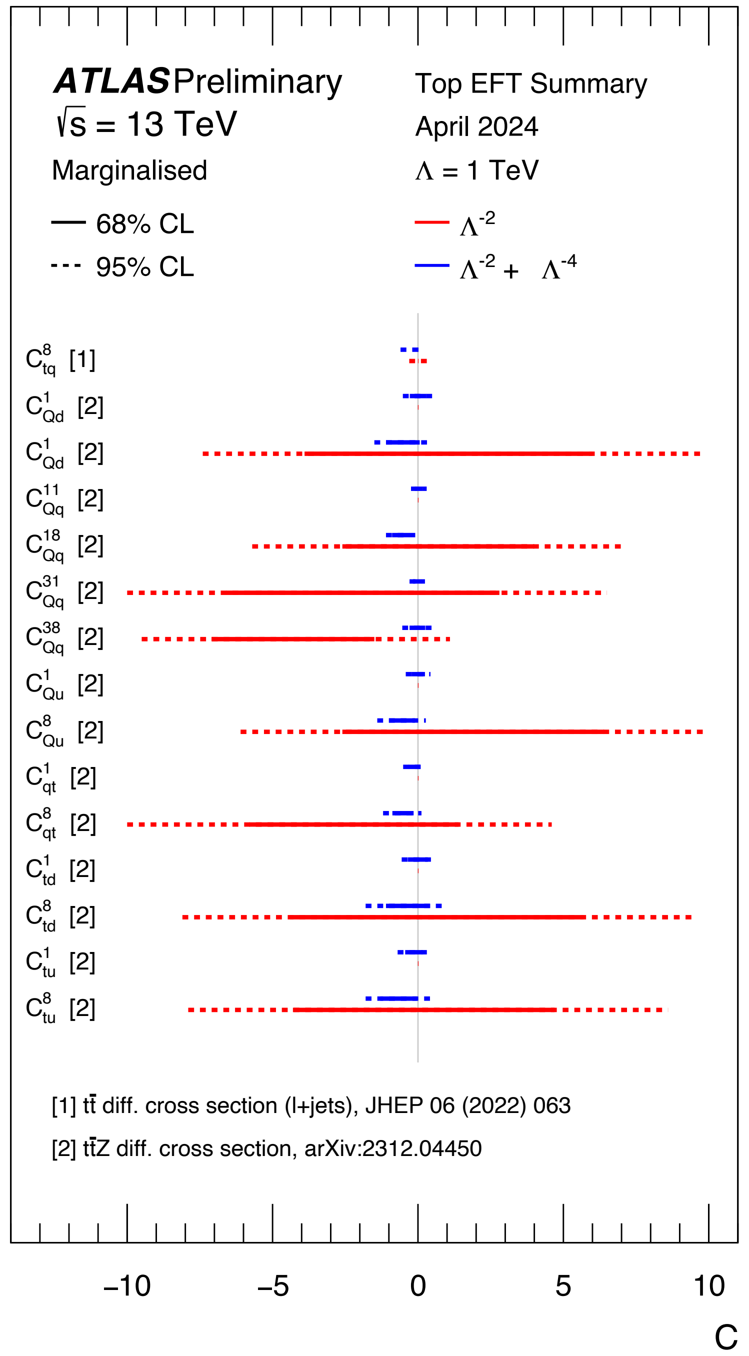
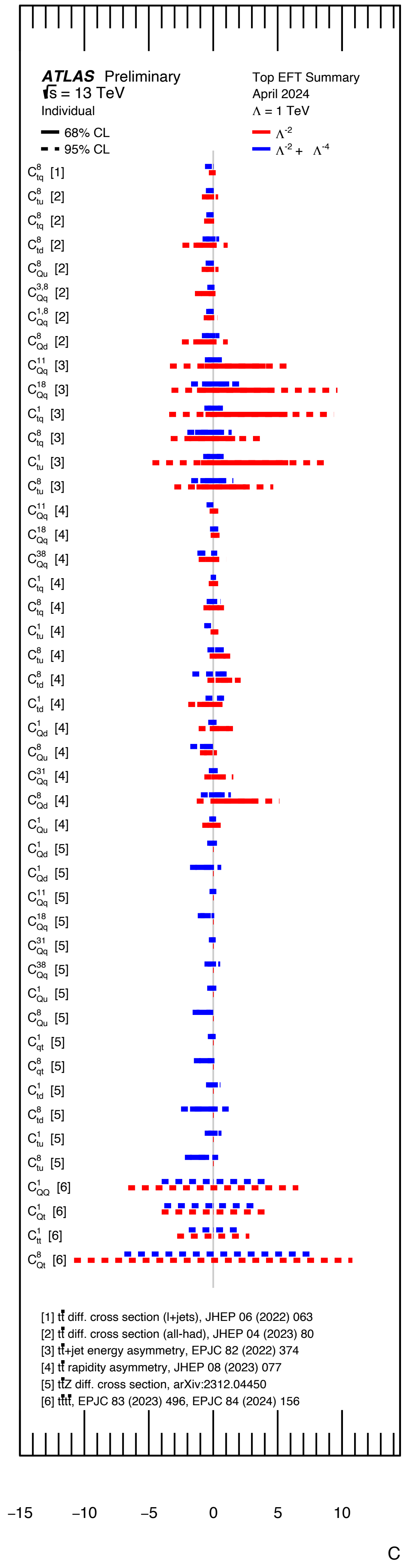
# ATLAS $tX$ and $t\bar{t} + X$

- ATLAS explores a rich programme of top-phillic measurements and searches.
- Provides complementary sensitivity to physics within the SM and beyond.
  - This talk shall highlight work on the following associated productions of top quarks using Run 2 measurements:
    - $t\bar{t}W$ production cross-sections
    - $t\bar{t}Z$ production cross-sections
    - $t\bar{t}\gamma$ production cross-sections
    - *Search for same-sign top pair production
    - *$t\bar{t}l^+l^-$ production measurement
      - *Also discussed in Maryam's talk yesterday

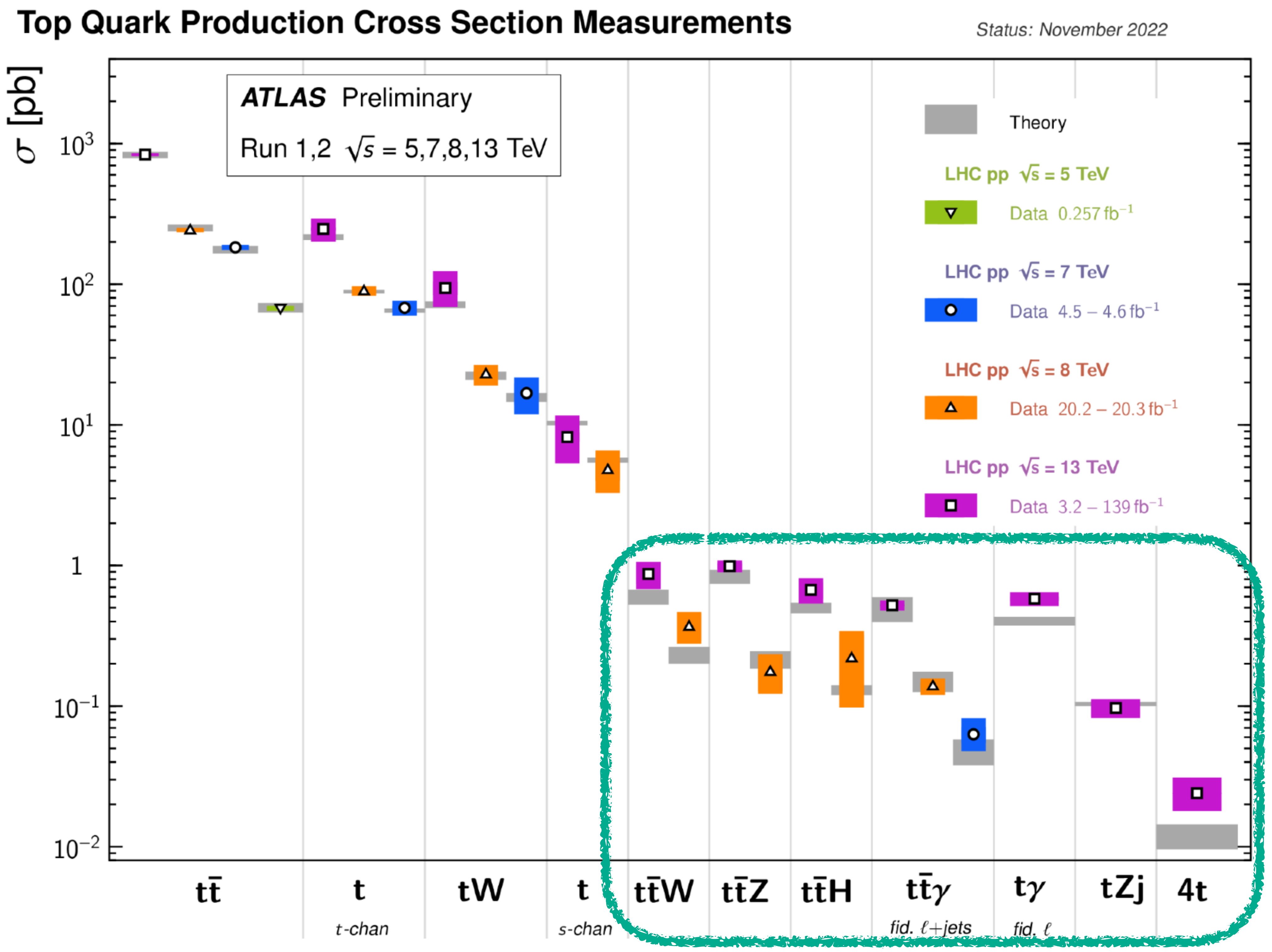



ATL-PHYS-PUB-2024-004

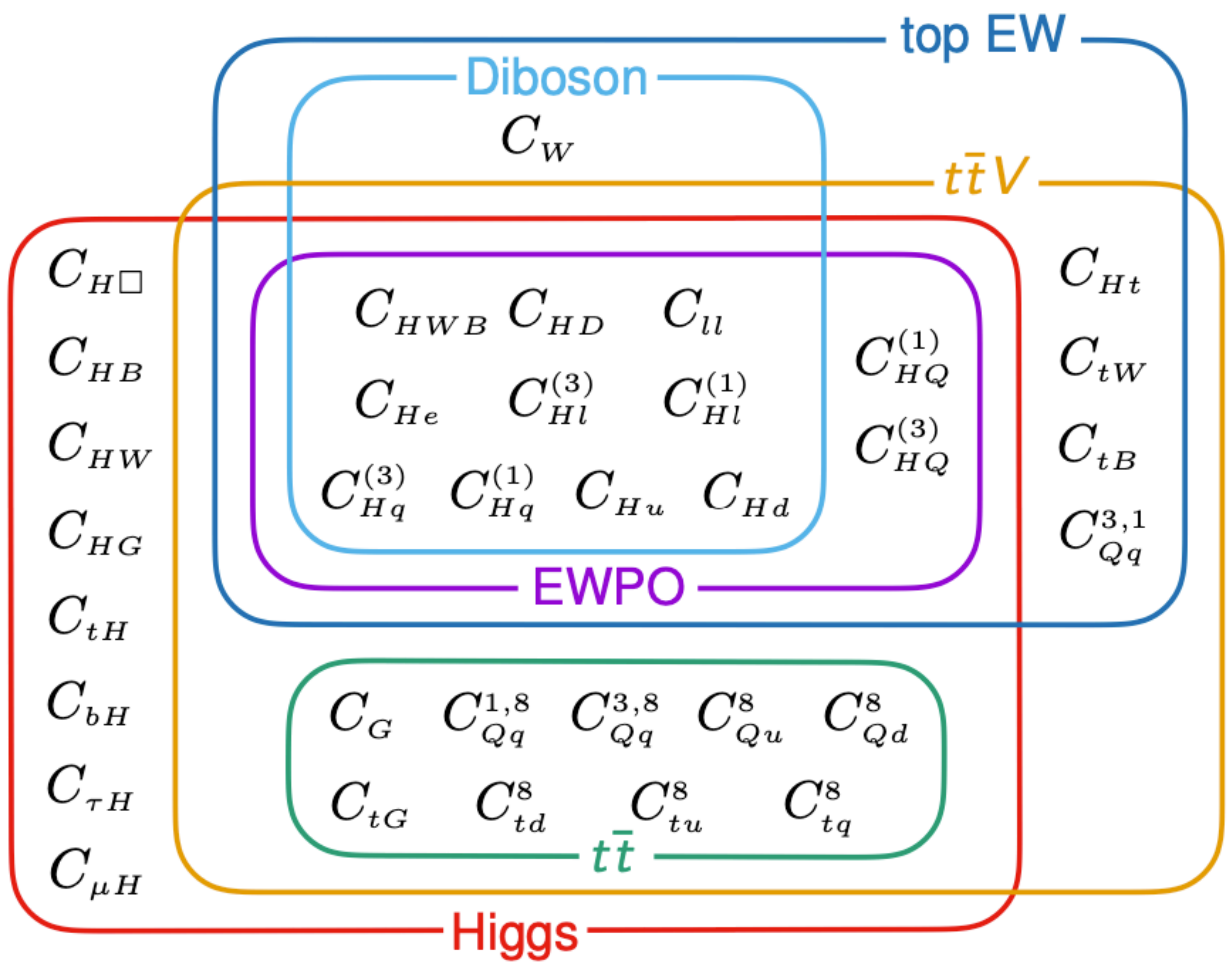
# Probing top quarks & EFT

- Rare associated production of top quarks are sensitive to various physics insertions:




ATL-PHYS-PUB-2022-051

- Probe of EW physics
- Higgs portal
- High-energies for observing massive BSM contributions
- Top EW sector is a strong probe of complementary EFT operators to other programmes at the LHC.



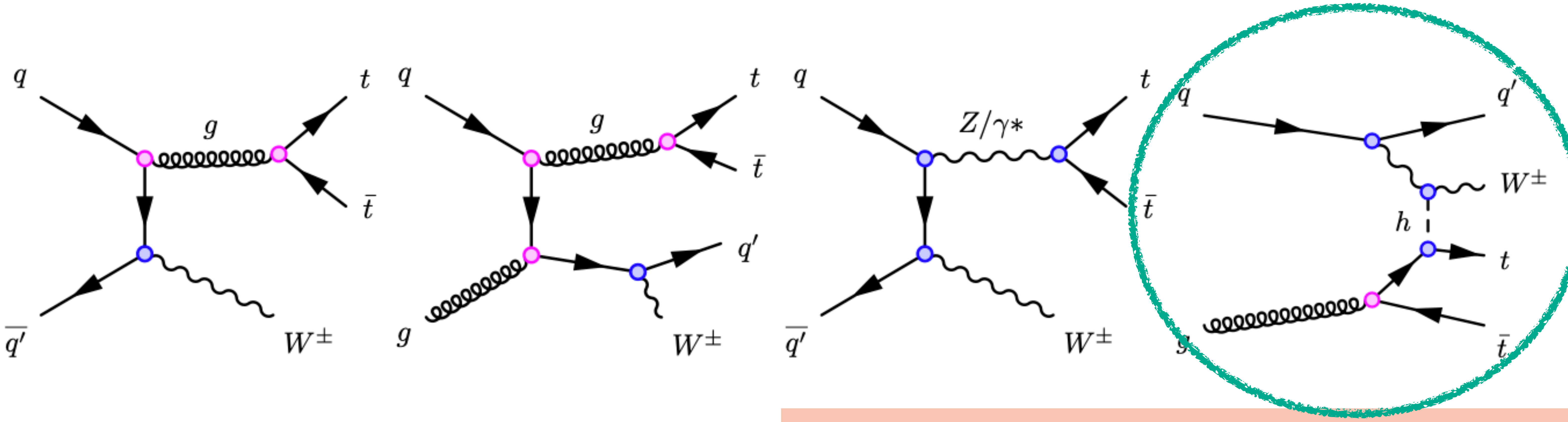

*JHEP* ***04*** *(2021) 279.*

# $t\bar{t}W$ production cross-sections

JHEP 05 (2024) 131.

- A rare associated top process which is a dominant background in SS dilepton searches.
- Understanding of $t\bar{t}W$ modelling is one of the key limitations on measurement.
- LO initial state sensitive to PDFs and complex QCD & EWK corrections.
    - Consequences: **charge-asymmetric** production & $tW$-scattering (could probe EFT)
- Measures inclusive cross-section and asymmetry in a maximum-likelihood fit.
- **First measurement of particle-level differential cross-sections at the LHC** using profile likelihood unfolding:

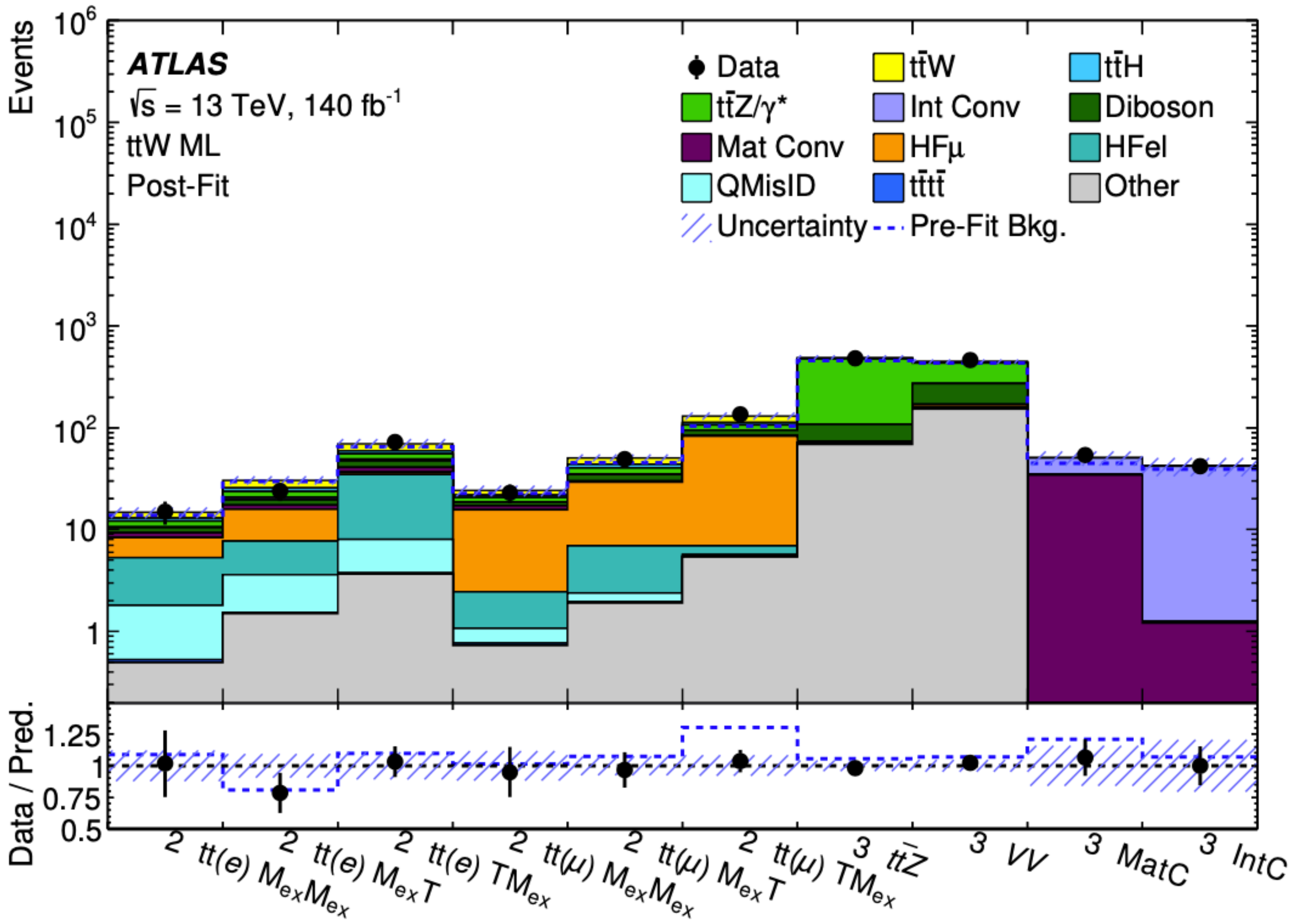
Choice of six variables motivated by theory or previously observed discrepancies.



