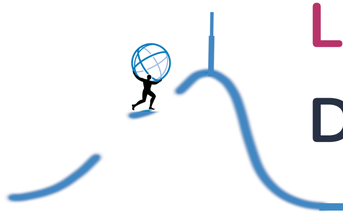


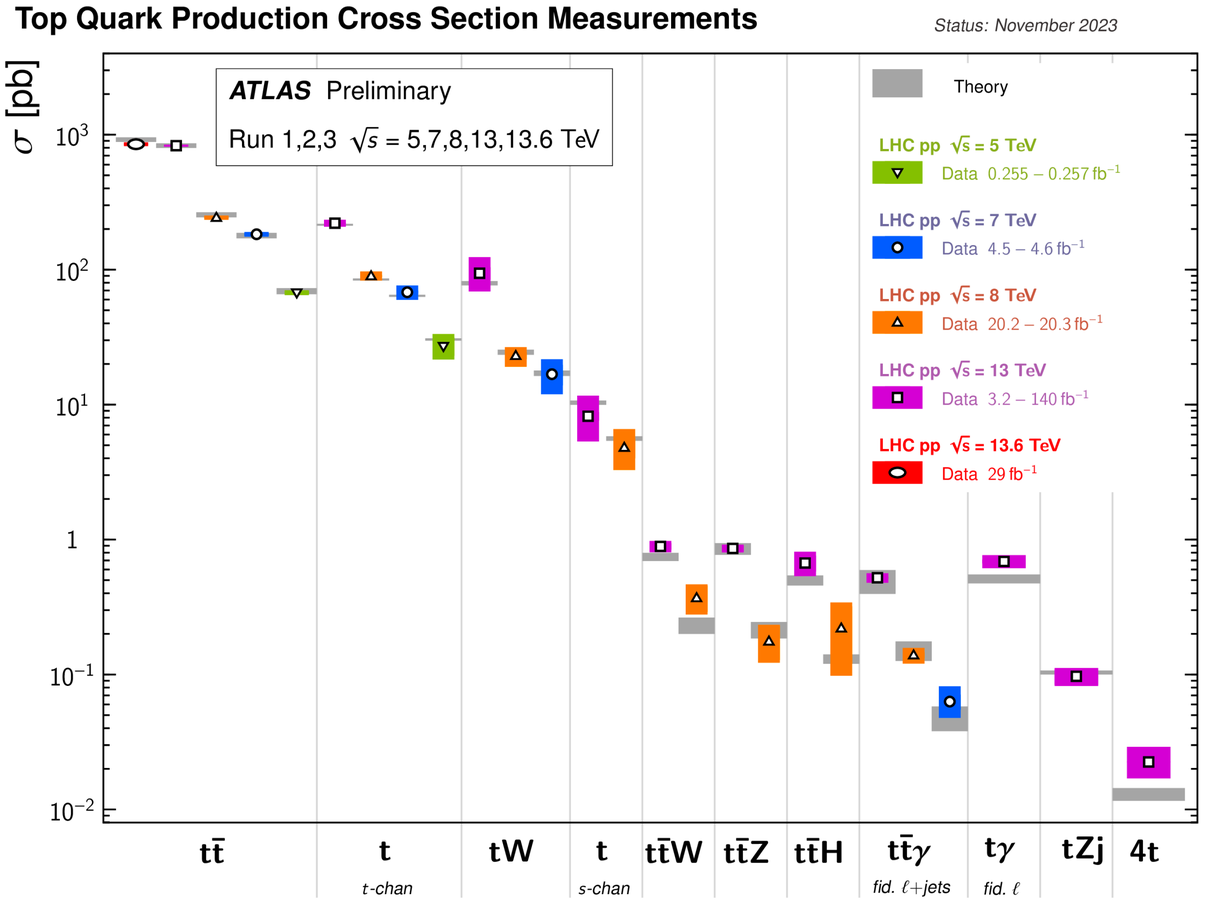
Les rencontres de Moriond 2024 (EW)

D. Boumediene - LPCA Clermont-Ferrand

Top Associated Production in ATLAS and CMS

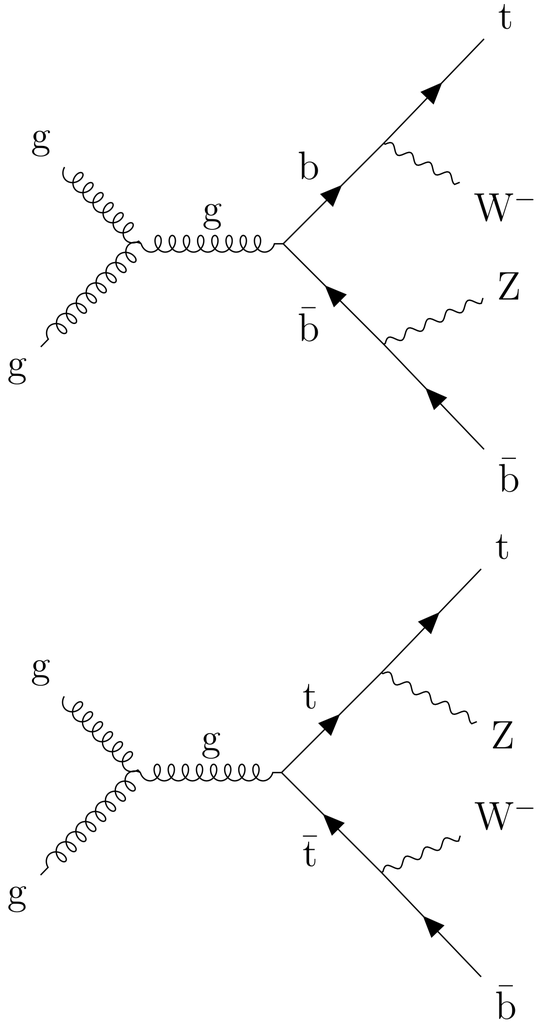
The Frontiers of Top Quark Production at the LHC