# $t\bar{t}W$ production cross-sections

[JHEP 05 (2024) 131.](#)

- Events used in this analysis are selected using high-efficiency dilepton triggers & must be trigger matched (~82% for signal events satisfying preselection):
  - They must have at least one primary vertex candidate & two leptons passing a tight isolation requirement.
- Categorisation into $2lSS$ and $3l$ SRs reduces migration of $3l$ $t\bar{t}W$ events into $2l$ (reconstruction inefficiencies).




Good closure shown for fit-derived background norm factors:

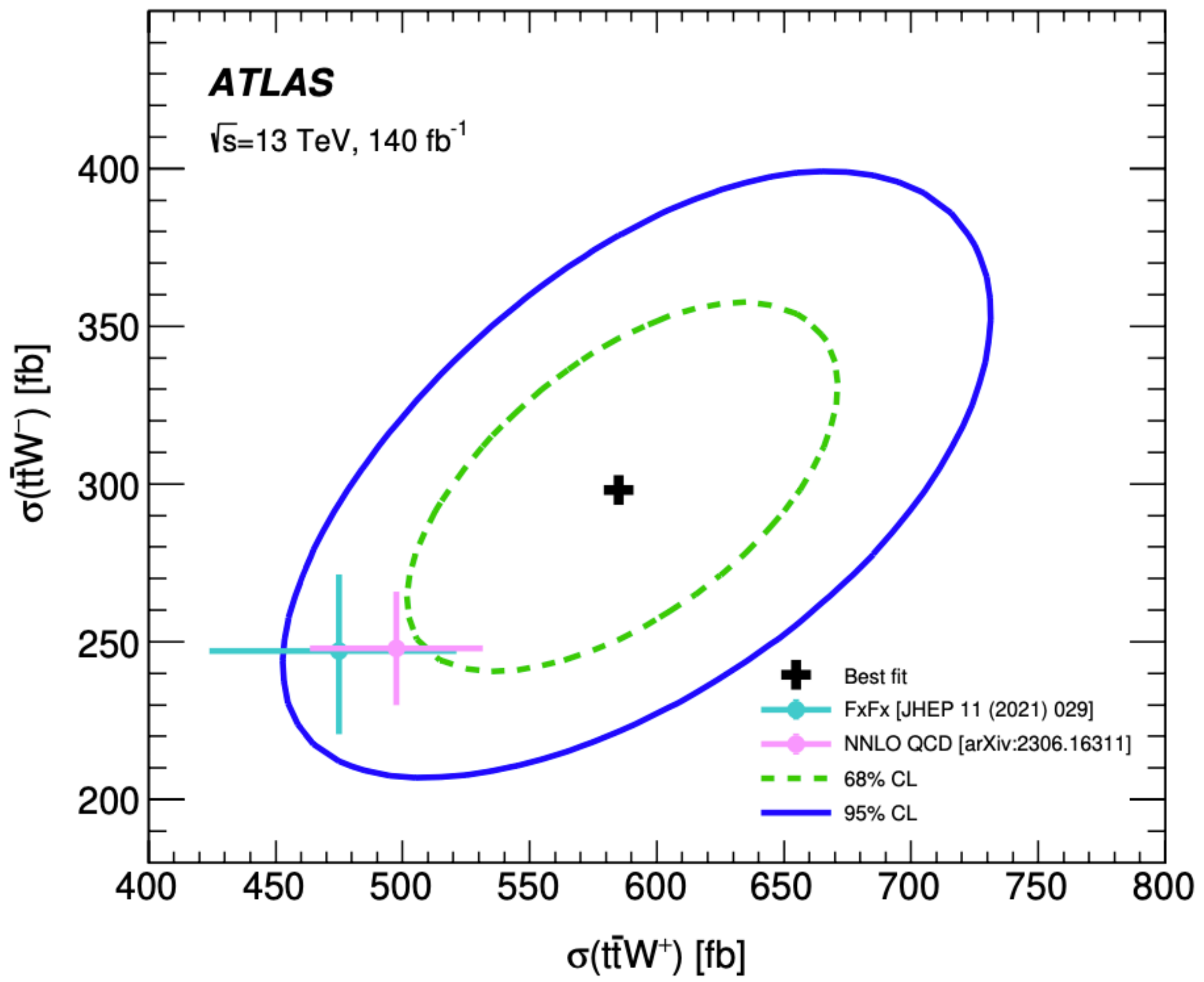
- **Dominated by $t\bar{t}Z$ & diboson** - CRs use on-shell-$Z$ OSSF pair.
- Inversion of selection on $3l$ invariant mass used in CRs for electron conversions.
- CRs for HF non-prompt leptons must have two leptons passing looser isolation requirement.

Additional data-driven corrections applied to $t\bar{t}$ and $VV$ kinematics to better model the data.

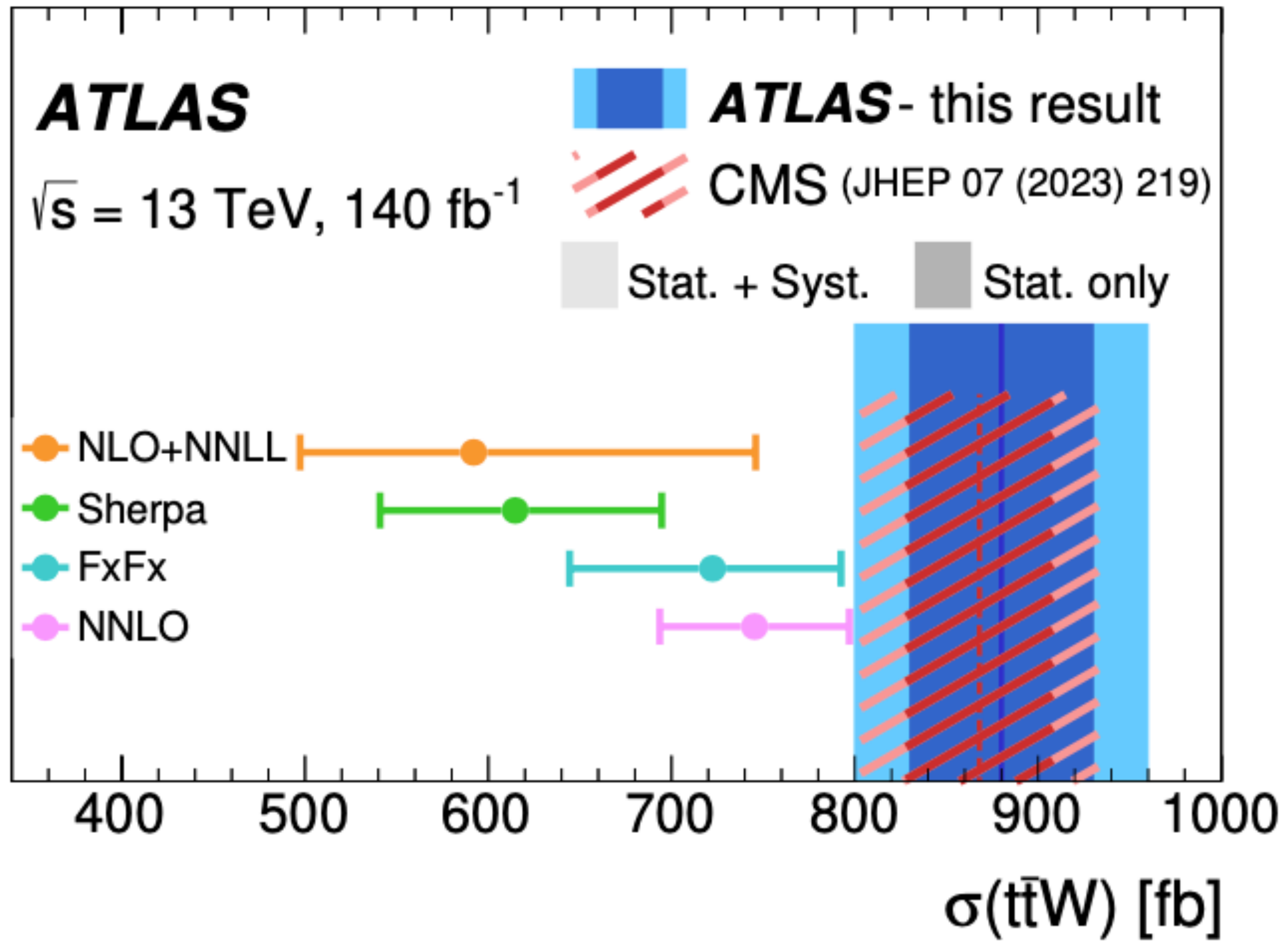
# $t\bar{t}W$ production cross-sections

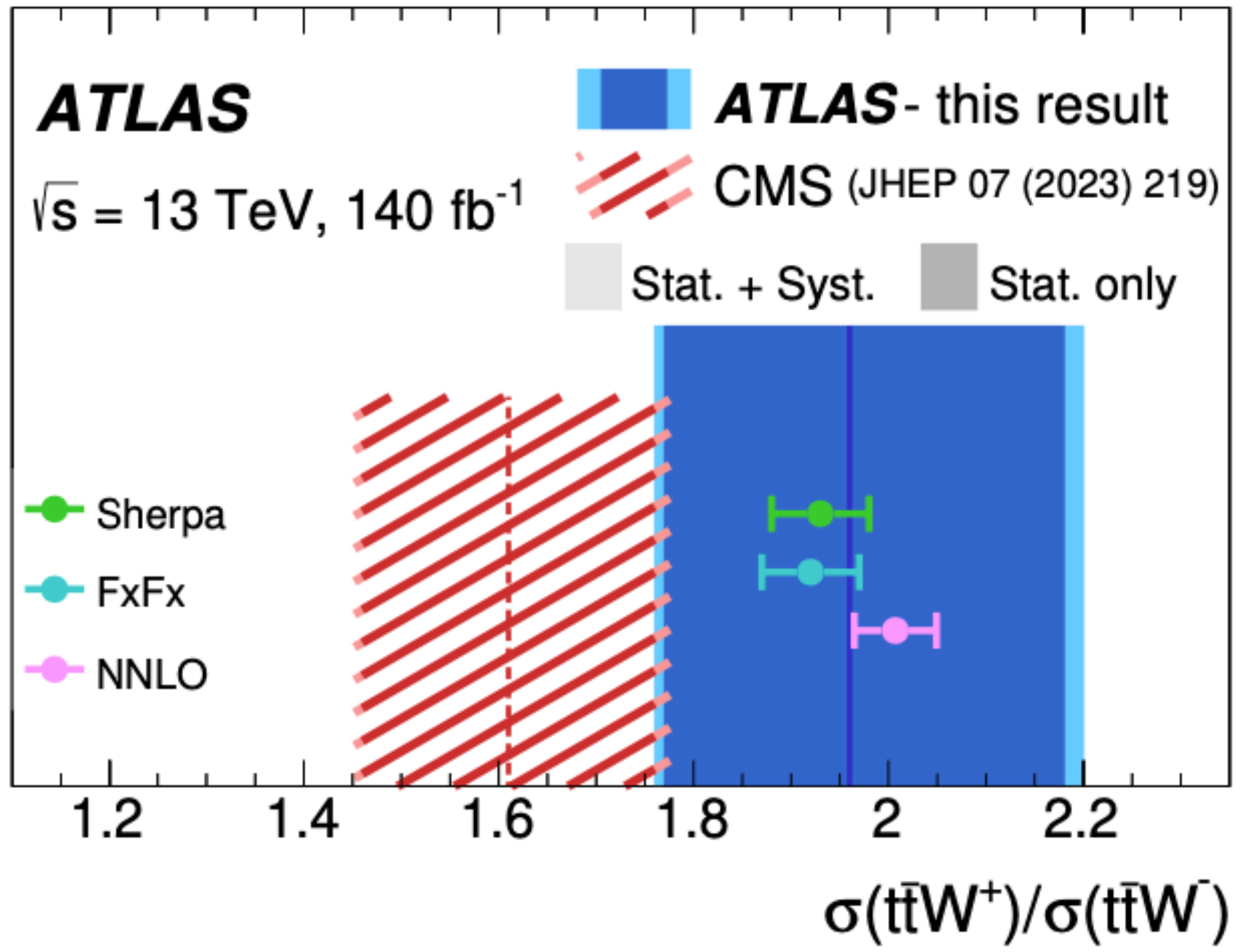
JHEP 05 (2024) 131.

- Uncertainty on results of maximum likelihood fit dominated by $t\bar{t}W$ signal modelling and prompt-lepton background normalisation.
- Inclusive cross-section measurement compatible with SM NNLO at a level of $1.4\sigma$.




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




- 58% correlation between $t\bar{t}W^{+/-}$

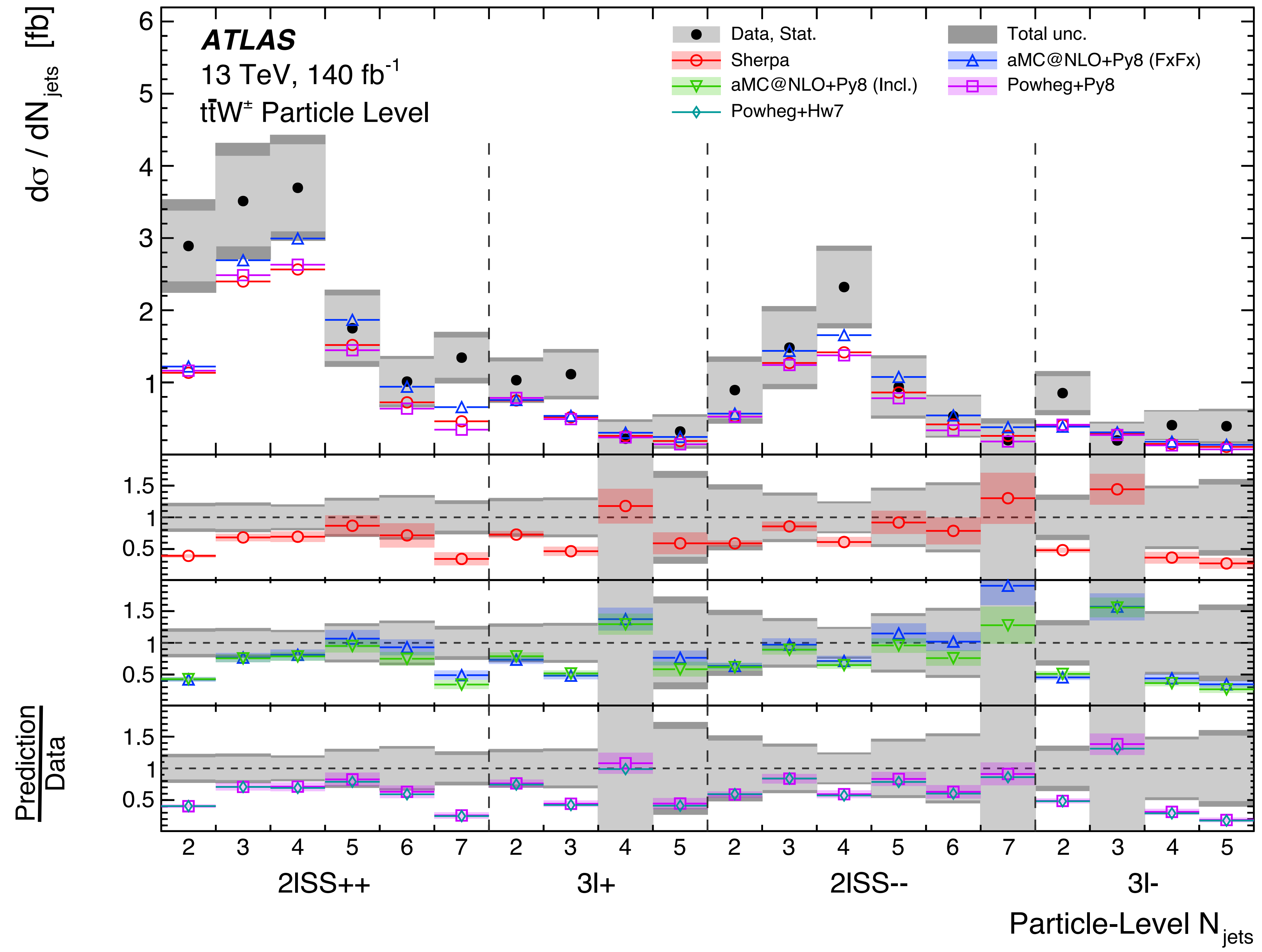
$$\sigma(t\bar{t}W^{+}) = 583 \pm 58 \text{ fb}$$
$$\sigma(t\bar{t}W^{-}) = 296 \pm 40 \text{ fb}$$

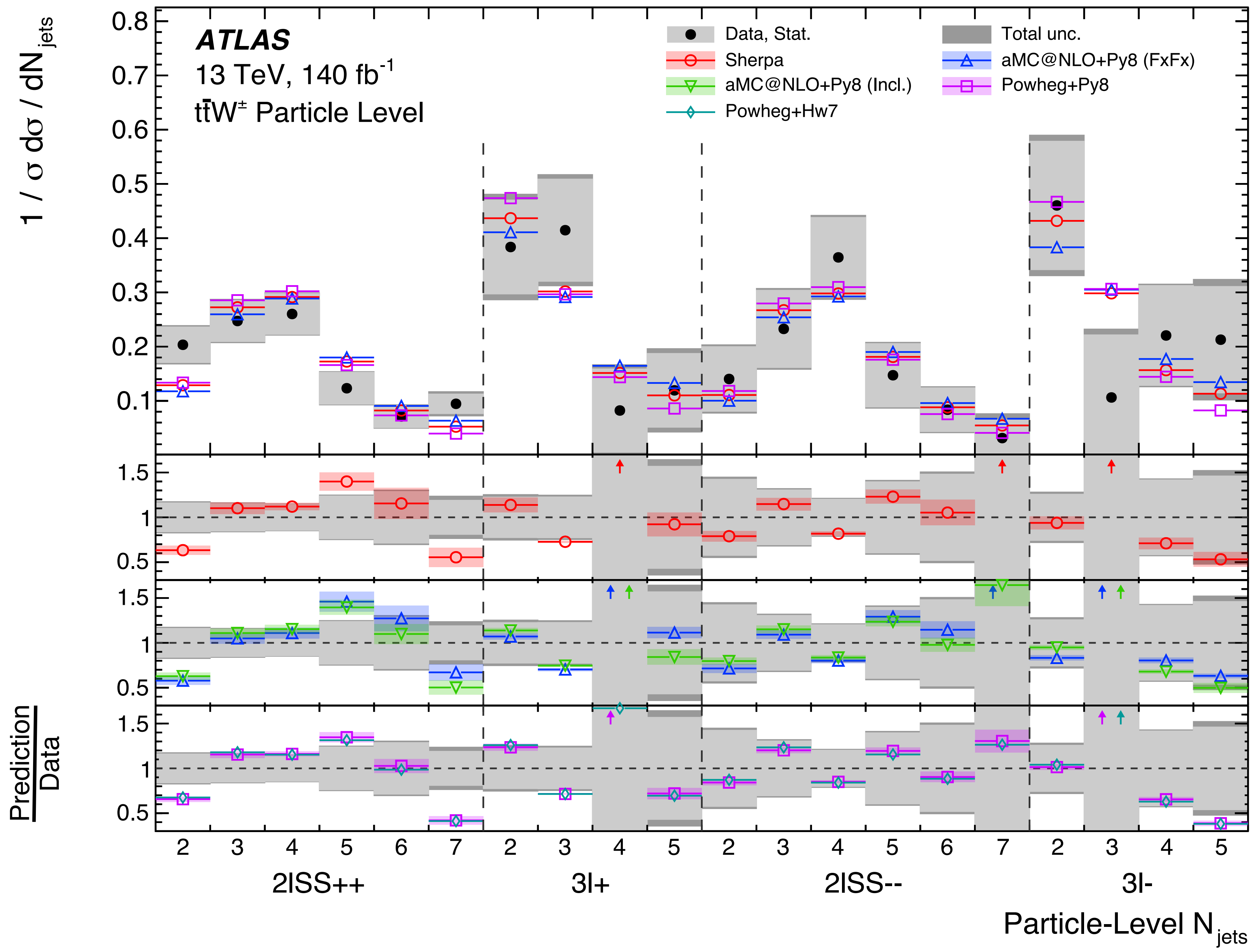
- Asymmetry measurement: $0.33 \pm 0.05$
- SHERPA 2.2.10 MEPS@NLO:

$$0.322 \pm 0.003 \pm 0.007(\text{scale}) \pm 0.003(\text{PDF})$$

# $t\bar{t}W$ production cross-sections

[JHEP 05 (2024) 131.](#)




Theory predictions generally agree well with normalised differential cross-section results

- At high jet multiplicities, predictions using NLO (FxFx) merging are in better agreement than NLO+PS from Powheg.
- Disagreement in cross-sections at lower jet multiplicities is independent of NLO merging vs NLO+PS modelling.

# $t\bar{t}Z$ production cross-sections

JHEP 07 (2024) 163.

- The coupling of the $Z$-boson to the top quark is still not well-constrained by the available data but is significantly modified by BSM physics.
- $t\bar{t}Z$ is a irreducible background in other rare-top analyses such as $t\bar{t}t\bar{t}$ production and in BSM searches.
- The first differential measurements made by CMS and ATLAS also extract inclusive cross-section measurements compatible with each other and the SM.
- This analysis refines the previous ATLAS measurement EPJC 81 (2021) 737:
    - Additional final state considered targeting all-hadronic decay of the $t\bar{t}$ system.
    - Improved calibrations, reduced experimental uncertainties, and updates to theoretical & modelling uncertainties.
    - Additional EFT and spin-correlation interpretations.

# $t\bar{t}Z$ production cross-sections

JHEP 07 (2024) 163.

A data-driven $t\bar{t}$ estimation is also used.

- An MVA approach is used in each channel to maximise signal discrimination

**←2l**

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

DNN for each multiplicity of ($b$-)jets discriminates signal from $t\bar{t}$ and $Z$+jets & it's distribution is used directly in the inclusive measurement.

$Z + b/c$ normalisations extracted from inclusive fit.

**3l**

| Variable | Preselection | | |
|---|---|---|---|
| $N_\ell$ $(\ell = e, \mu)$ | $= 3$ | | |
| | $\geq 1$ OSSF lepton pair with $\mid m_{\ell\ell} - m_Z \mid < 10$ GeV | | |
| | for all OSSF combinations: $m_{\text{OSSF}} > 10$ GeV | | |
| $p_T(\ell_1, \ell_2, \ell_3)$ | $> 27,\ 20,\ 15$ GeV | | |
| $N_{\text{jets}}$ $(p_T > 25$ GeV$)$ | $\geq 3$ | | |
| $N_{b\text{-tagged jets}}$ | $\geq 1$@85% | | |
| | **SR-3ℓ-ttZ** | **SR-3ℓ-tZq** | **SR-3ℓ-WZ** |
| DNN-tZq output | $< 0.43$ | $\geq 0.43$ | — |
| DNN-WZ output | $< 0.27$ | $< 0.27$ | $\geq 0.27$ |
| $N_{b\text{-tagged jets}}$ | — | — | $\geq 1$@60% |

3-class DNN to separate from $tZq$ and $WZ$ & cut on $b$-tag in SR-$3l$-$WZ$ reduces $WZ + l/c$.

**4l→**

| Variable | Preselection | |
|---|---|---|
| $N_\ell$ $(\ell = e, \mu)$ | $= 4$ | |
| | $\geq 1$ OSSF lepton pair with $\mid m_{\ell\ell} - m_Z \mid < 20$ 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 | $= 0$ | |
| $N_{\text{jets}}$ $(p_T > 25$ GeV$)$ | $\geq 2$ | |
| $N_{b\text{-tagged jets}}$ | $\geq 1$@85% | |
| | **SR-4ℓ-SF** | **SR-4ℓ-DF** |
| $\ell\ell^{\text{non-}Z}$ | $e^+e^-$ or $\mu^+\mu^-$ | $e^\pm\mu^\mp$ |
| DNN output | $\geq 0.4$ | — |

Cut on DNN output in SR-$4l$-SF suppresses $ZZ$+jets.

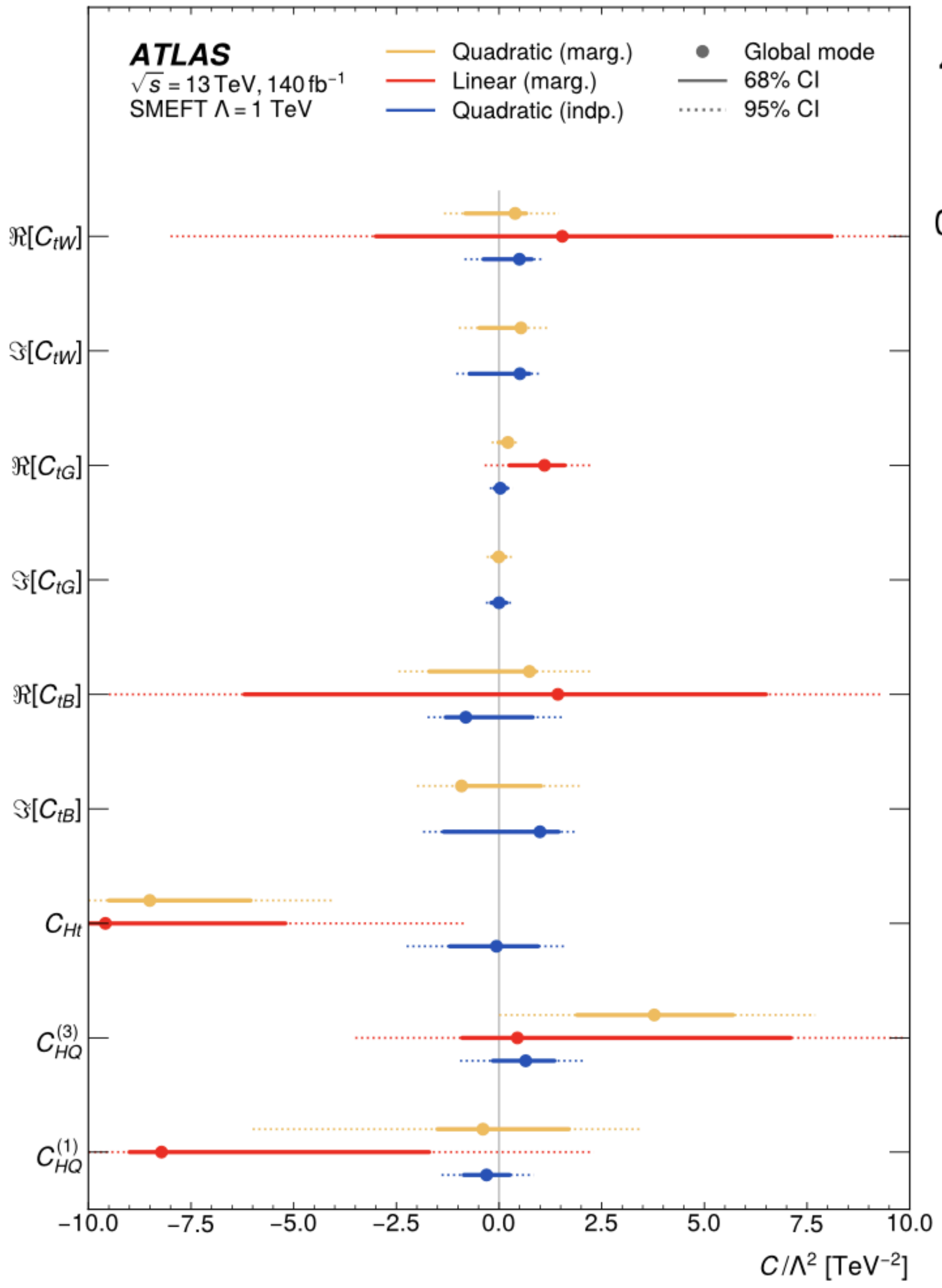
Dominant $ZZ + b$ component normalised using CRs with inverted DNN cut

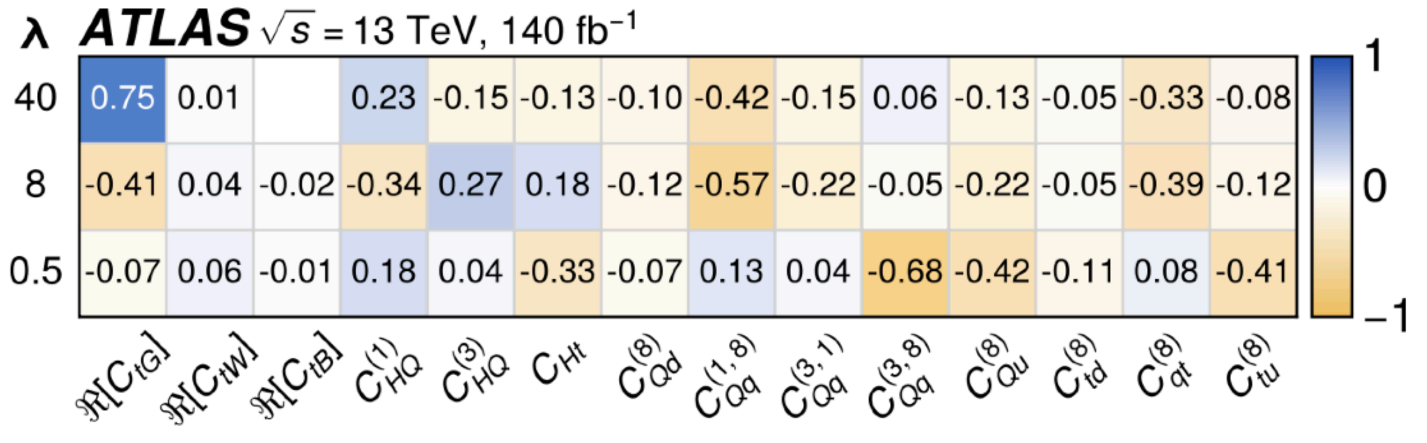
# $t\bar{t}Z$ production cross-sections

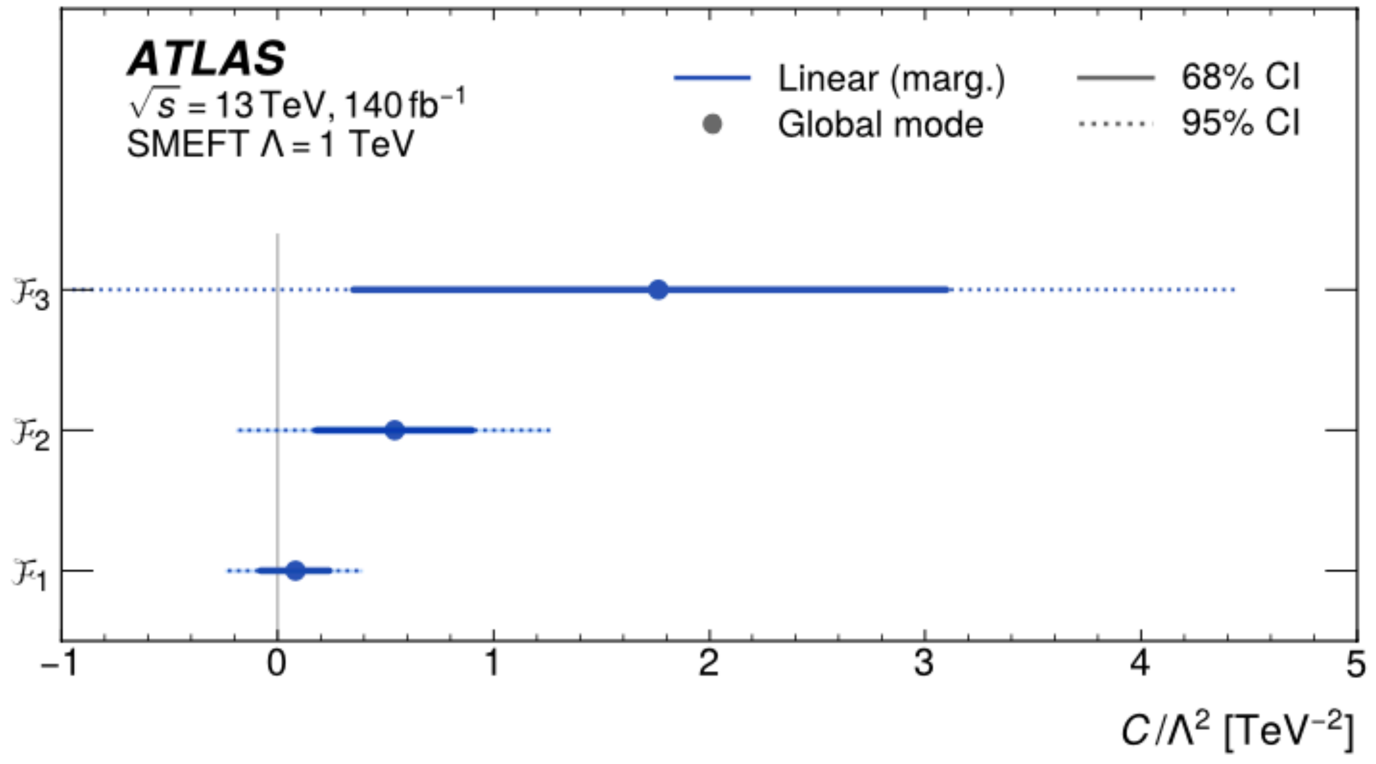
[JHEP 07 (2024) 163.](JHEP 07 (2024) 163.)

- Combined inclusive fit result has a precision of 6% vs 10% previously.
- Unfolded differential cross-sections show good agreement with data for most variables:
  - $Z$ & top $p_T$ are typically most sensitive to top-$Z$ & four-quark operators .
- Slightly asymmetric limits on some operators are due to the interplay different operators.
- Also do a fit on the rotated EFT directions
  - Highlights sensitivity to modifications to quark-initiated $t\bar{t}Z$ channel & of the top-gluon vertex.

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



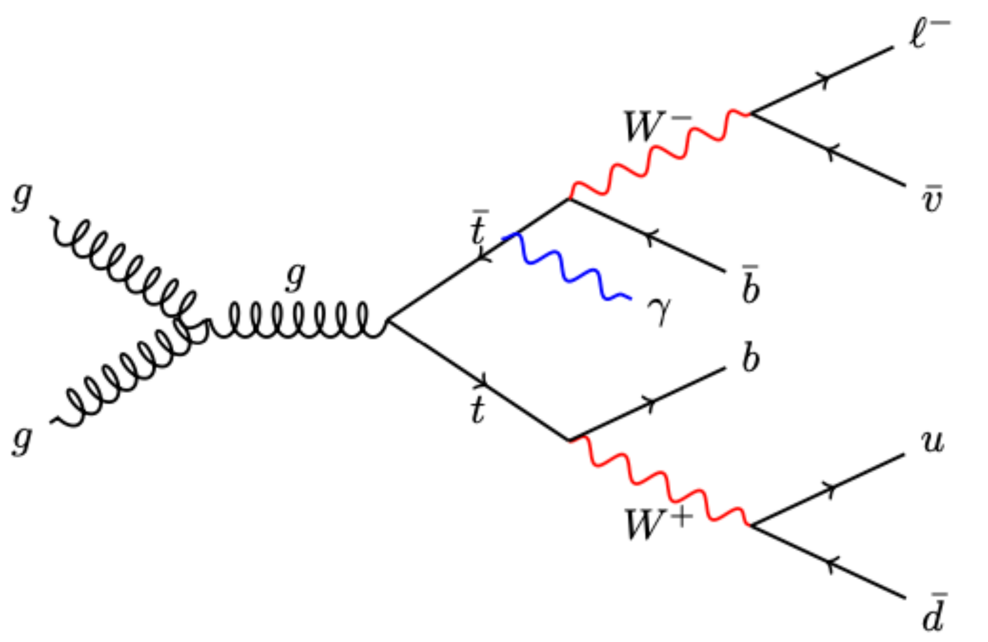



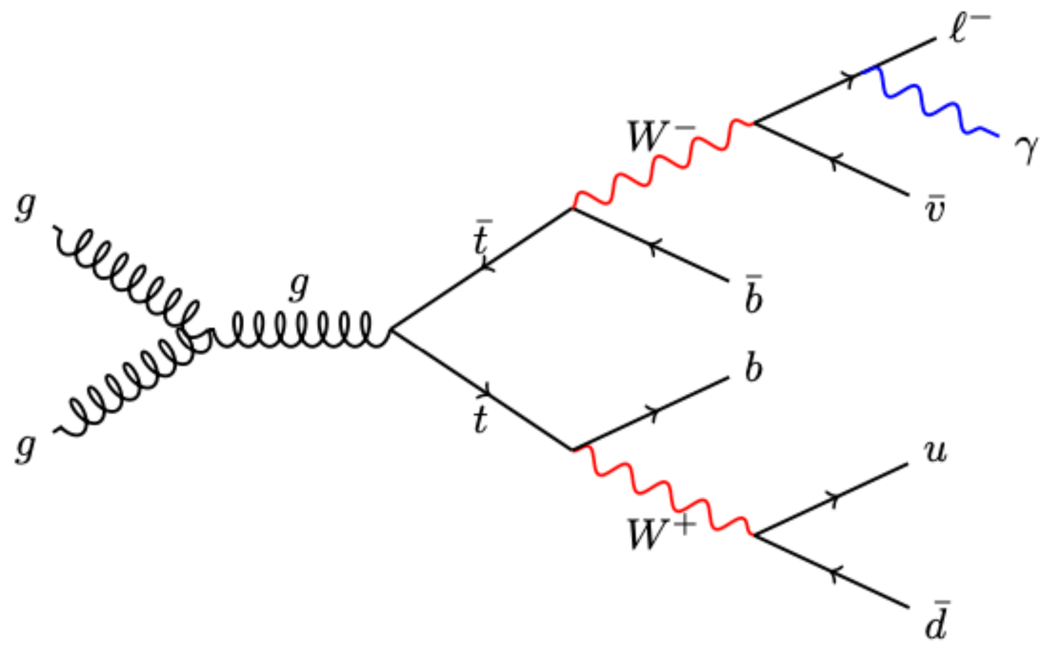
# $t\bar{t}\gamma$ production cross-sections

[JHEP 10 (2024) 191.](#)

- Focus on this analysis is measurement of $t\bar{t}\gamma$ with improved separation of production-mode events from the decay mode.
  - Interference between the two is negligible both in the SM and in EFT.
  - Production mode is most sensitive to measurements of the top-$\gamma$ coupling.
- Measurements exploit channels at stable particle level in a fiducial phase space using events with exactly one photon, at least one $b$-tagged jet, and considering light-leptons only
  - Single-lepton - 3-class NN with 40 input variables ($t\bar{t}\gamma$ prod. vs dec. vs bkgs)
  - Dilepton - Binary classify ($t\bar{t}\gamma$ prod. vs bkgs)
- Non-prompt/fake backgrounds estimated using data-driven techniques.