- **Variety of processes** with differing cross-sections, some of which are notably small at the LHC.
- **Probing Top Quark Couplings** for understanding Electroweak Symmetry Breaking (EWSB) and searching for new physics.
- **EFT Operators Spectrum:** Sensitive to a wide range of Effective Field Theory (EFT) operators, including t-V vertices and four-fermion vertices.
- **Increasing Precision:** Despite often small cross-sections, the accumulating data from LHC enables probing of smaller processes with enhanced precision.
- **BSM Contributions:** Numerous possibilities for Beyond the Standard Model (BSM) contributions that could modify top quark couplings.
- **Discussed Today:** $t\bar{t}Z, tWZ, t\bar{t}W, t\bar{t}\gamma, tW$ new since Moriond 2023



tWZ production

- **Probing** tZ and tW couplings, could be impacted by BSM physics
- **Interference at NLO in QCD:** some diagrams of the $t\bar{t}Z$ interfere with the tWZ at NLO QCD.
- **Theoretical predictions vs measurements:** compare measurement with theoretical predictions at full next-to-leading order (NLO)

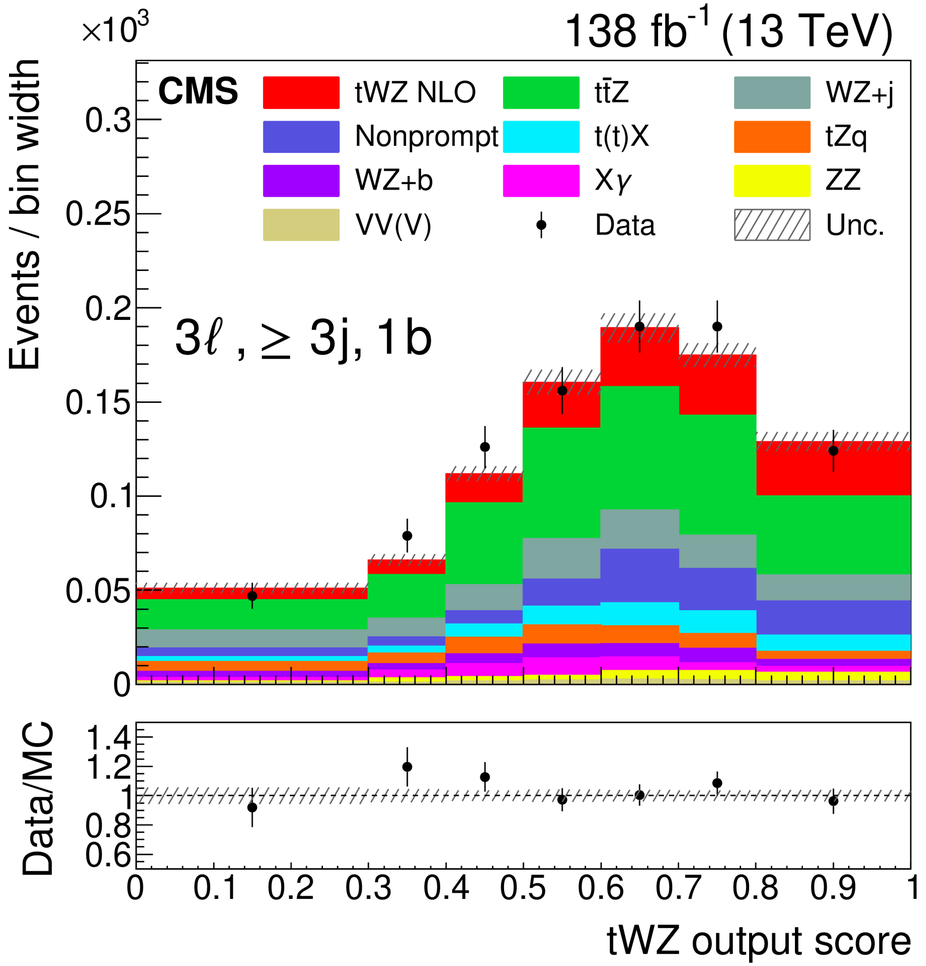


arXiv:2312.11668 (2023)

tWZ production

arXiv:2312.11668 (2023)

- **Control region** to account for di-boson production processes.
- **Employment of DNN classification** to enhance differentiation between the tWZ process and backgrounds.
- **Evidence for tWZ production** with a measured signal strength of **2.6 ± 0.4 (stat) ± 0.7 (syst)**
- **Simultaneous** measurement of $t\bar{t}Z$ and tWZ



Measured tWZ production cross-section in tension with SM predictions

tWZ production

arXiv:2312.11668 (2023)

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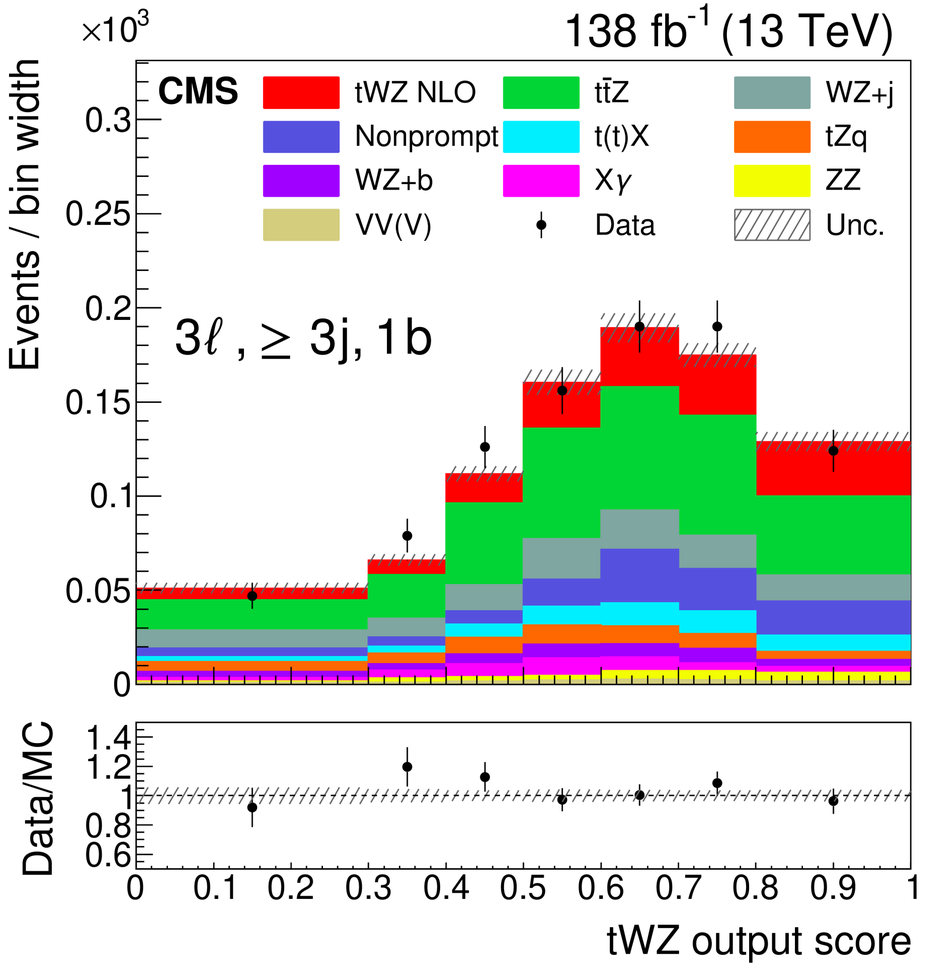