$t\bar{t}\gamma$ production




$t\bar{t}\gamma$ decay

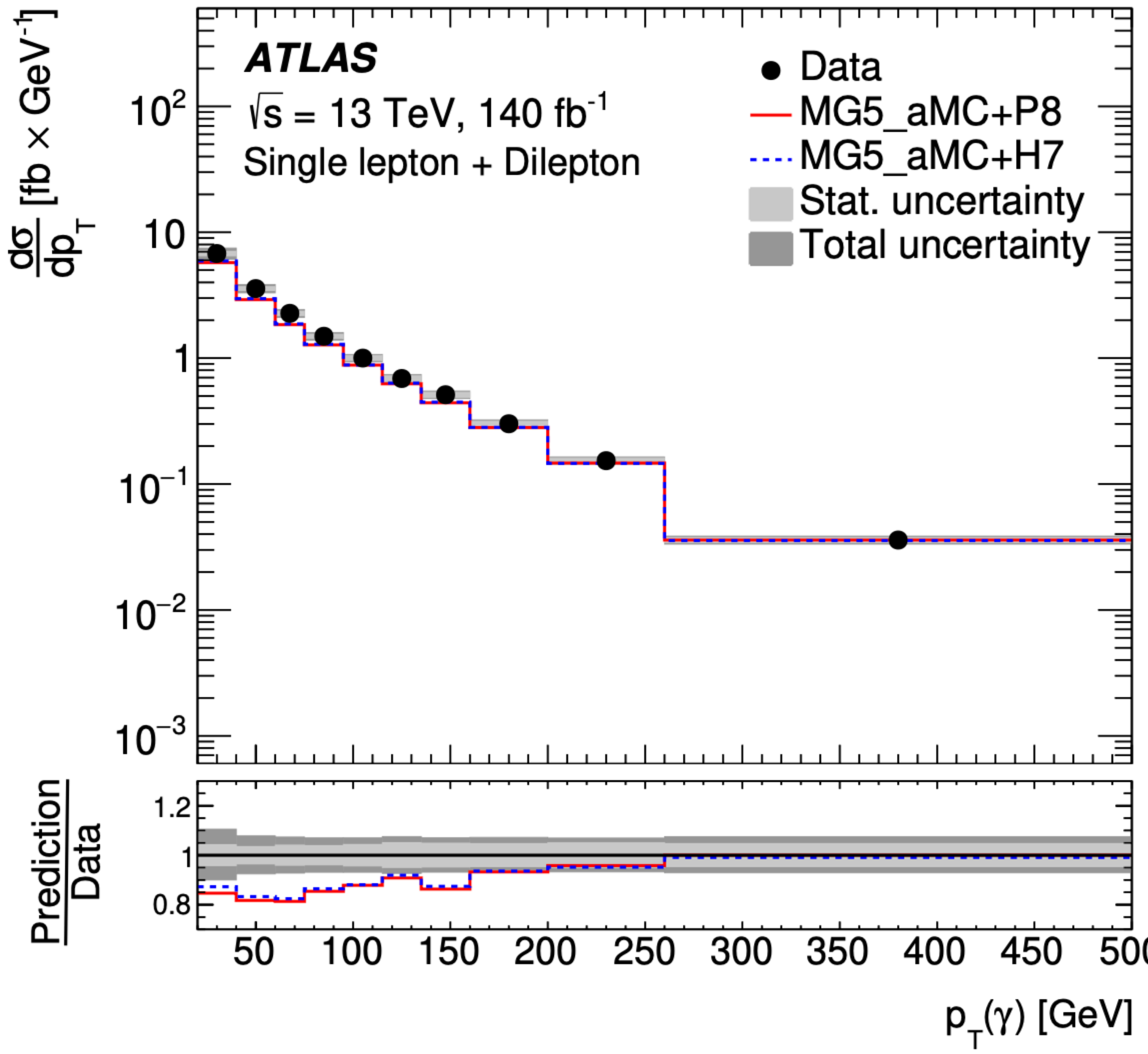
# $t\bar{t}\gamma$ production cross-sections

JHEP 10 (2024) 191.

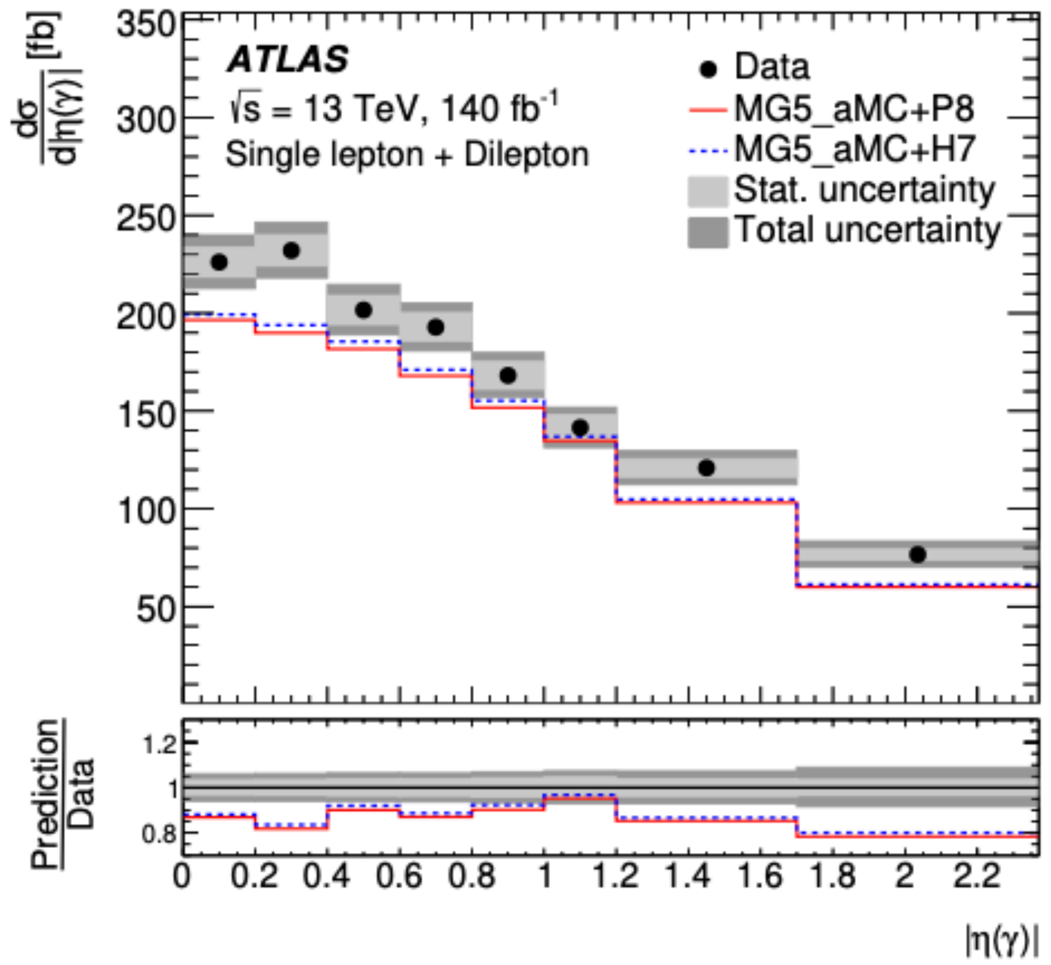
- Measured production cross-section across both channels reduces parton-shower, JES, & flavour-tagging uncertainties:

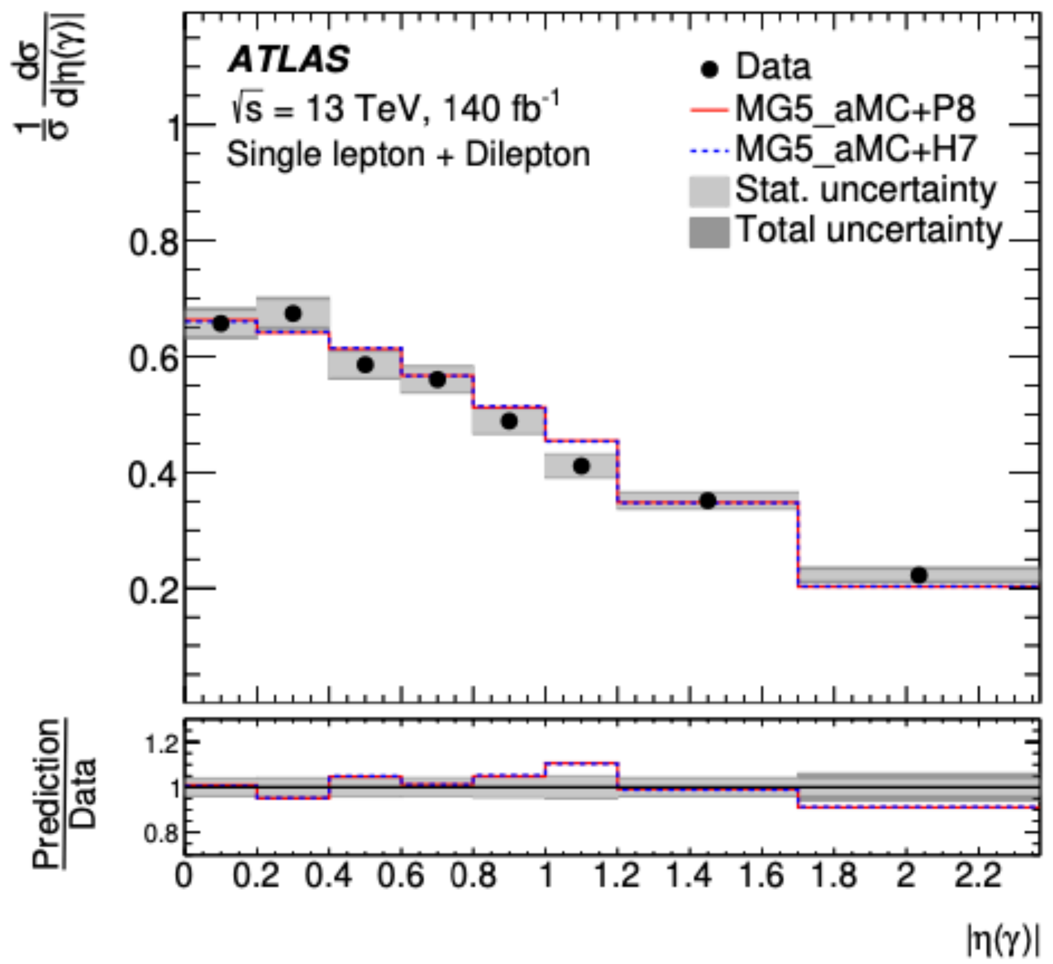
$$\sigma_{t\bar{t}\gamma\ \text{production}} = 319 \pm 15\,\text{fb} = 319 \pm 4\,(\text{stat})\,{}^{+15}_{-14}(\text{syst})\ \text{fb}$$

- $p_T(\gamma)$ is slightly softer in MC prediction of production mode than in data but angular shapes are well-modelled.




MADGRAPH predictions underestimate $t\bar{t}\gamma$ production.



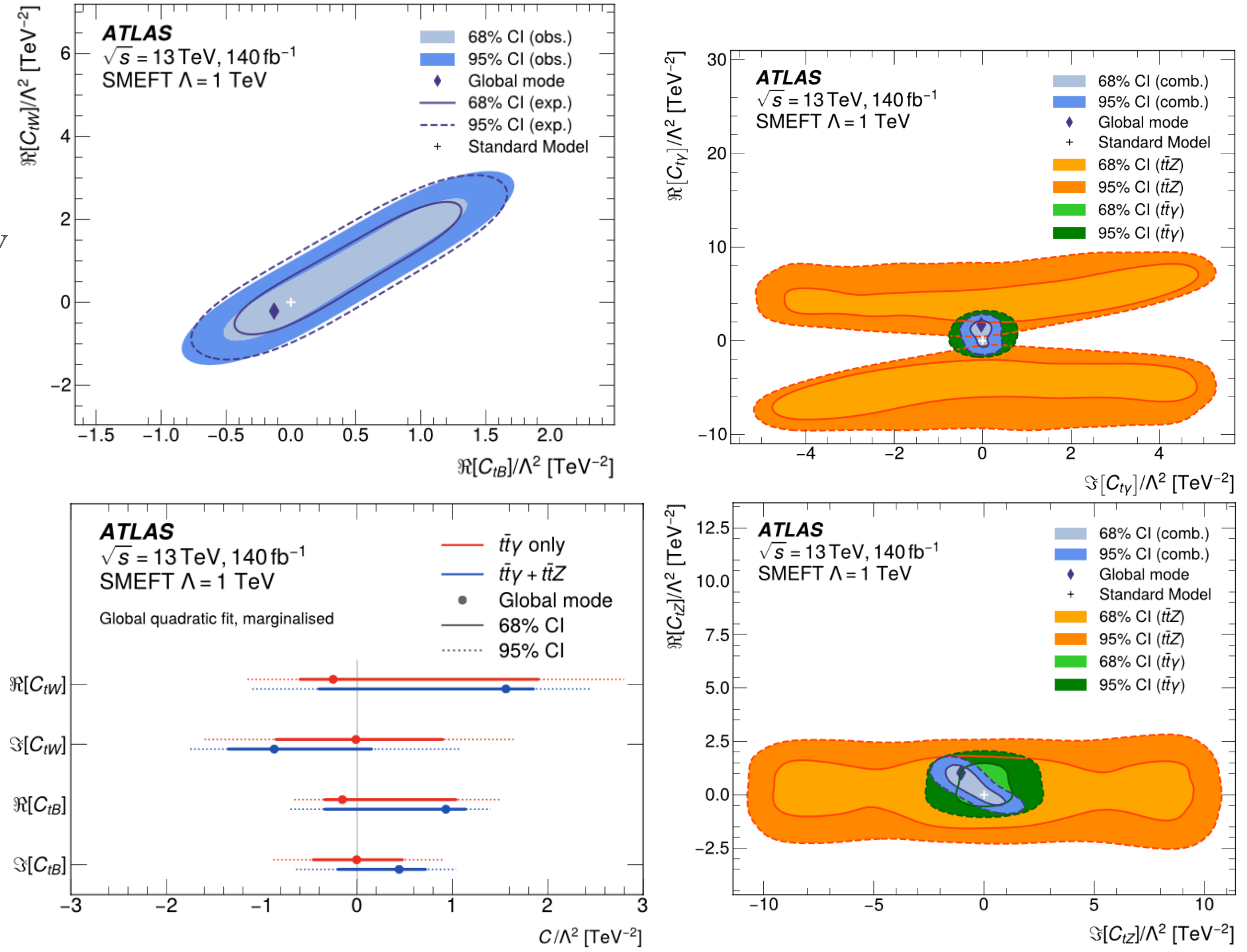




Photon $p_T$ used to obtain limits on EFT parameters in $t\bar{t}\gamma$ production and $t\bar{t}Z$.

# $t\bar{t}\gamma$ production cross-sections

[JHEP 10 (2024) 191.](#)

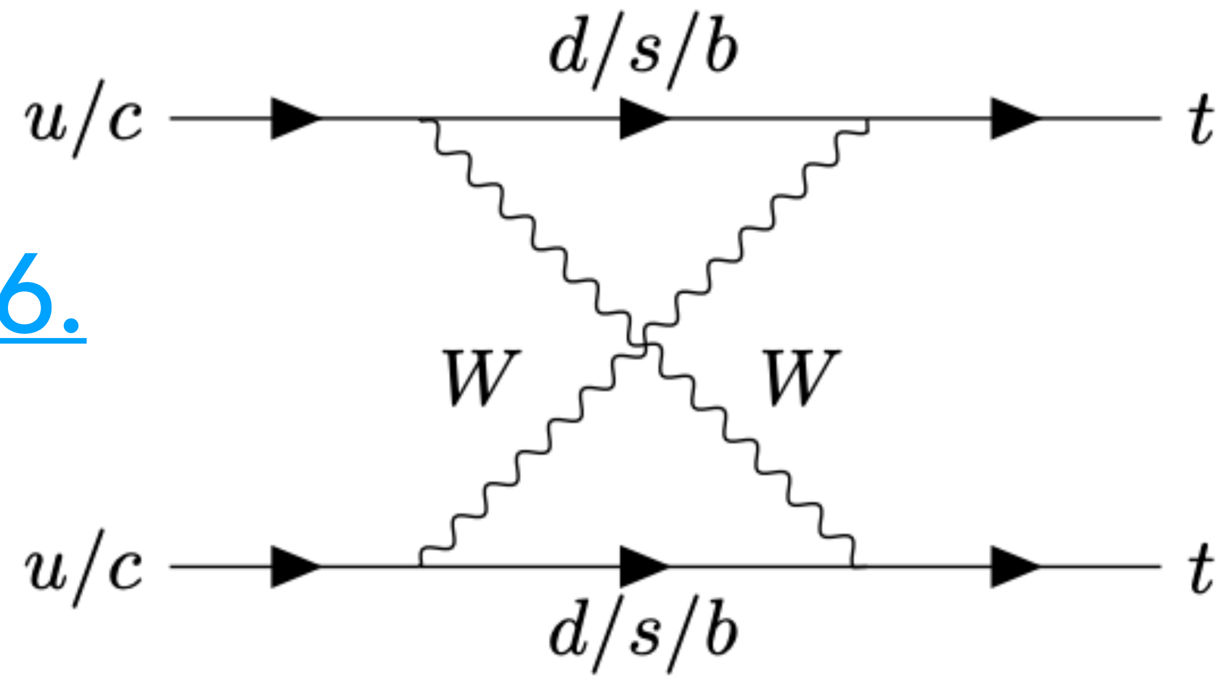
- Fit performed only on $t\bar{t}\gamma$ production dominated by quadratic EFT terms.
  - Linear relationship observed between $C_{tW}$ and $C_{tB}$.
  - Best-fit values in agreement with SM despite slightly larger measured production cross-section.
- A combined measurement with $t\bar{t}Z$ reduces limits from independent fits by up to 20%.
- $t\bar{t}Z$ alone is unable to resolve some degeneracies;
  - Resolved in combination with $t\bar{t}\gamma$.

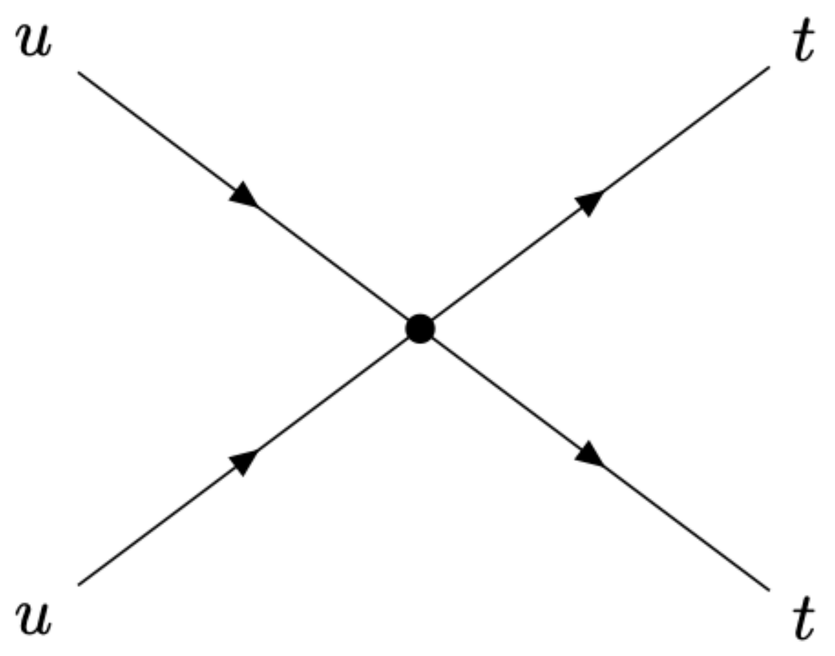


# Search for same-sign top quarks

JHEP 02 (2025) 084.

- The SM production of same-sign top quarks is not detectable at the LHC, predicted $\sigma(pp \to tt)_{\rm SM} \simeq 4 \cdot 10^{-15}\,{\rm pb}$ JHEP 10 (2015) 146.
- Observation would immediately imply some BSM process.




$$\mathcal{O}_{tu}^{(1)} = [\bar{t}_{\rm R}\gamma^\mu u_{\rm R}][\bar{t}_{\rm R}\gamma_\mu u_{\rm R}],$$
$$\mathcal{O}_{Qq}^{(1)} = [\bar{Q}_{\rm L}\gamma^\mu q_{\rm L}][\bar{Q}_{\rm L}\gamma_\mu q_{\rm L}],$$
$$\mathcal{O}_{Qq}^{(3)} = [\bar{Q}_{\rm L}\gamma^\mu \sigma^a q_{\rm L}][\bar{Q}_{\rm L}\gamma_\mu \sigma^a q_{\rm L}],$$
$$\mathcal{O}_{Qu}^{(1)} = [\bar{Q}_{\rm L}\gamma^\mu q_{\rm L}][\bar{t}_{\rm R}\gamma_\mu u_{\rm R}],$$
$$\mathcal{O}_{Qu}^{(8)} = [\bar{Q}_{\rm L}\gamma^\mu T^A q_{\rm L}][\bar{t}_{\rm R}\gamma_\mu T^A u_{\rm R}].$$

Already constrained by measurements of $B_d$ mixing and dijet production JHEP 03 (2008) 049.

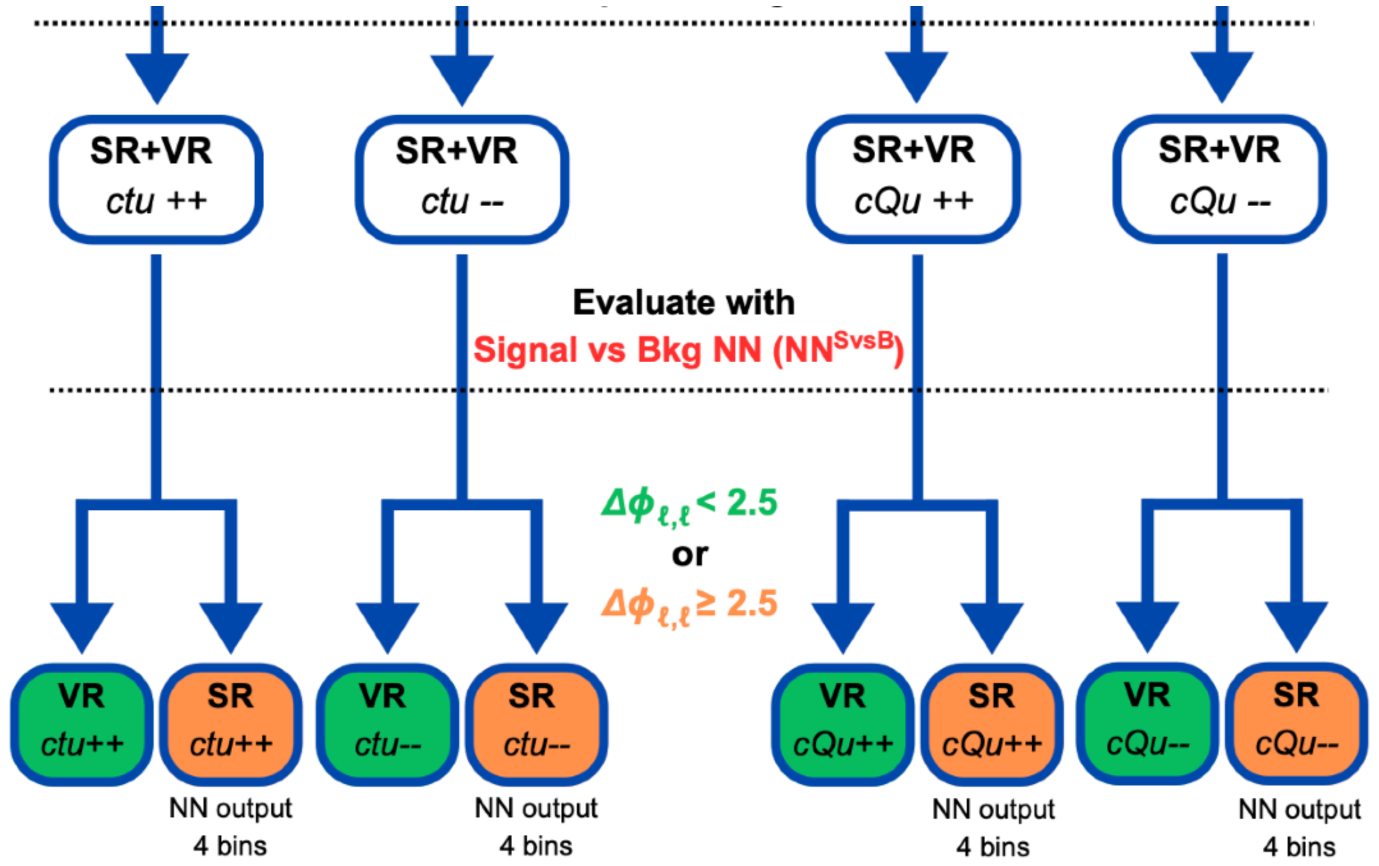
| Chirality | left-left | left-right | right-right |
|---|---|---|---|
| $\sigma(pp \to tt)$ | 62 fb | 51 fb | 38 fb |
| $\lvert c\rvert/\Lambda^2\,({\rm TeV}^{-2})$ | 0.053 | 0.137 | 0.042 |

- A previous ATLAS analysis at 8 TeV set 95% CL limits assuming chiral contact interactions JHEP 10 (2015) 150.
- Previous ATLAS upper limit on SS top production cross-section at 13 TeV of 89 fb assumes a BSM FCNC mediator with a mass of 1 TeV JHEP 12 (2018) 039.

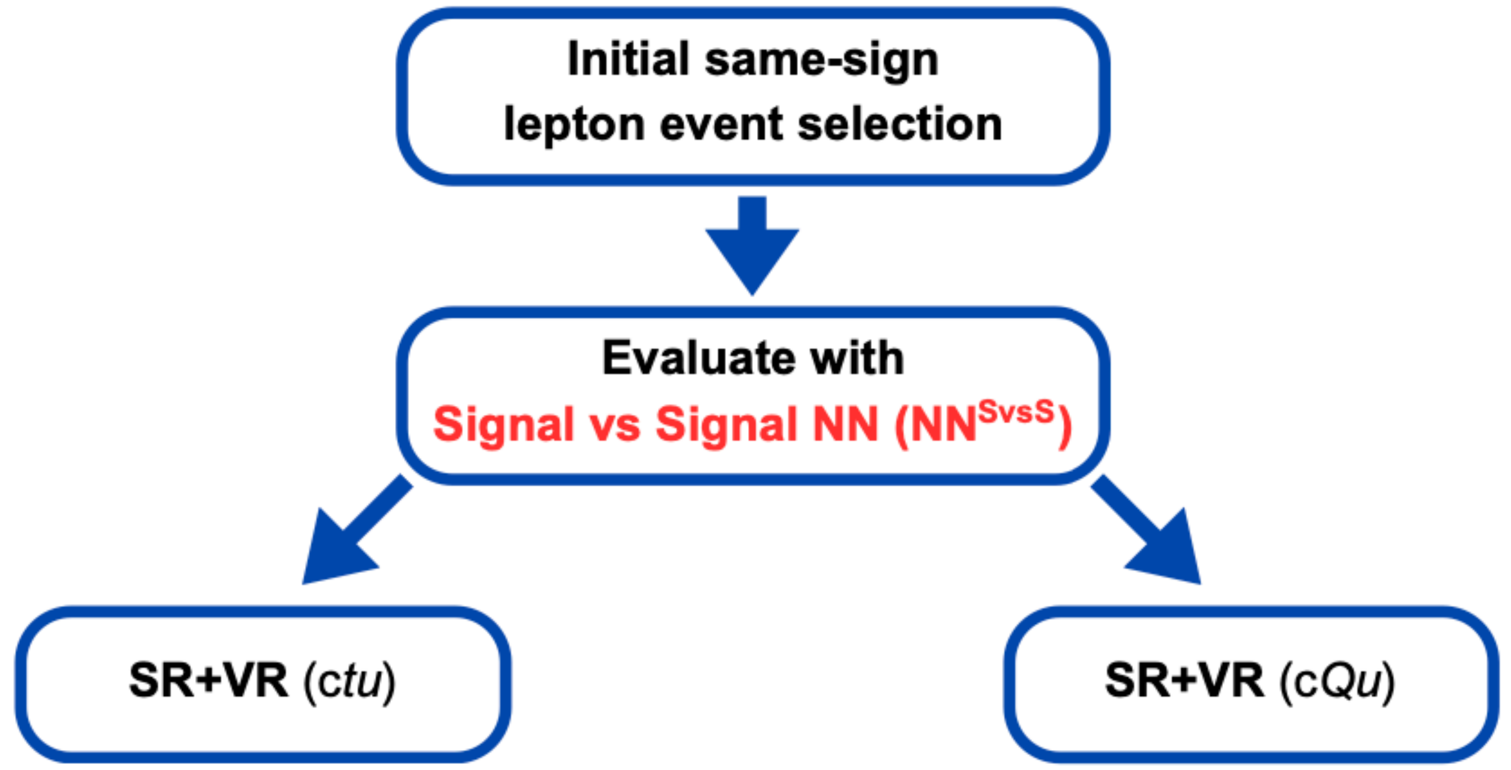
# Search for same-sign top quarks

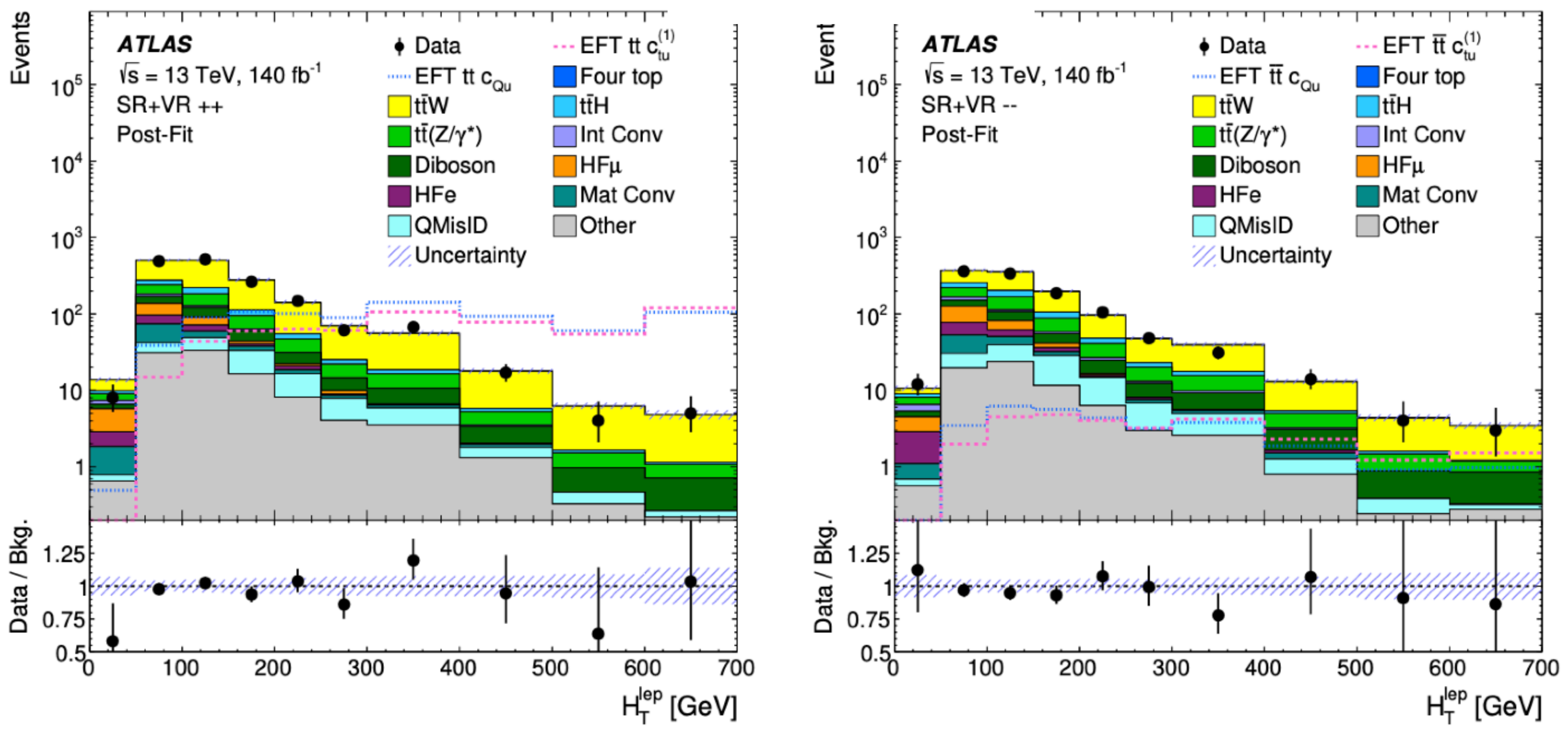
[JHEP 02 (2025) 084.](JHEP 02 (2025) 084.)

- Dilepton final state is characterised by two SS leptons $(e, \mu)$, two $b$-jets (tagged at the 70% WP), and $E_T^{miss}$.
- **Signal vs Signal NN:** Trained on two SS-top benchmarks Selection on NN has 65% classification efficiency.
- **Signal vs Bkg NN:** Trained separately for each of the SRs.
- **Dedicated CRs** for $t\bar{t}Z$, $VV$ & non-prompt leptons.




- Production of $t\bar{t}W$ is the dominant background and is constrained by the data using NN distribution in the SRs.




$$c_{tu}^{(1)} = 0.04,\ c_{Qu}^{(1)} = 0,\ c_{Qu}^{(8)} = 0$$

$$c_{tu}^{(1)} = 0,\ c_{Qu}^{(1)} = 0.1,\ c_{Qu}^{(8)} = 0.2$$

# Search for same-sign top quarks

[JHEP 02 (2025) 084.](#)

- Post-fit yields are consistent with observed data & pre-fit yields (<0.001 signal events).

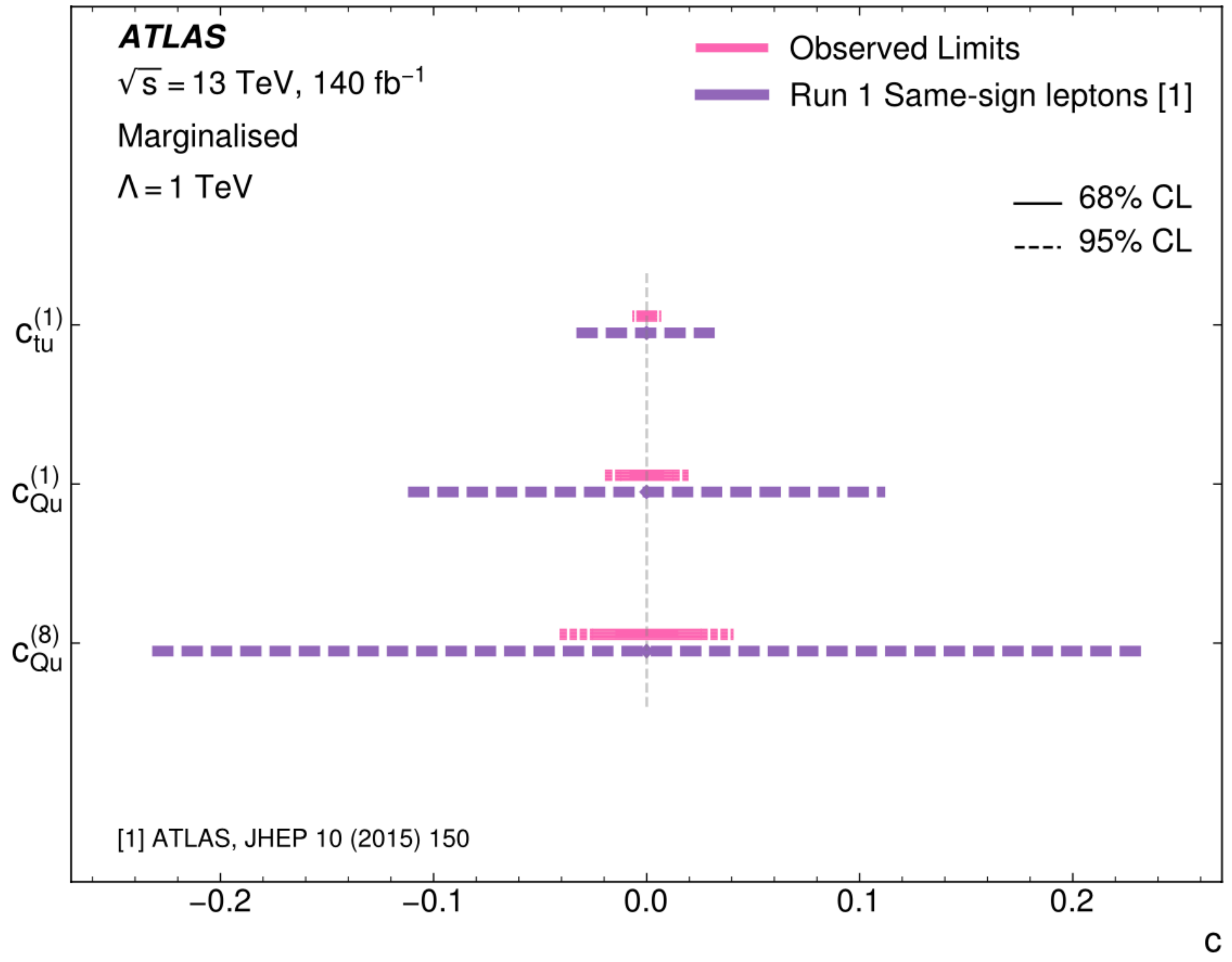
**Wilks' theorem: SciPost Phys. Core 6 (2023) 013.**