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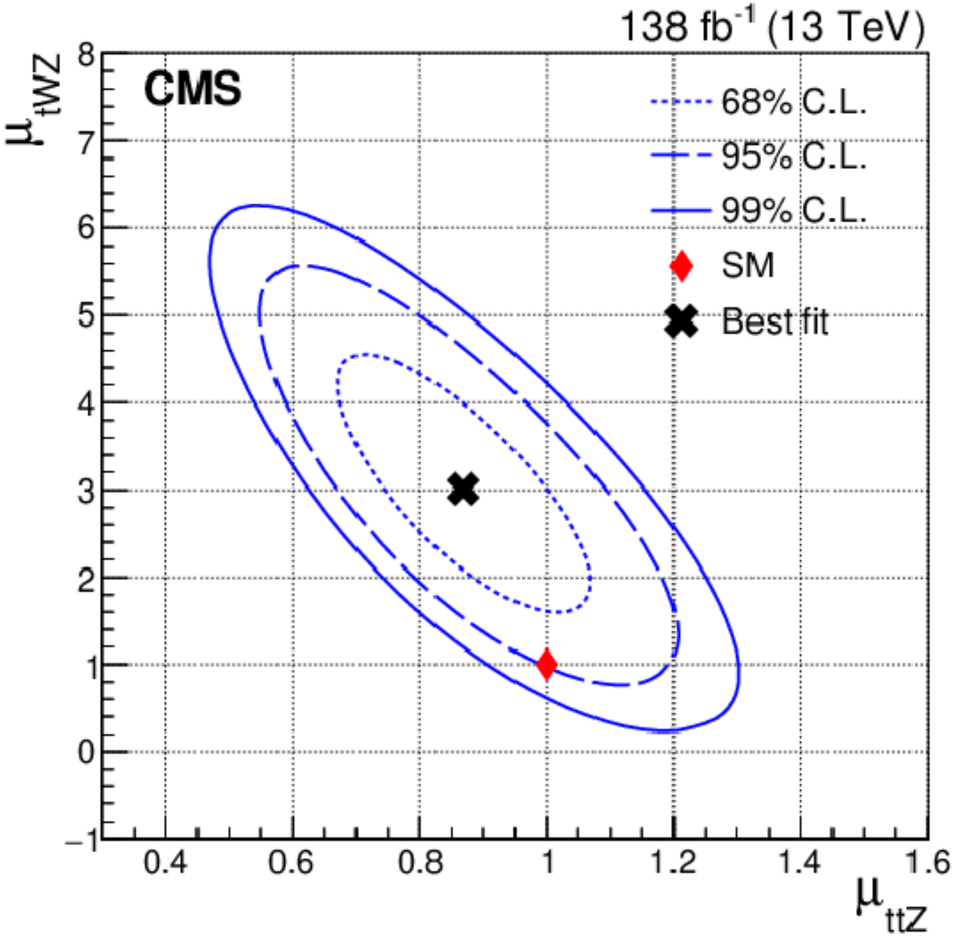
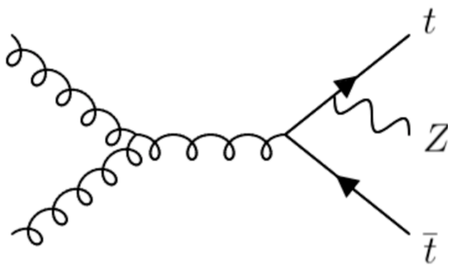
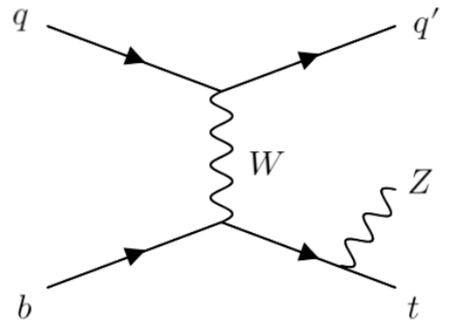


Measured tWZ production cross-section in tension with SM predictions

ttZ, tWZ, tZq production

- **Constraining top-Z and top-W Couplings:** could be impacted by BSM physics.
- ttZ **in rare-Top analyses and BSM Searches:** is an irreducible background in several searches
- **Theoretical predictions vs measurements:** compare measurement with theoretical predictions at full next-to-leading order (NLO), including EW corrections, and enhanced by NNLL accuracy resummation.





ATLAS EXPERIMENT

arXiv:2312.04450 (2023) ➔ $t\bar{t}Z$

NEW!

CMS

CMS-PAS-TOP-23-004 (2024) ➔ $t\bar{t}Z, tWZ, tZ$

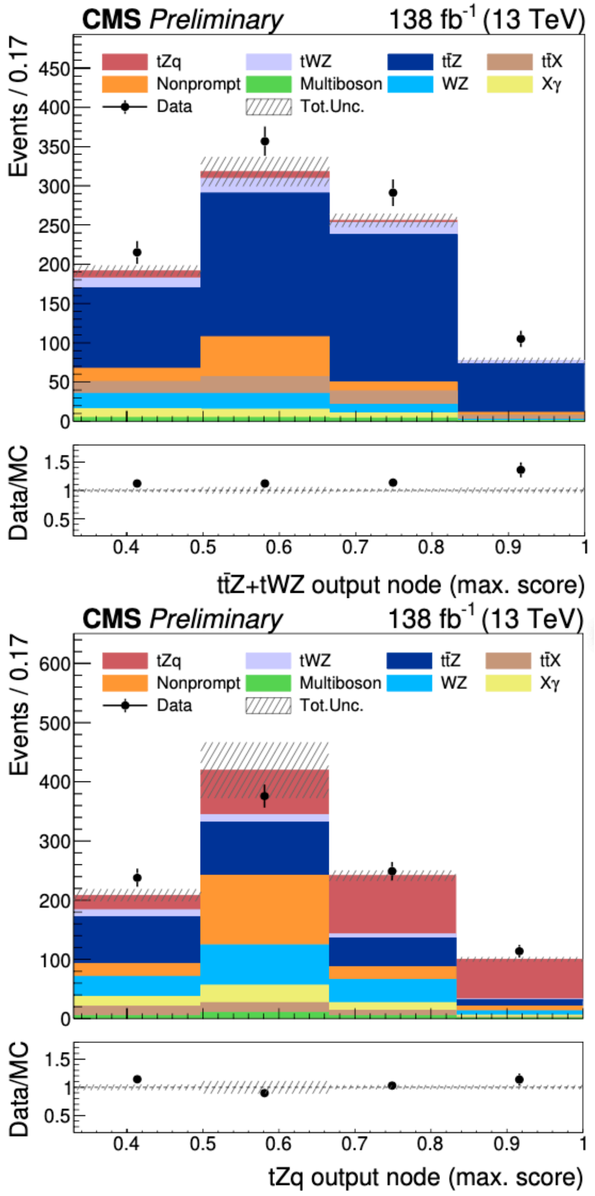
▸ cf. Federica Colombina's talk

ttZ, tWZ, tZq production

- **Leptonic signature:** 3ℓ with a Z mass resonance
- **Main backgrounds:** WZ, $t\bar{t}$ with non-prompt leptons, Z+jets.
- **Multivariate analysis for classification:** multiclass deep neural network (DNN) creates 3 categories: $t\bar{t}Z + tWZ$, tZq, backgrounds
- **Inclusive measurement:** performed in the 3ℓ, adding 4ℓ channel. Independent and first simultaneous measurement of $t\bar{t}Z$ and tWZ production cross-sections.
- **Differential measurement:** performed for $t\bar{t}Z + tWZ$ and tZq productions at parton level.

CMS-PAS-TOP-23-004 (2024)

NEW!



ttZ, tWZ, tZq production

CMS-PAS-TOP-23-004 (2024)

NEW!

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- **Inclusive measurement:** performed in the 3ℓ, adding 4ℓ channel. Independent and first simultaneous measurement of $t\bar{t}Z$ and tWZ production cross-sections.
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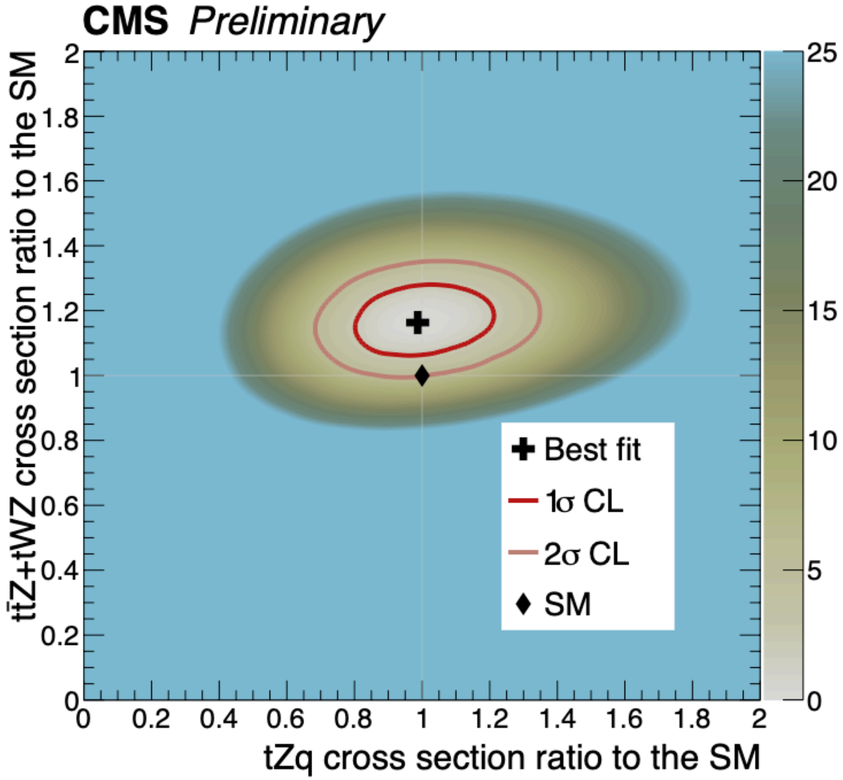

$$\sigma(t\bar{t}Z + tWZ) = 1.14 \pm 0.05\,(\text{stat}) \pm 0.04\,(\text{syst})\ \text{pb}$$

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

tZq measurement in agreement with SM predictions

$t\bar{t}Z + tWZ$ measurement in tension with SM predictions

ttZ, tWZ, tZq production

CMS-PAS-TOP-23-004 (2024)

NEW!