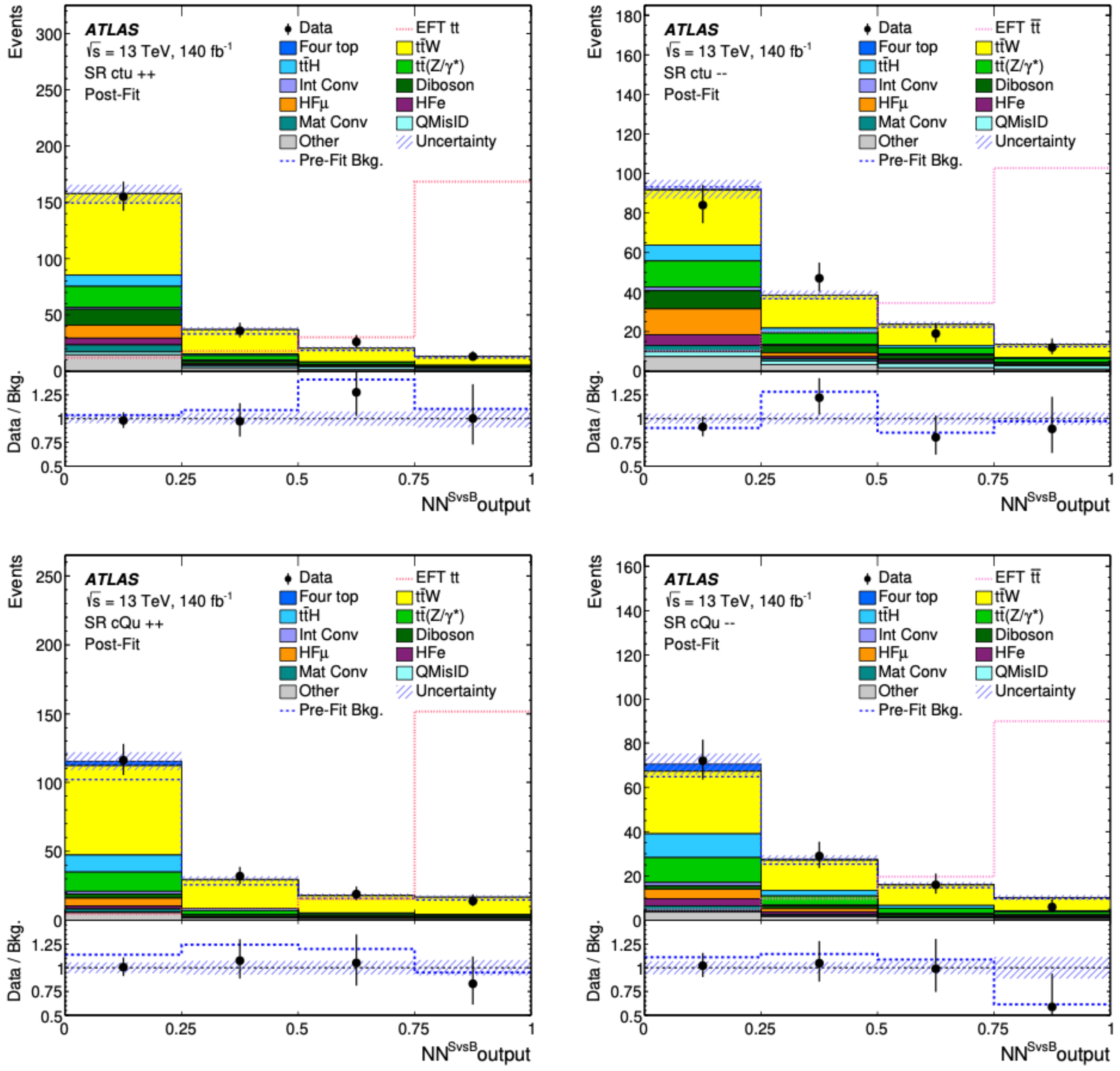
**Some over-coverage is observed for WC close to 0 leading to at most 9% looser observed limits.**

(Statistically dominated)

| Uncertainties | Wilson Coefficient CIs at 95% CL ($\times 10^{-2}$) $c_{tu}^{(1)}$ | $c_{Qu}^{(1)}$ | $c_{Qu}^{(8)}$ |
|---|---|---|---|
| Statistical uncertainty only | $[-0.65, 0.65]$ | $[-1.9, 1.9]$ | $[-3.9, 3.9]$ |
| Statistical + modeling uncertainties | $[-0.67, 0.67]$ | $[-1.9, 1.9]$ | $[-4.0, 4.0]$ |
| Total uncertainty | $[-0.68, 0.68]$ | $[-2.0, 2.0]$ | $[-4.1, 4.1]$ |

Large charge asymmetry in SS top production means $(++)$ dominates sensitivity.

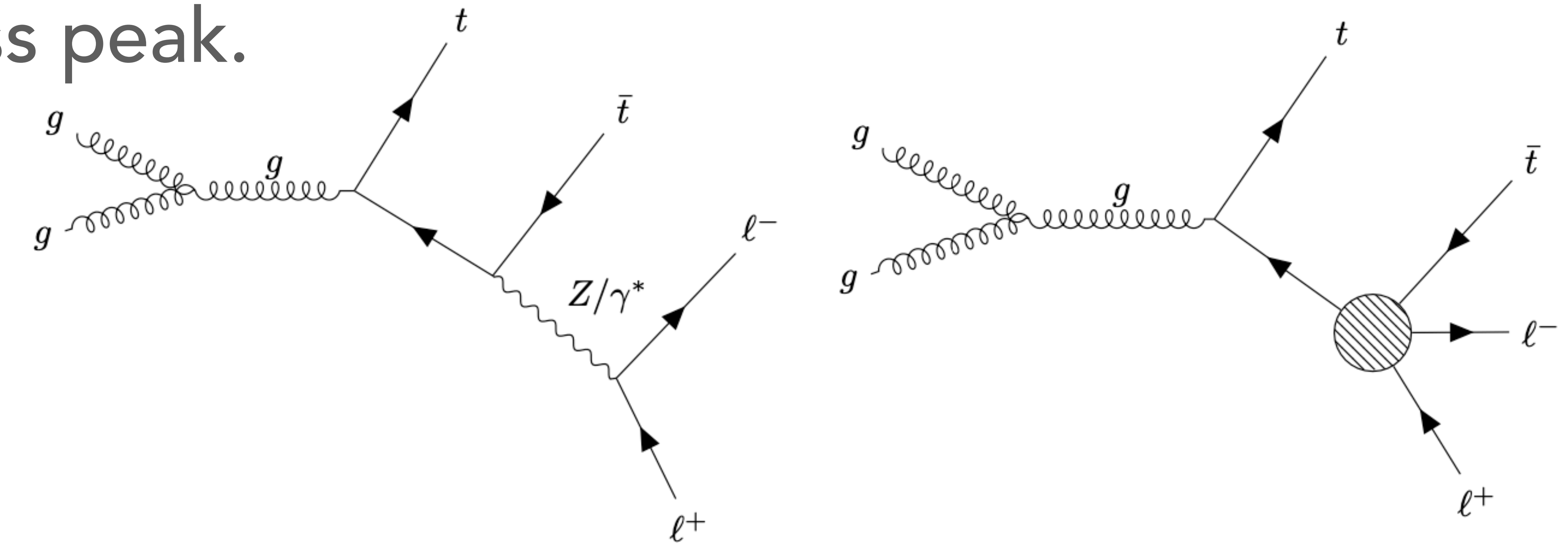


# Measurement of high-mass $t\bar{t}l^+l^-$ production

[arXiv:2504.05919v1](https://arxiv.org/abs/2504.05919v1)

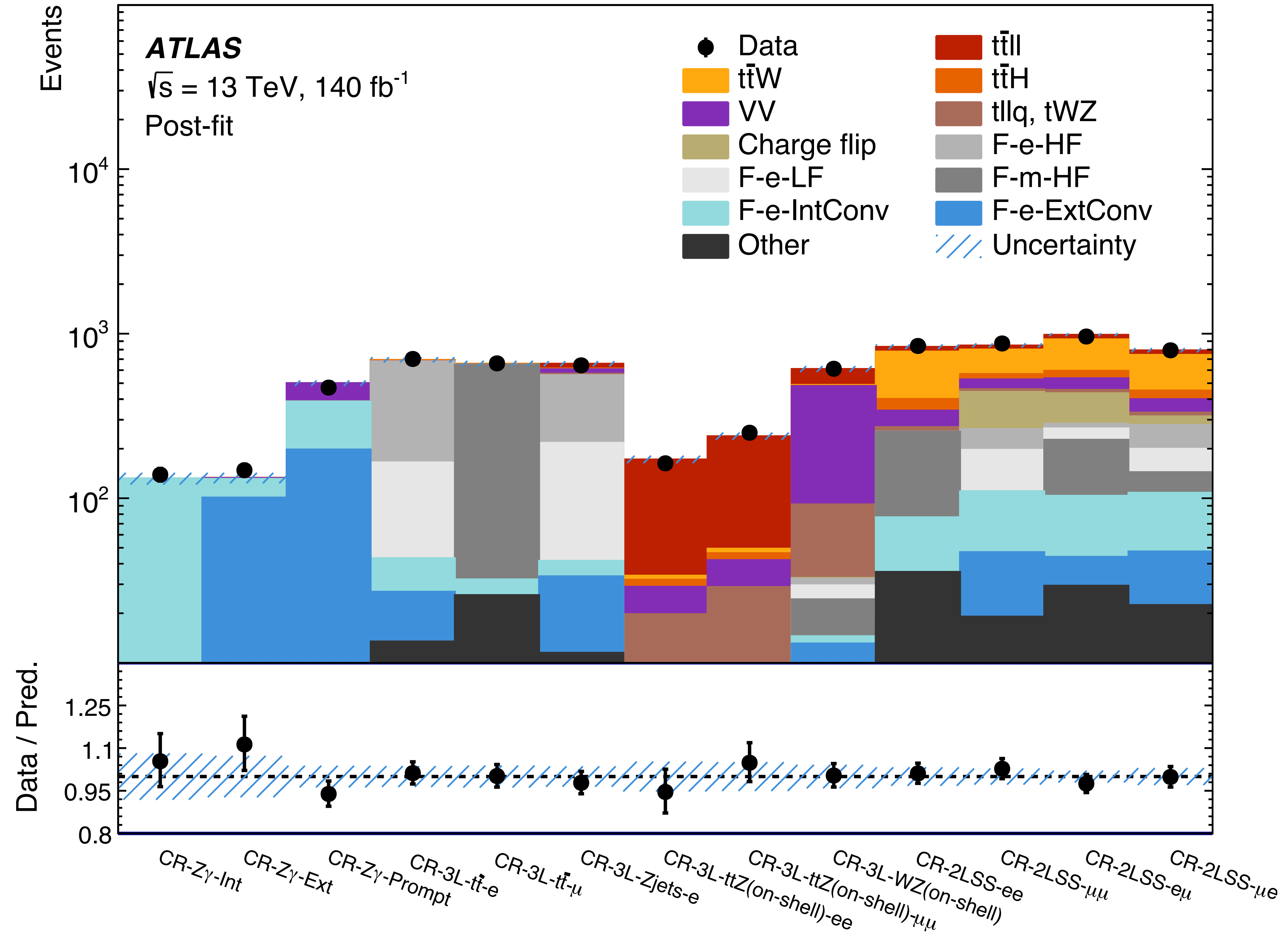
- While detailed measurements of on-shell $t\bar{t}Z$ gives direct sensitivity to $t$-$Z$ coupling, off-shell $t\bar{t}l^+l^-$ production has not yet been measured by ATLAS.
  - Sensitive to the effective $t\bar{t}l^+l^-$ coupling & thus the top-lepton EFT operators which contribute.
- Analysis focuses on high dilepton invariant mass region by selecting three isolated leptons $(e, \mu)$ with extensions of $t\bar{t}Z$ production measurement to deal with larger background contributions away from the mass peak.
  - Flavour-inclusive measurements and those split by $e/\mu$ probe SM, possible LFU violation, and possible new physics via EFT.

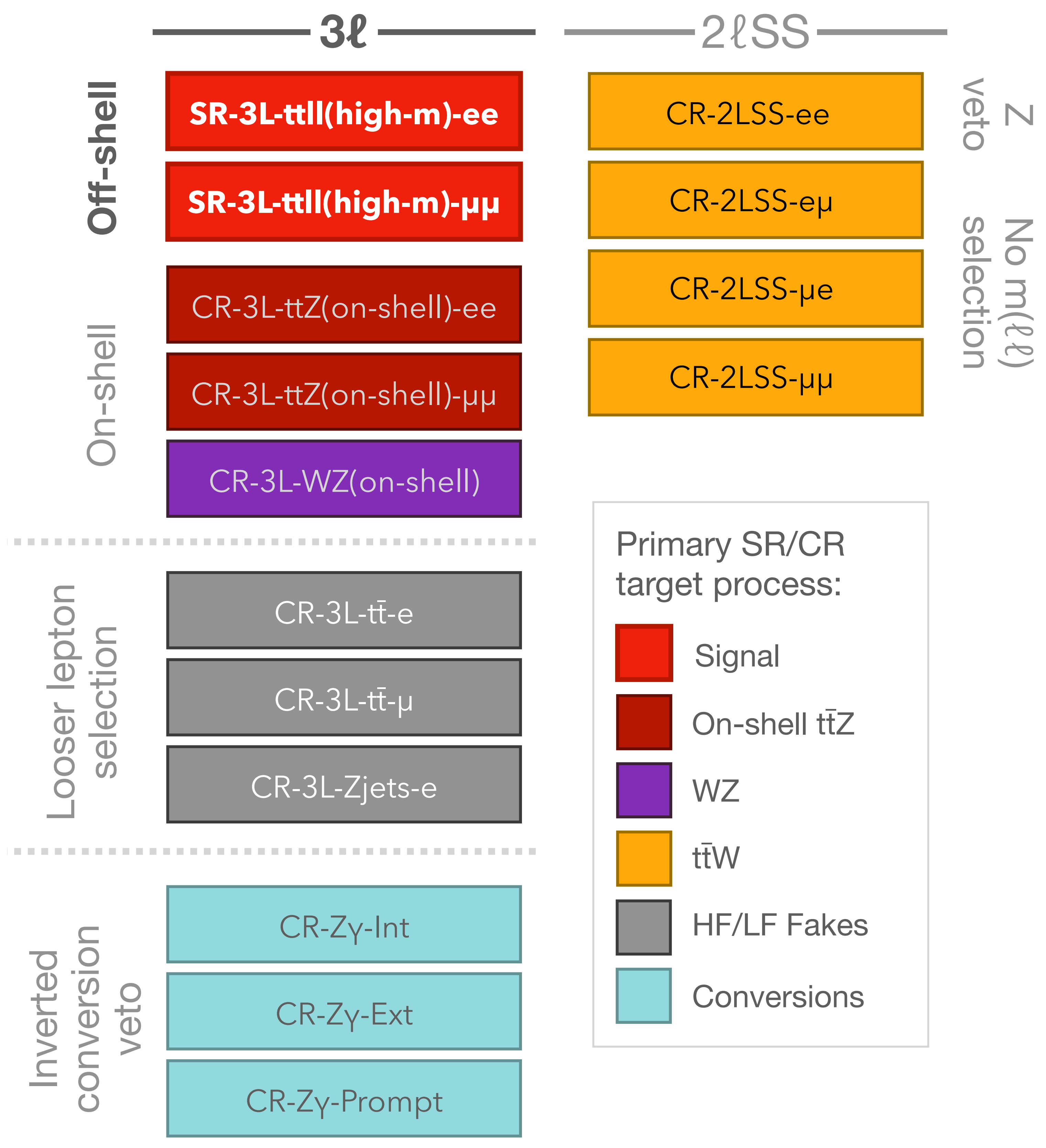


# Measurement of high-mass $t\bar{t}l^+l^-$ production

arXiv:2504.05919v1

- SRs are split by lepton flavour and binned in the dilepton invariant mass to increase sensitivity to four-fermion EFT operators.
- Dominated by $t\bar{t}W$ background
- CRs defined to reduce uncertainty on low MC-stats fake leptons.
- Estimation of $t\bar{t}Z$ & $WZ$+jets uses same 3-class DNN from on-shell analysis.



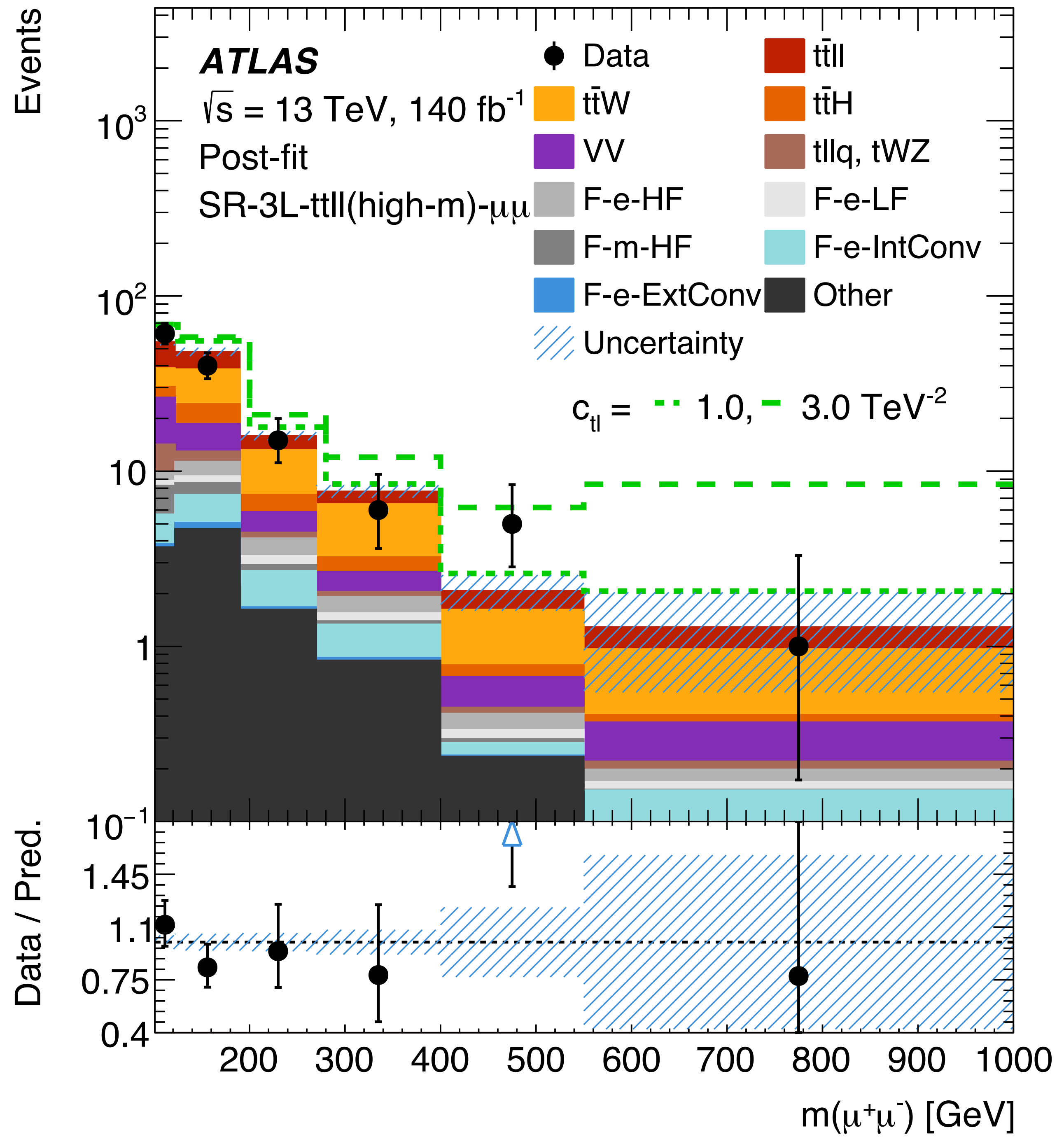
# Measurement of high-mass $t\bar{t}l^+l^-$ production