- **Leptonic signature:** 3ℓ with a Z mass resonance
- **Main backgrounds:** WZ, $t\bar{t}$ with non-prompt leptons, Z+jets.
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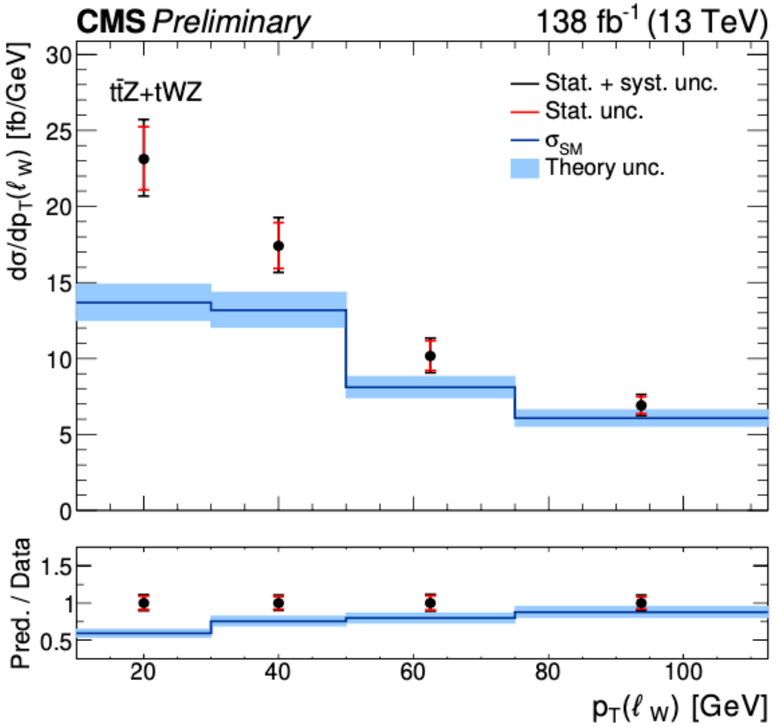


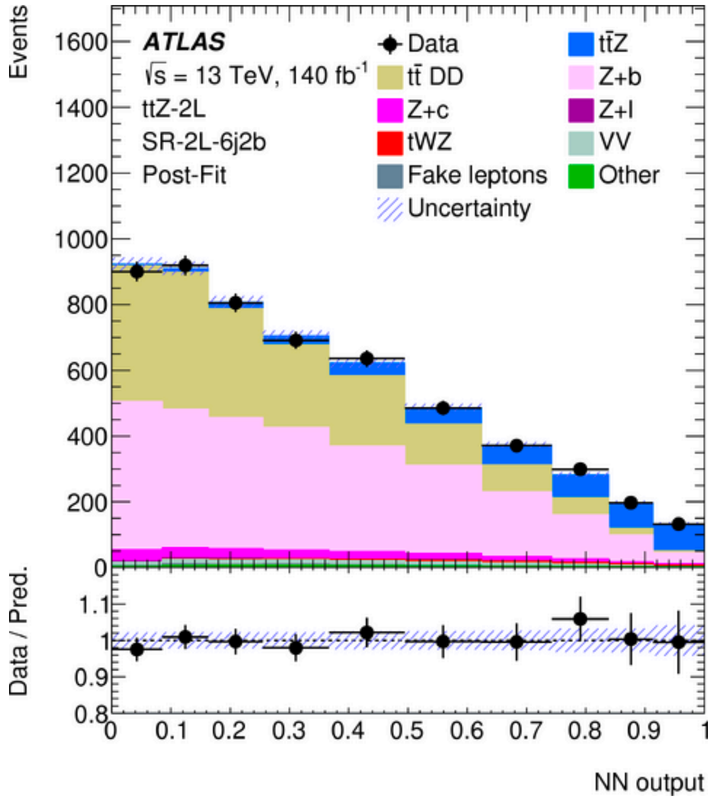
$t\bar{t}Z + tWZ$ measurement: higher tension at low top lepton p_T

▸ cf. Federica Colombina's talk for more details

ttZ production

- **Orthogonal channels by lepton multiplicity:** 2ℓ, 3ℓ, 4ℓ
- **Main backgrounds:** $t\bar{t}$, Z+jets, tZq, diboson (particularly WZ+jets and ZZ+jets), with heavy-flavour components in 3ℓ, 4ℓ.
- **Multivariate analysis for discrimination:** deep neural networks (DNNs)
- **Differential measurement:** performed in the 3ℓ and 4ℓ channels at parton and particle level.
- **Top quark spin correlation** using angular information
- **EFT interpretation** using SMEFT, top–boson scenario and four-quark scenario

arXiv:2312.04450 (2023)



$$\sigma_{t\bar{t}Z} = 0.86 \pm 0.06\,\text{pb} = 0.86 \pm 0.04(\text{stat.}) \pm 0.04(\text{syst.})\,\text{pb}.$$

$$\sigma_{t\bar{t}Z}^{\text{NLO+NNLL}} = 0.86^{+0.08}_{-0.09}\,\text{pb}$$

Measurement in agreement with SM predictions (arXiv:1610.07922)

ttZ production

arXiv:2312.04450 (2023)