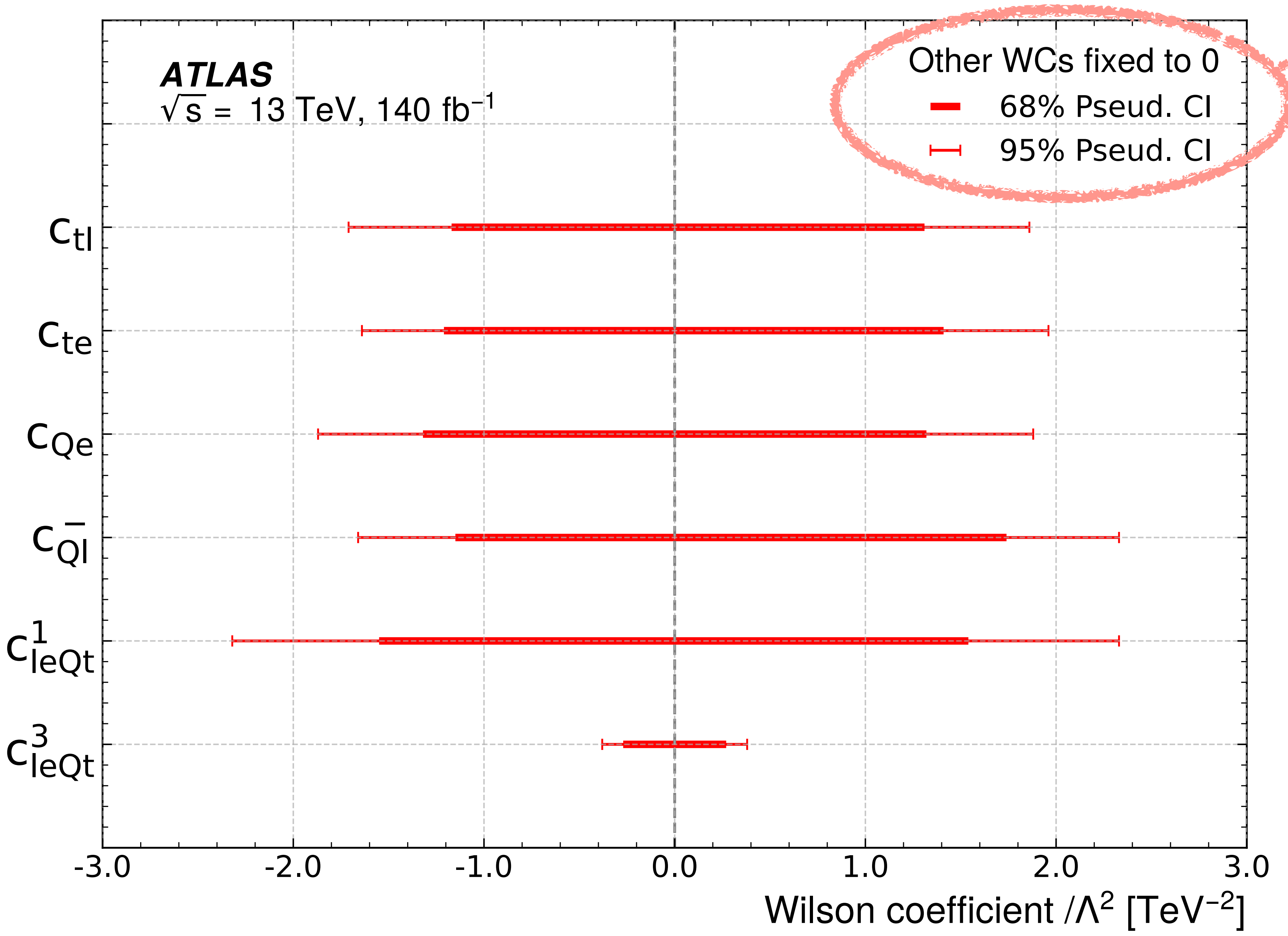
arXiv:2504.05919v1

UNIVERSITY OF SUSSEX

- No significant deviations from the SM: $\mu_{t\bar{t}W} = 1.18 \pm 0.11$
- Compatible with previous ATLAS measurements in similar phase-space.
- In individual-operator fits, constraints are dominated by quadratic EFT terms.

Justified by Wilks' theorem




| | $O(\Lambda^{-4})\,[\mathrm{TeV}^{-2}]$ | | |
|---|---|---|---|
| | Best fit | 68% Asymp. CI | 95% Asymp. CI |
| $c_{tl(22)} - c_{tl(11)}$ | 0.79 | [−2.28, 2.32] | [−3.44, 3.45] |
| $c_{te(22)} - c_{te(11)}$ | −0.43 | [−2.10, 2.36] | [−3.34, 3.51] |
| $c_{Qe(22)} - c_{Qe(11)}$ | −0.66 | [−2.39, 2.43] | [−3.62, 3.71] |
| $c^{-}_{Ql(22)} - c^{-}_{Ql(11)}$ | −1.14 | [−2.38, 2.37] | [−3.72, 3.54] |
| $c^{1}_{leQt(22)} - c^{1}_{leQt(11)}$ | −1.32 | [−3.03, 3.03] | [−4.58, 4.58] |
| $c^{3}_{leQt(22)} - c^{3}_{leQt(11)}$ | −0.20 | [−0.50, 0.50] | [−0.75, 0.75] |

Cancellation of systematics limited by Run 2 data statistics but may be useful in a future analysis.

# Summary

- Measurements of rare $tX$ and $t\bar{t}+X$ production processes provide a rich environment with which to test the SM and beyond.
- Recent analyses by the ATLAS collaboration provide competitive results:
    - Improvements over some previous measurements by utilising MVA signal discrimination and robust background estimations.
- Detailed insights into SM processes are observed as well as probes into new physics through constraints on EFT operators.
    - Work demonstrates some of the interplay between various associated top production processes and new physics contributions described in the SMEFT.
- Exciting results which contribute to a rich and growing field continue to show what the LHC can do.

# BACKUP

# Associated production of $tX$ and $t\bar{t} + X$, including their EFT interpretation

Caley Yardley
On behalf of the ATLAS Collaboration

SM@LHC2025, Durham
9th April 2025

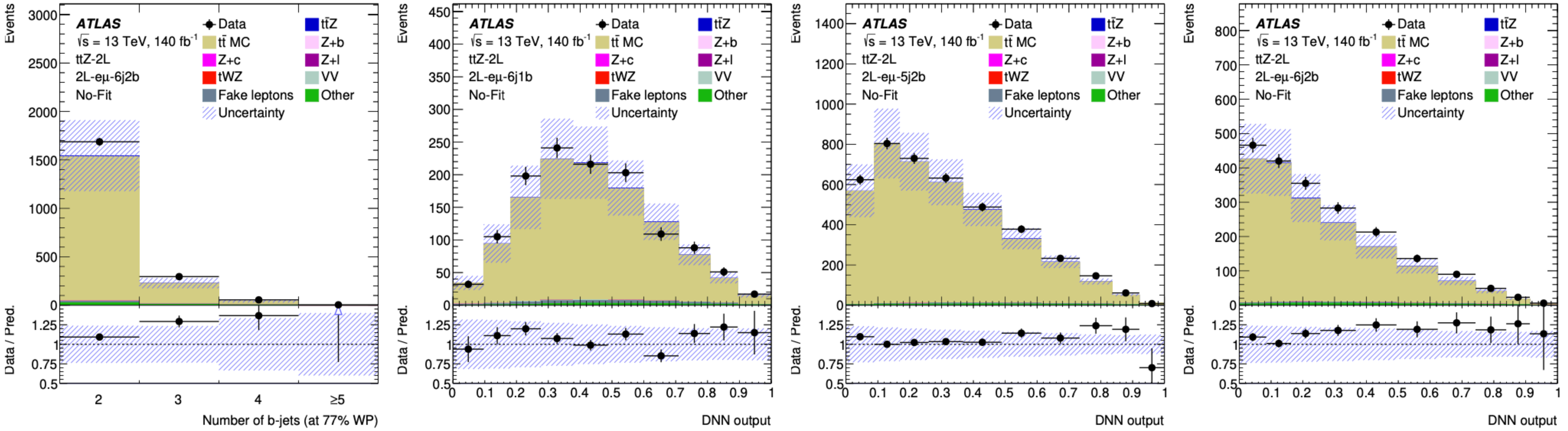
# Backup - $t\bar{t}Z$ production cross-sections

JHEP 07 (2024) 163.

- $2lOS$ uses both *multi-hypothesis hadronic top/$W$ reconstruction* and SPANet where the transverse momentum of the reconstructed $t\bar{t}$ system is input in the MVA.
- $3l$ $t\bar{t}$ reconstruction is done by first reconstructing the hadronic-side top quark from jets compatible with a $W$ candidate and $b$-jet then building the leptonic-side top quark.
- Two Neutrino Scanning Method used in $4l$ region to reconstruct $t\bar{t}Z$ with output weight used as input to $4l$ MVA to discriminate between $t\bar{t}Z$ and $t\bar{t}$.

Data-driven $t\bar{t}$ estimation:

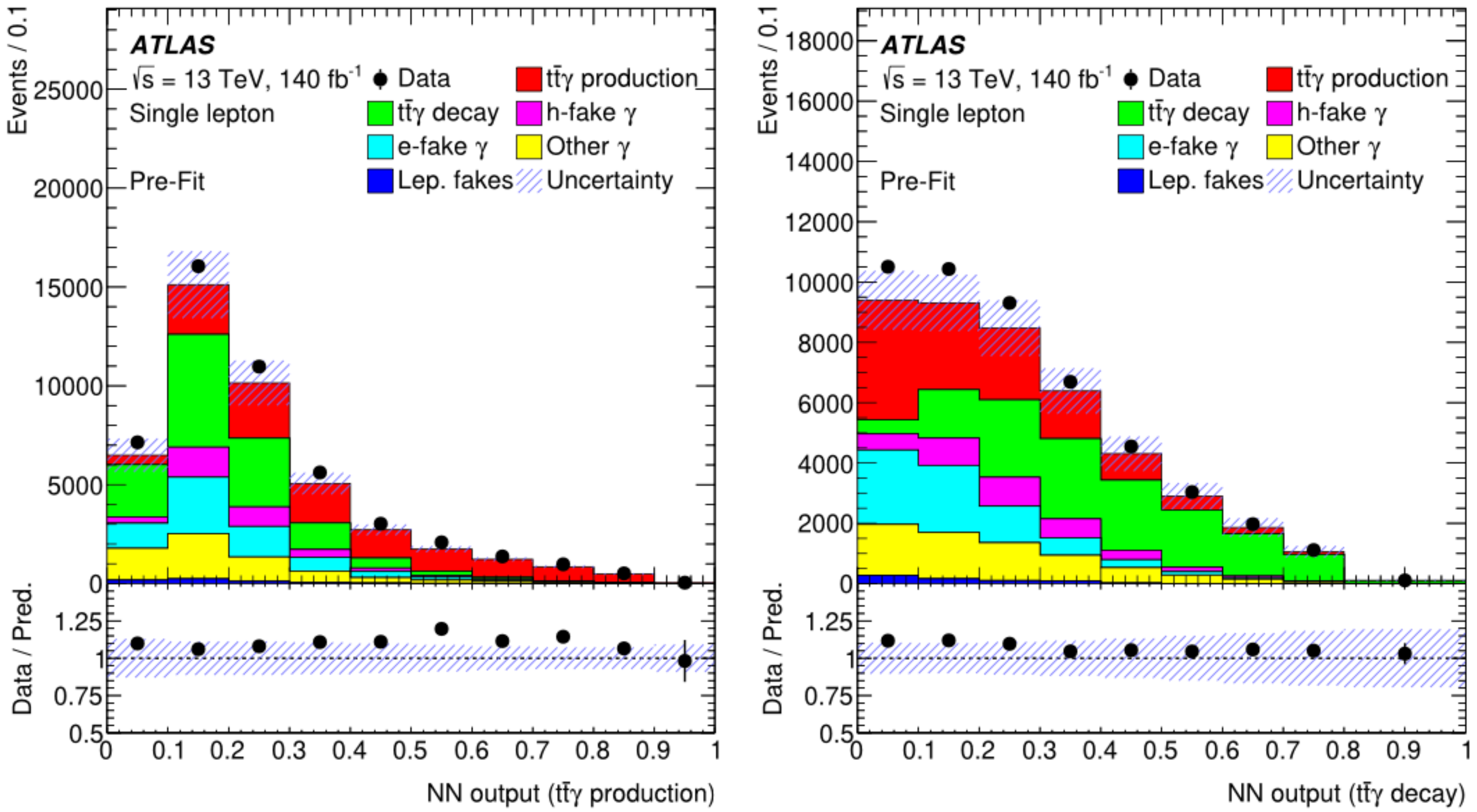
A template-fit method estimates contribution of non-prompt leptons in $3l$ channel using CRs requiring one fail-tight lepton.



# Backup - $t\bar{t}\gamma$ production cross-sections

[JHEP 10 (2024) 191.](#)

- Non-prompt/fake backgrounds estimated using data-driven techniques.
- 3-class NN ($t\bar{t}\gamma$ prod. vs dec. vs bkgs) with 40 input variables is used in single-lepton channel - uses invariant masses from $t\bar{t}\gamma$ reconstruction.




| Category | Single-lepton channel | Dilepton channel |
|---|---|---|
| $t\bar{t}\gamma$ production | $12450 \pm 740$ | $2400 \pm 99$ |
| $t\bar{t}\gamma$ decay | $13400 \pm 3100$ | $3100 \pm 640$ |
| h-fake (‘ABCD method’ →) | $3600 \pm 1200$ | $220 \pm 82$ |
| e-fake (Tag-and-probe →) | $6900 \pm 980$ | $57.9 \pm 7.0$ |
| $W\gamma$ | $2700 \pm 1400$ | — |
| $tW\gamma$ | $1180 \pm 580$ | $290 \pm 150$ |
| Other prompt $\gamma$ | $2500 \pm 600$ | $820 \pm 170$ |
| Lepton fake (‘matrix method’ →) | $640 \pm 110$ | — |
| Total | $43900 \pm 4600$ | $6900 \pm 710$ |
| Data | 47767 | 7379 |

| Category | $t\bar{t}\gamma$ decay classifier | fake $\gamma$ classifier | other prompt $\gamma$ classifier | purity |
|---|---|---|---|---|
| SR $t\bar{t}\gamma$ production | $< 0.15$ | $< 0.2$ | $< 0.5$ | 73% |
| CR $t\bar{t}\gamma$ decay | $> 0.25$ | — | $< 0.4$ | 71% |
| CR fake $\gamma$ | $< 0.15$ | $> 0.2$ | $< 0.5$ | 50% |
| CR Other $\gamma$ | remaining events | | | 26% |

- Subleading $b$-tagging score provides discrimination.
- Binary NN with 26 variables used in dilepton channel.
- Slight underestimate of data is likely due to smaller production cross-section in MC which was observed in previous measurements.

# Backup - Search for same-sign top quarks

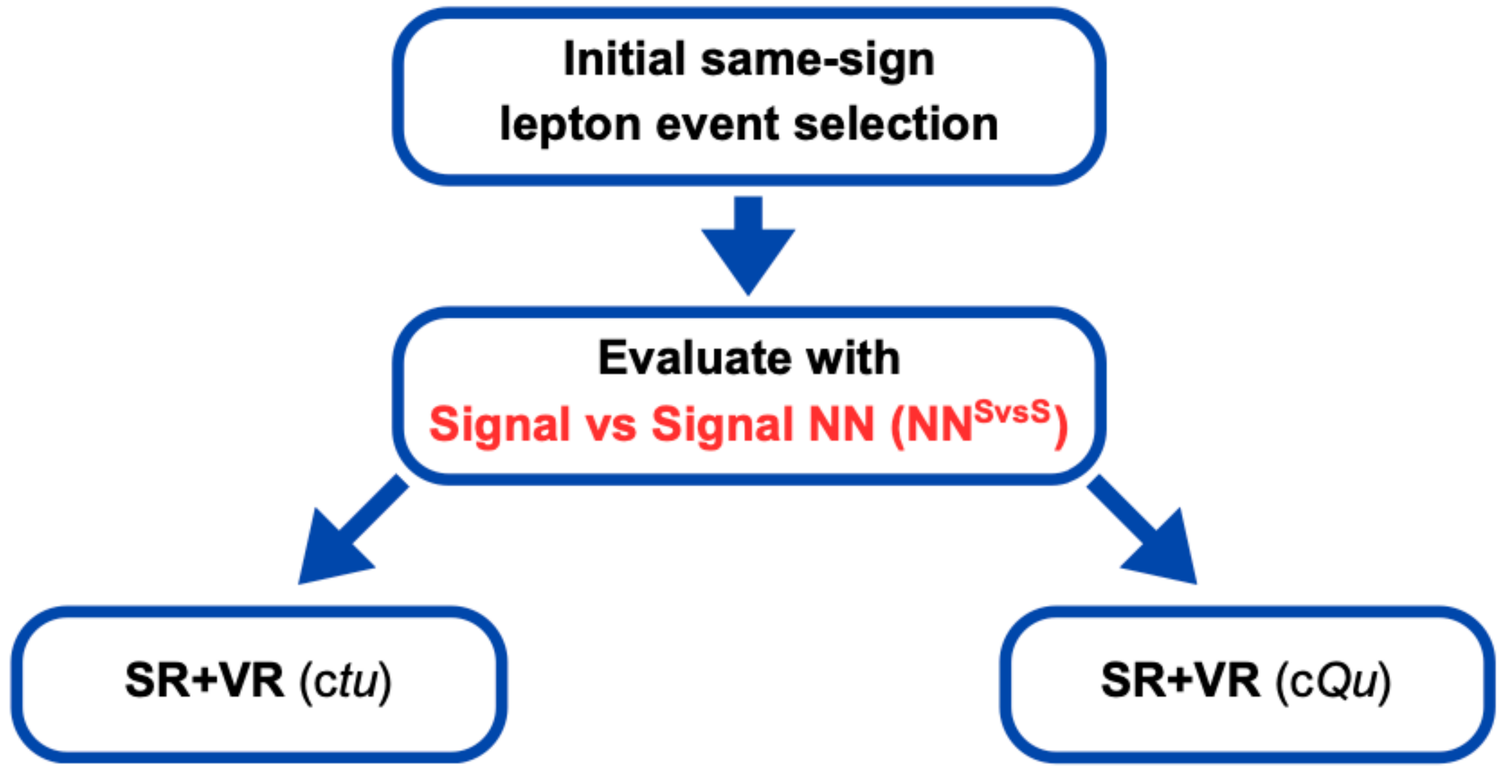
JHEP 02 (2025) 084.