- **Orthogonal channels by lepton multiplicity:** 2ℓ, 3ℓ, 4ℓ
- **Main backgrounds:** $t\bar{t}$, Z+jets, tZq, diboson (particularly WZ+jets and ZZ+jets), with heavy-flavour components in 3ℓ, 4ℓ.
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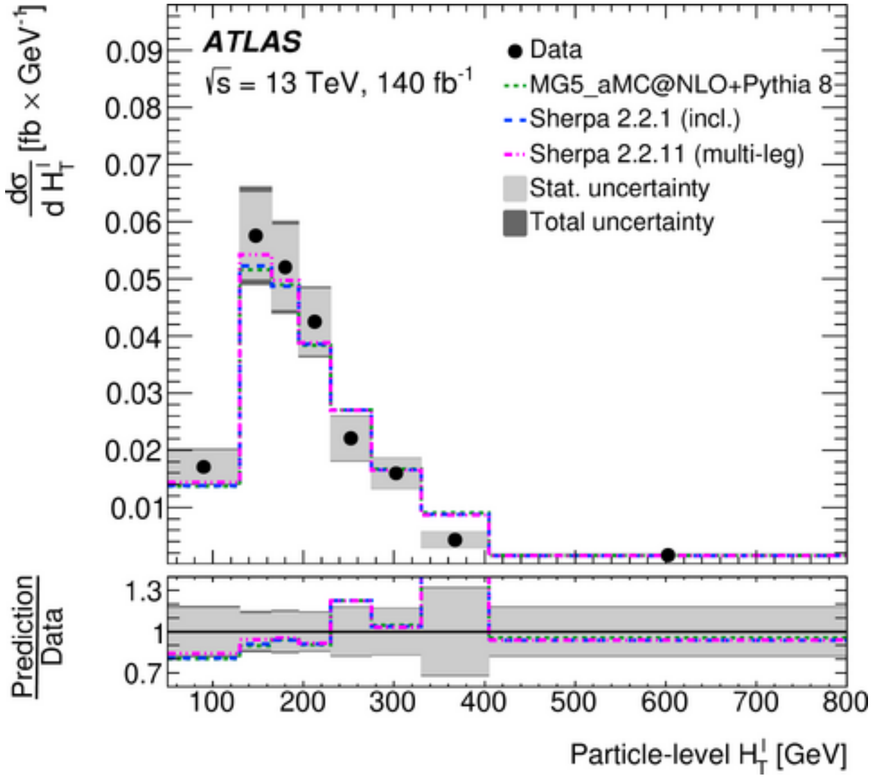

- **Unfolded cross-sections as a function of** 13 variables

Measurement in agreement with SM predictions

ttZ production

- **Orthogonal channels by lepton multiplicity:** 2ℓ, 3ℓ, 4ℓ
- **Main backgrounds:** $t\bar{t}$, Z+jets, tZq, diboson (particularly WZ+jets and ZZ+jets), with heavy-flavour components in 3ℓ, 4ℓ.
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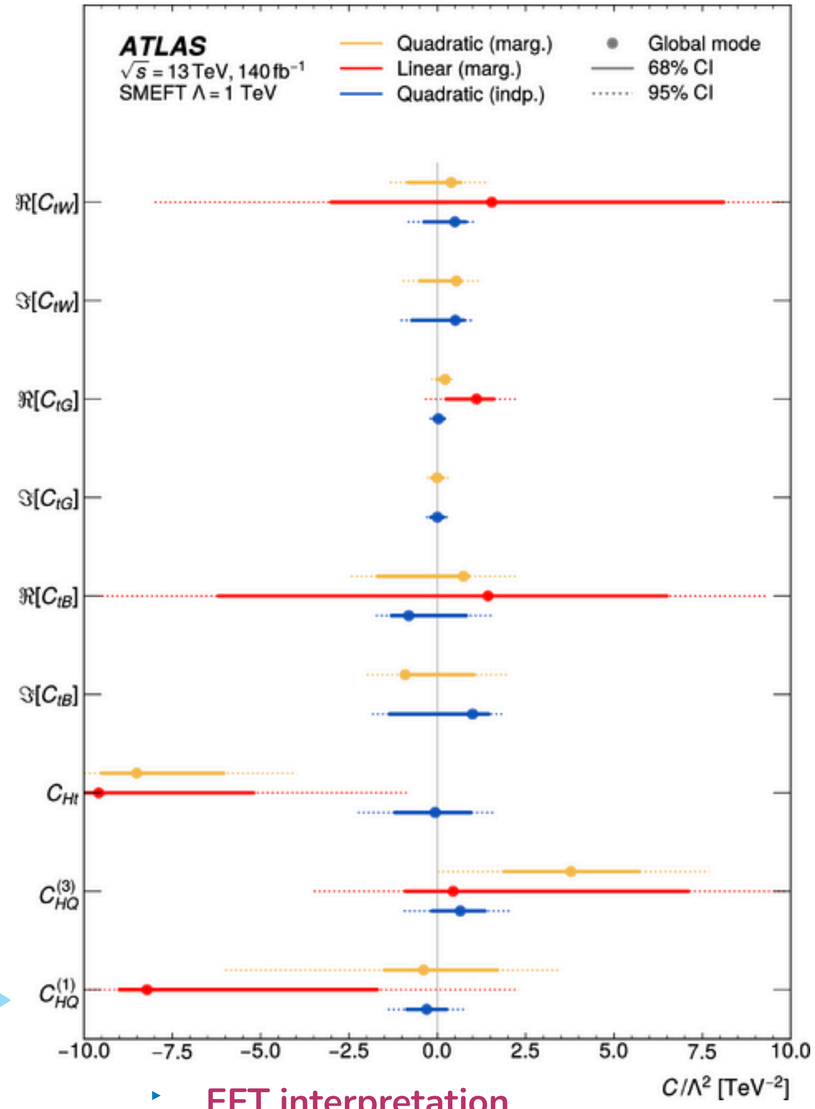
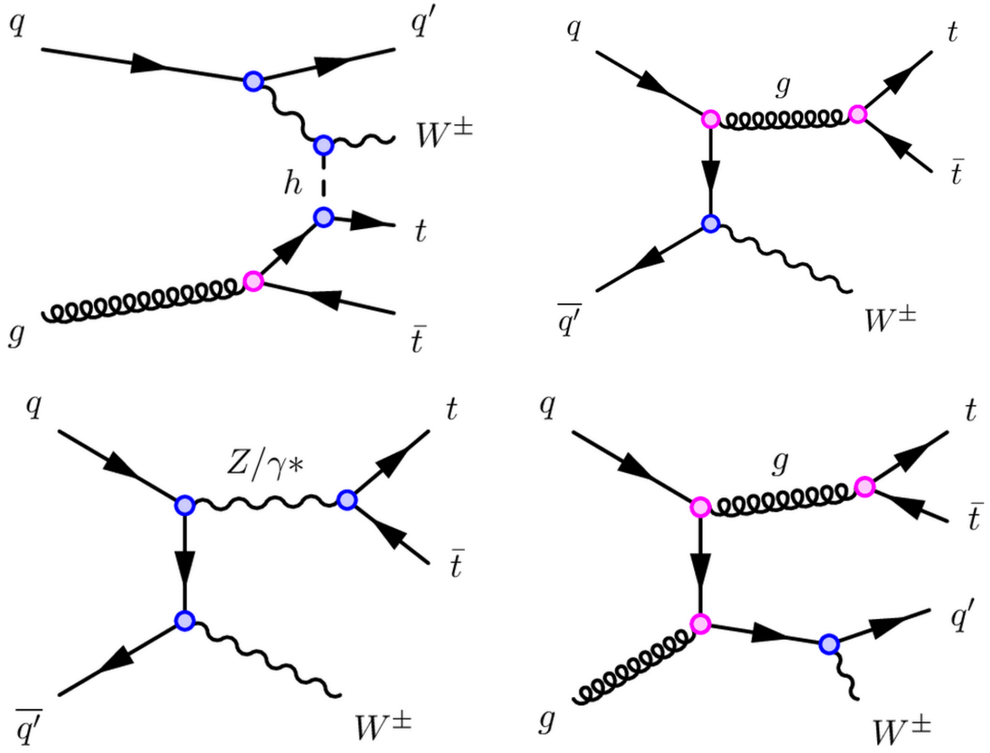


- EFT interpretation
- No significant deviation observed

▸ cf. Mark Owen's talk on EFT

ttW production

- **Key to background understanding:** Major background for many LHC searches, especially for processes that yield same-sign dilepton pairs.
- **Signal modelling** is sensitive to higher-order corrections.
- **Resolving data-model tensions:** precise measurements can address discrepancies observed in previous measurements (ttH).



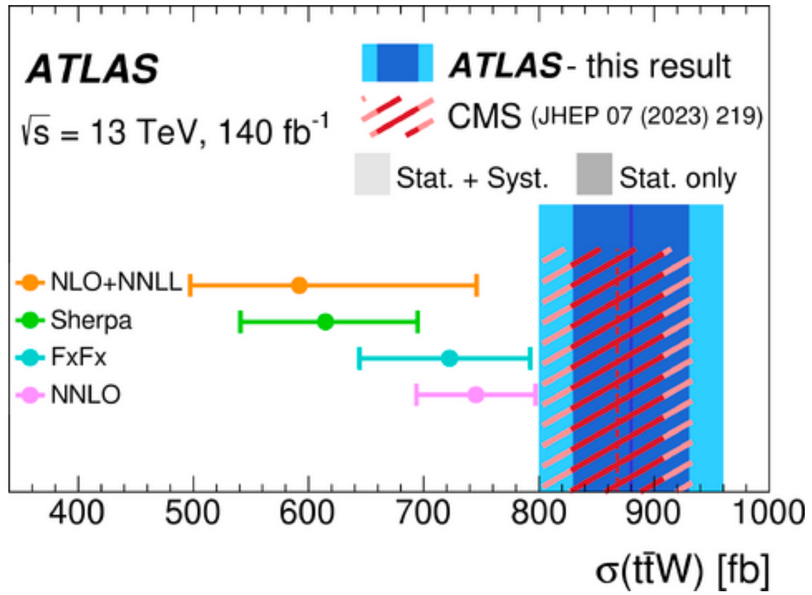
arXiv:2401.05299

JHEP 07 (2023) 219

ttW production

arXiv:2401.05299

- **Signature:** same-charge 2ℓ and 3ℓ.
- **Main irreducible backgrounds** $t\bar{t}Z/\gamma^*$, WZ and $t\bar{t}H$
- **Control regions for background normalisation:** diboson, $t\bar{t}Z$, electron-from-photon conversions and leptons from hadron decays.
- **Subcategories for measurement:** events in SRs are further subdivided for inclusive or differential $t\bar{t}W$ cross-section measurements, with **48** 2ℓ and **8** 3ℓ categories.
- **Measurement:** multiclass neural network (2ℓ) and $m_{\ell\ell\ell}$ (3ℓ) for best precision on cross-section



- **Standard Model** NNLO cross-section

$$745 \pm 50\,(\text{scale}) \pm 13(2\text{ loop app.}) \pm 19(\text{PDF}, \alpha_s)\,\text{fb}$$

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

Measured inclusive cross-section compatible with SM NNLO prediction at 1.5 σ (Phys. Rev. Lett. 131 (2023) 231901)

ttW production

arXiv:2401.05299

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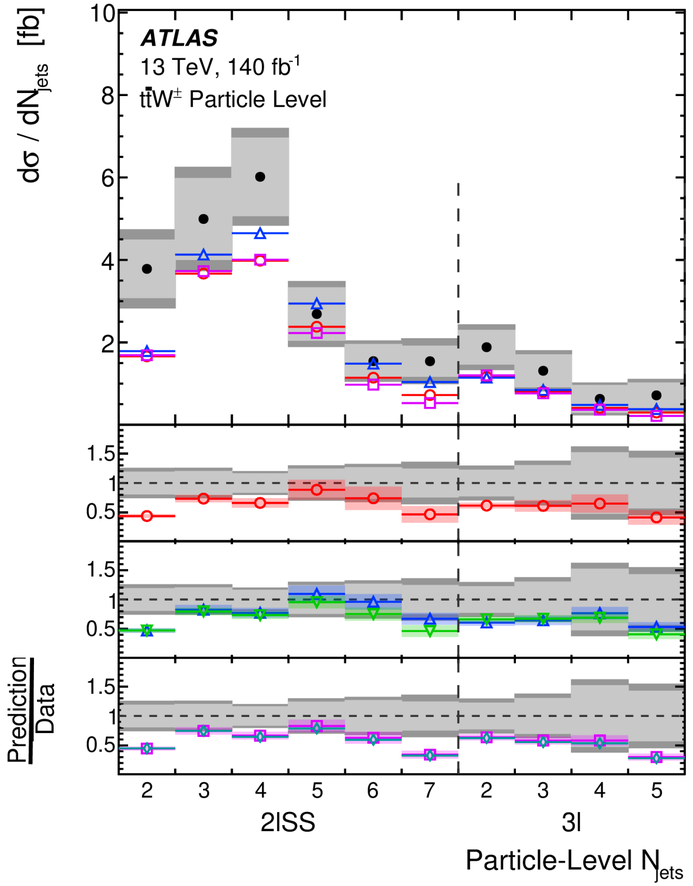