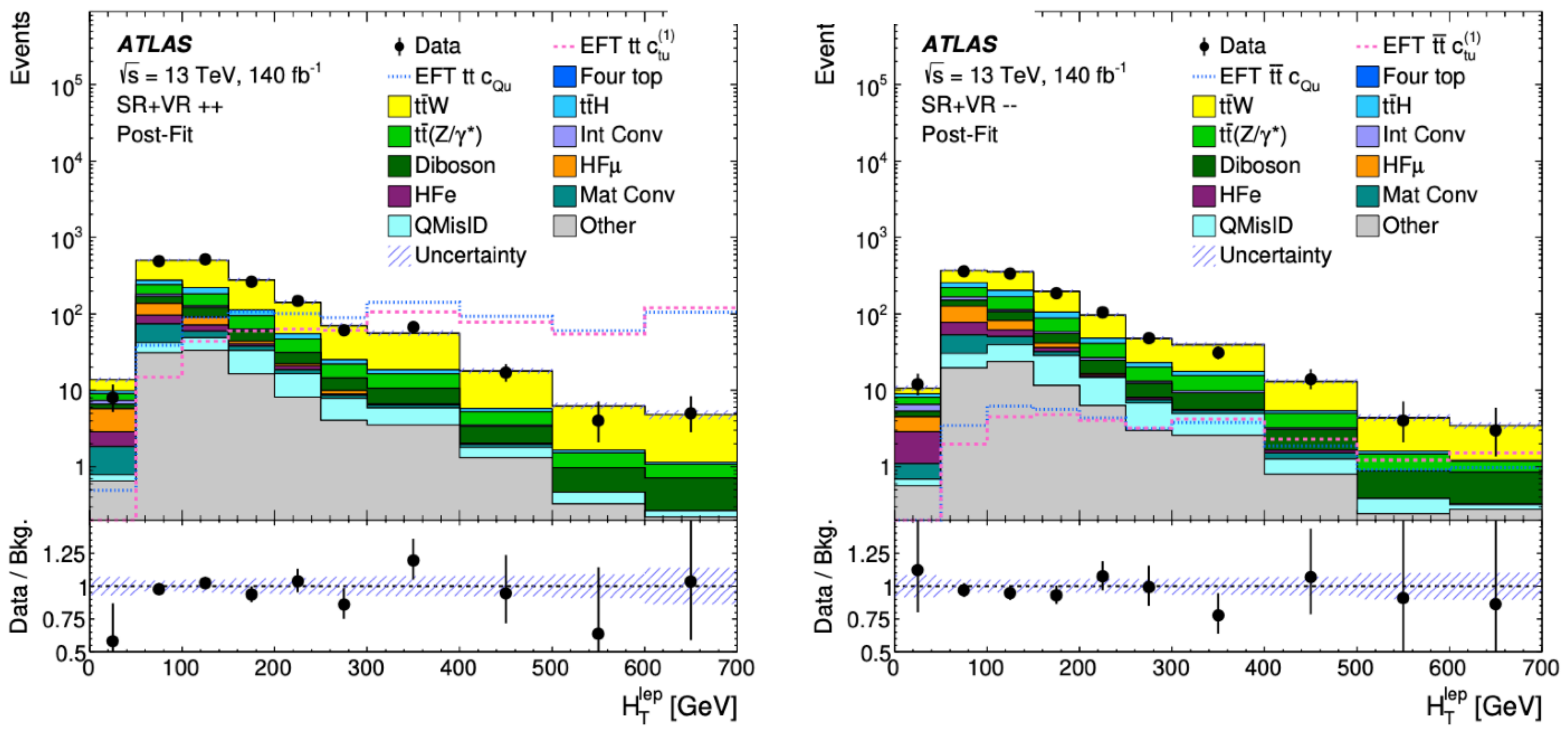
- **Pre-selection makes use of non-prompt lepton BDT WP:**

  Precisely two SS leptons with $p_T > 20$ GeV & at least two jets
  **Either** leptons are *Tight* & both jets satisfy 77% *b*-tag WP;
  **Or** leptons are *VeryTight* & one jet fulfills *b*-tag WP.

- **Signal vs Signal NN:** Trained on two SS-top benchmarks
  Selection on NN has 65% classification efficiency:

| **Efficiency * acceptance** | **SRtu** | **SRQu** |
|---|---|---|
| $\mathcal{O}_{tu}^{(1)}$ | *26.8%* | *12.4%* |
| $\mathcal{O}_{Qu}$ | *15.8%* | *19.5%* |



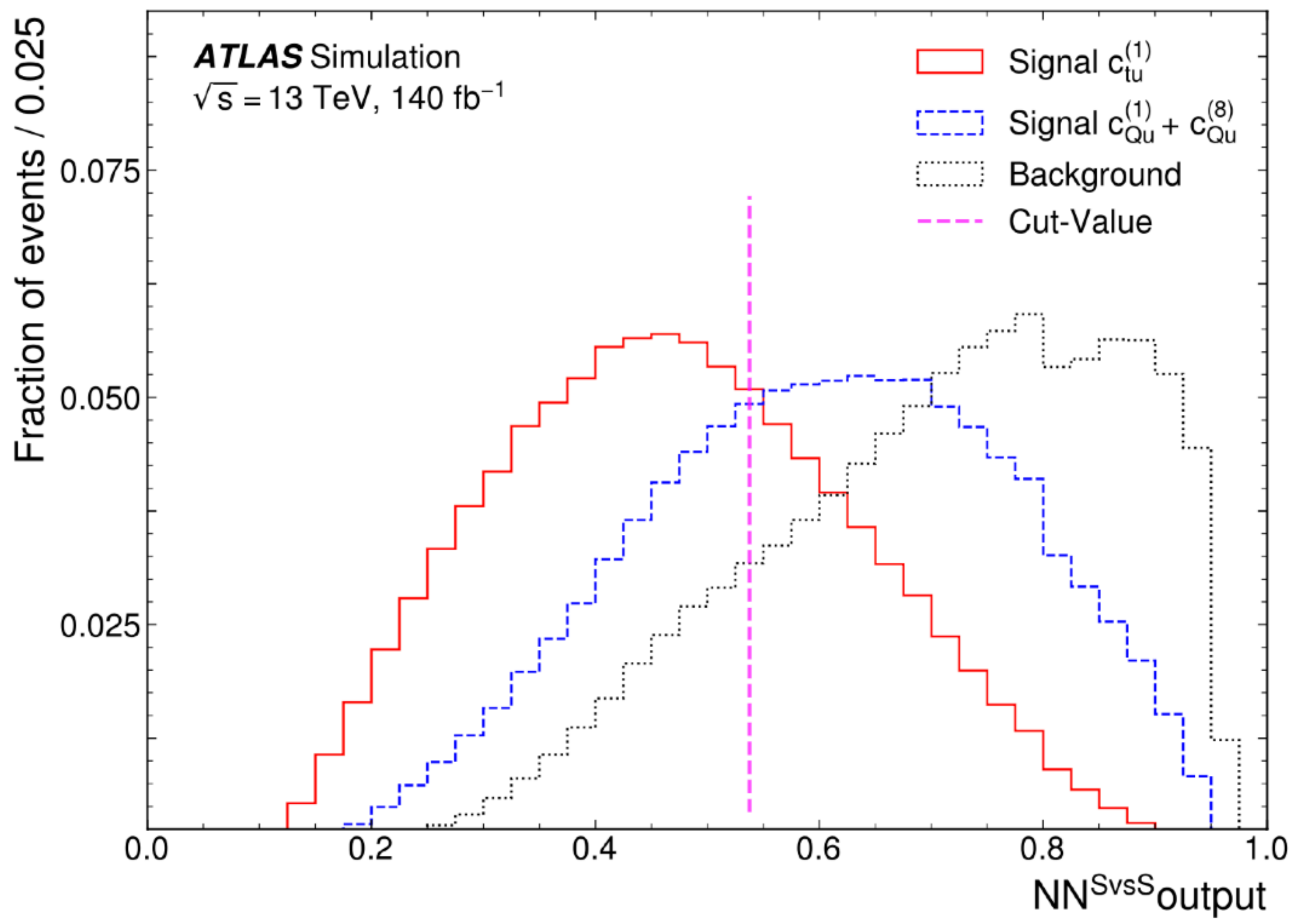

$$c_{tu}^{(1)} = 0.04,\ c_{Qu}^{(1)} = 0,\ c_{Qu}^{(8)} = 0$$

$$c_{tu}^{(1)} = 0,\ c_{Qu}^{(1)} = 0.1,\ c_{Qu}^{(8)} = 0.2$$

# Backup - Search for same-sign top quarks

[JHEP 02 (2025) 084.](#)

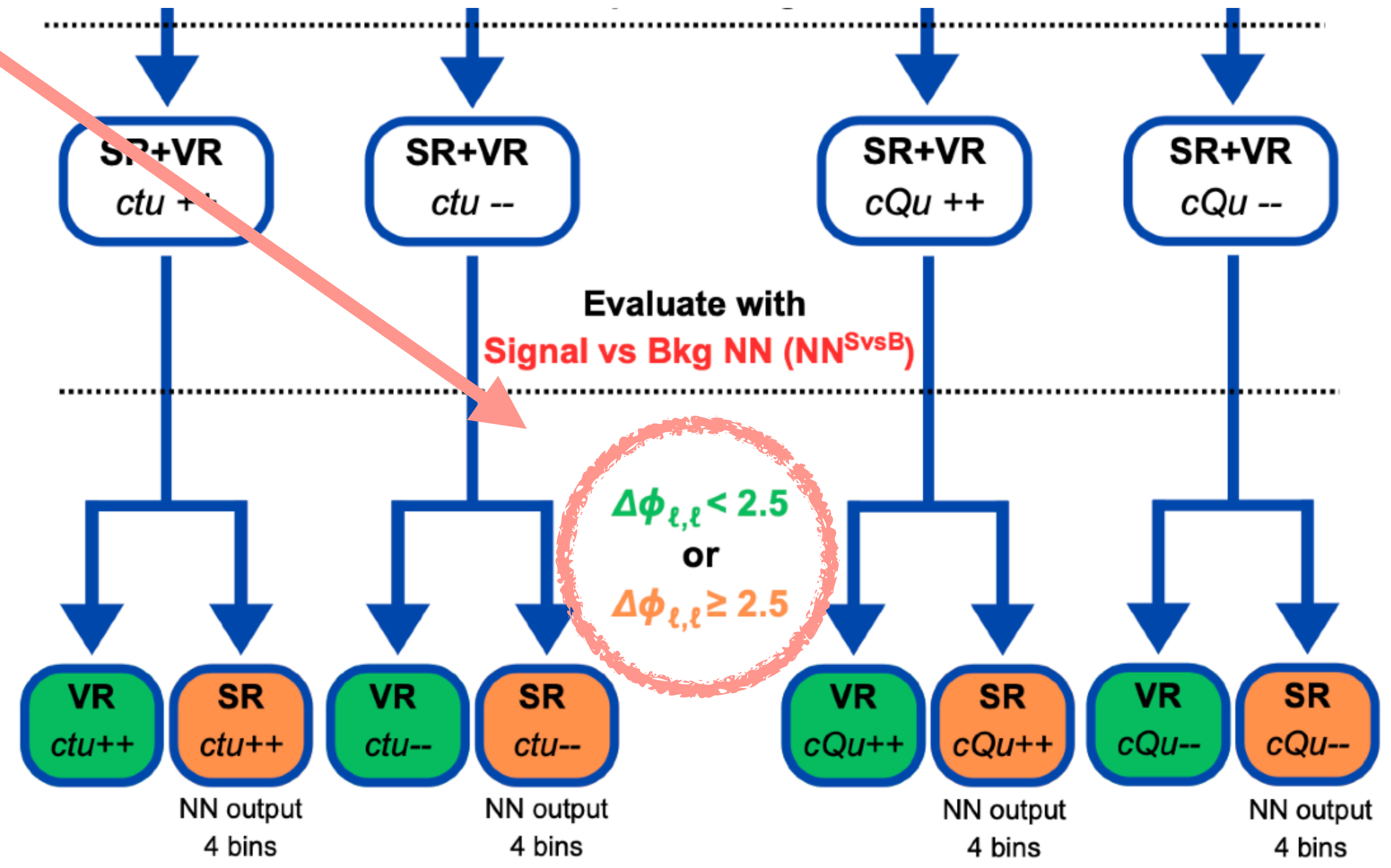
- **Signal vs Bkg NN:** Uses six kinematic quantities which show significant differences between target operator & charge configuration thus trained separately for each of the four SRs.
  - Subsequent cut on angular distribution results in background rejection of ~25% for SR(tu) and ~86% for SR(Qu).




- **Dedicated control regions**

  $t\bar{t}Z$ **and** $VV$: Require two OSSF + one lepton.

  **Non-prompt** leptons from decay of hadrons: at least one lepton is *Tight-not-VeryTight*.



# Backup - Search for same-sign top quarks

JHEP 02 (2025) 084.

- The set of $NN^{SvsS}$ are trained to classify EFT benchmarks using the following nine kinematics quantities:
  - $\Delta\phi_{l,l}$, $\Delta R_{l,l}$, $\Delta\eta_{l,l}$ between the two leptons and $m(l,l)$
  - Scalar sum of the $p_T$ of all the jets and scalar sum of the $p_T$ of all the leptons
  - $p_T$ of the leading jet, $E_T^{miss}$ and the invariant mass of the leptons and $E_T^{miss}$

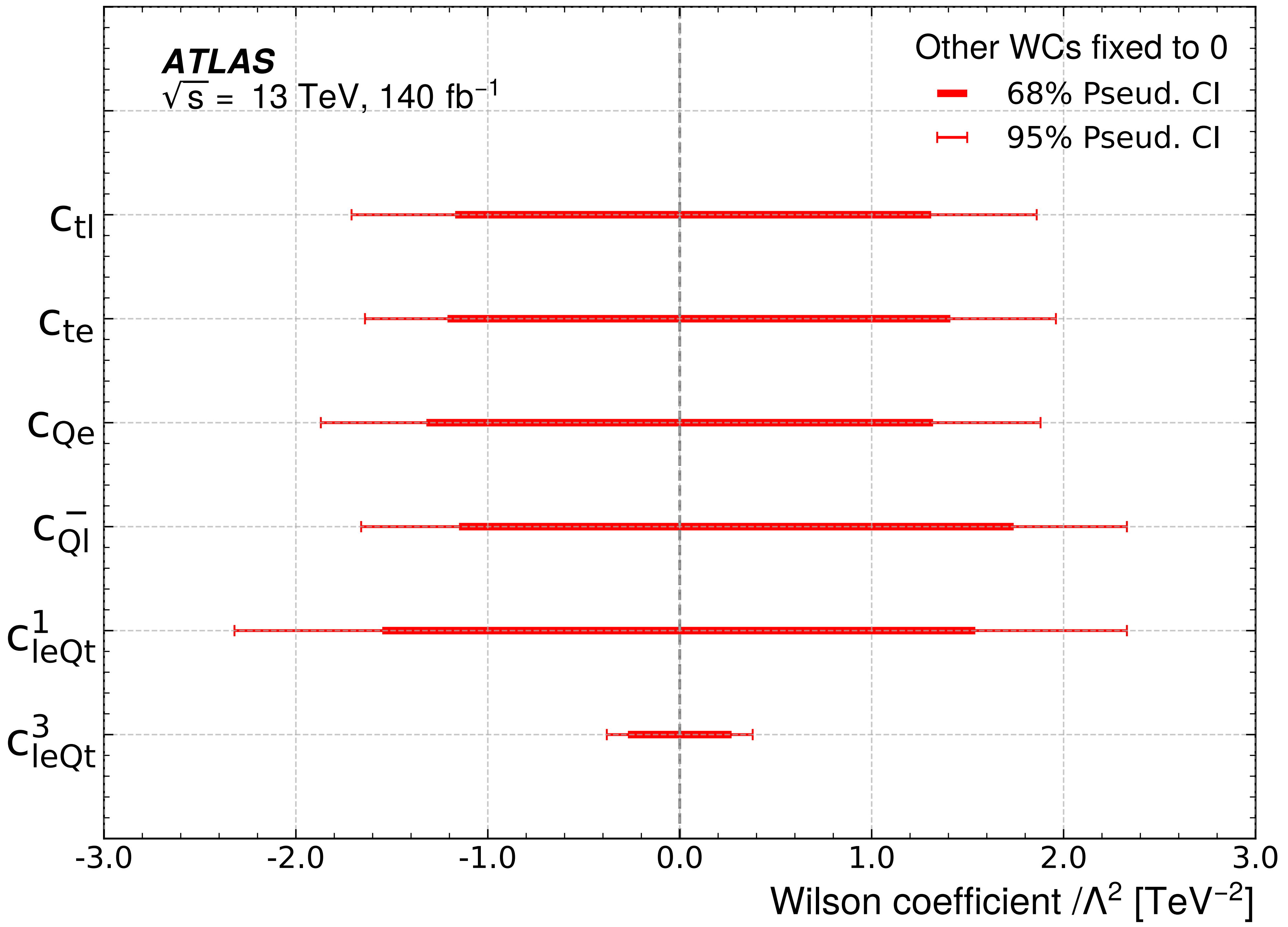
- The set of $NN^{SvsB}$ are trained to classify SS top-quark signal from backgrounds using the following:
  - Sum of the $p_T$ of the leptons, the $p_T$ of the leading jet, and $N_{jets}$
  - $b$-tagging scores of the leading and sub-leading $p_T$ jets
  - The transverse mass of the leptons and $E_T^{miss}$

# Backup - Measurement of high-mass $t\bar{t}l^+l^-$ production

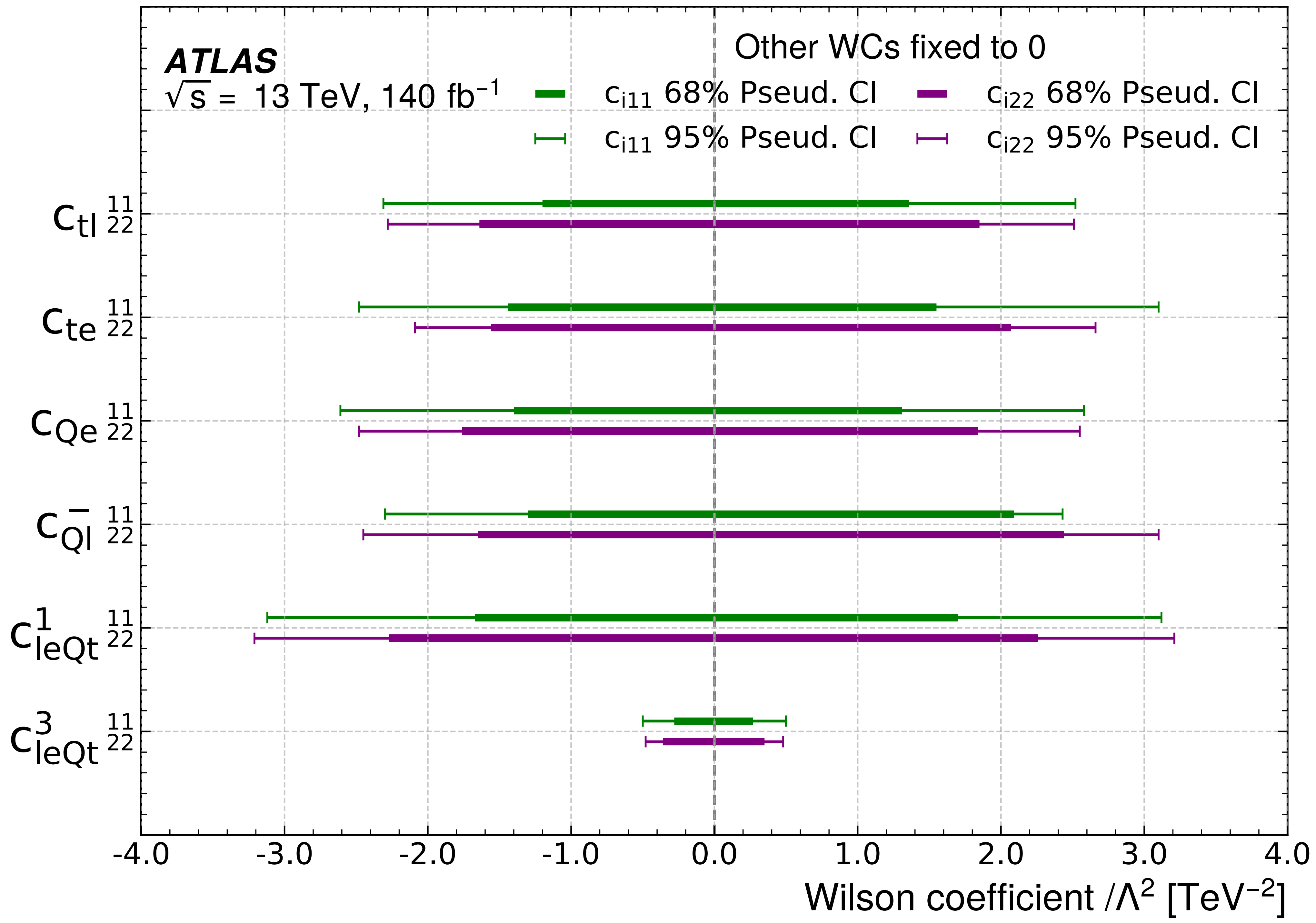
arXiv:2504.05919v1

- Wilks' theorem violation justifies coverage-adjusted CIs using toy pseudodata.

## Flavour inclusive




## Flavour split



# Backup - Measurement of high-mass $t\bar{t}l^+l^-$ production

arXiv:2504.05919v1

- Wilks' theorem violation justifies coverage-adjusted CIs using toy pseudodata.