Unfolded cross-sections as a function of:

Event kinematic (N_{jets}, H_T), distances ($\Delta\phi_{\ell\ell}$,$\Delta\eta_{\ell\ell}$, $\Delta R_{\ell b}$)

ttW production

JHEP 07 (2023) 219

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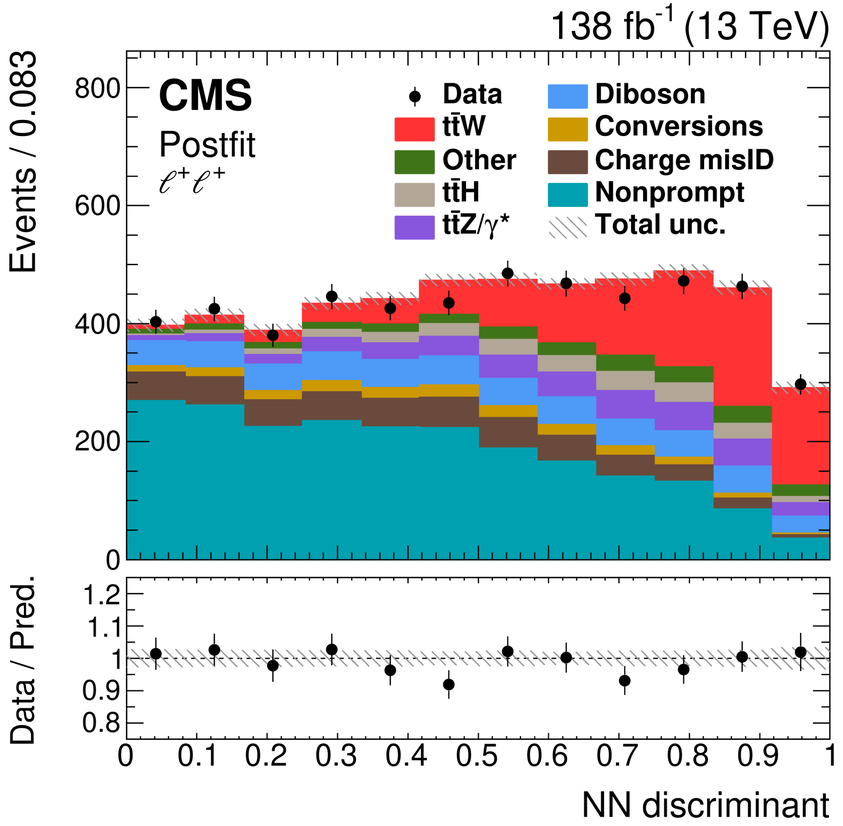
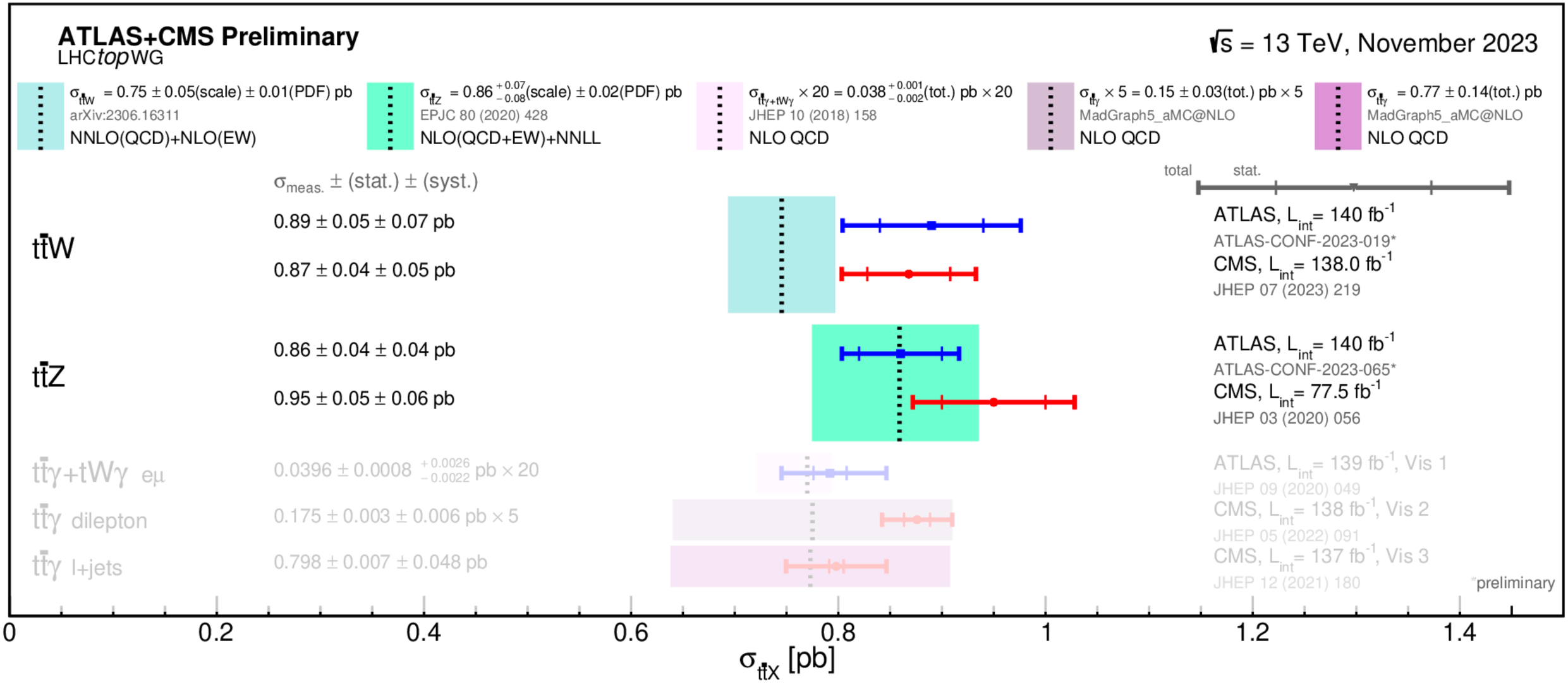


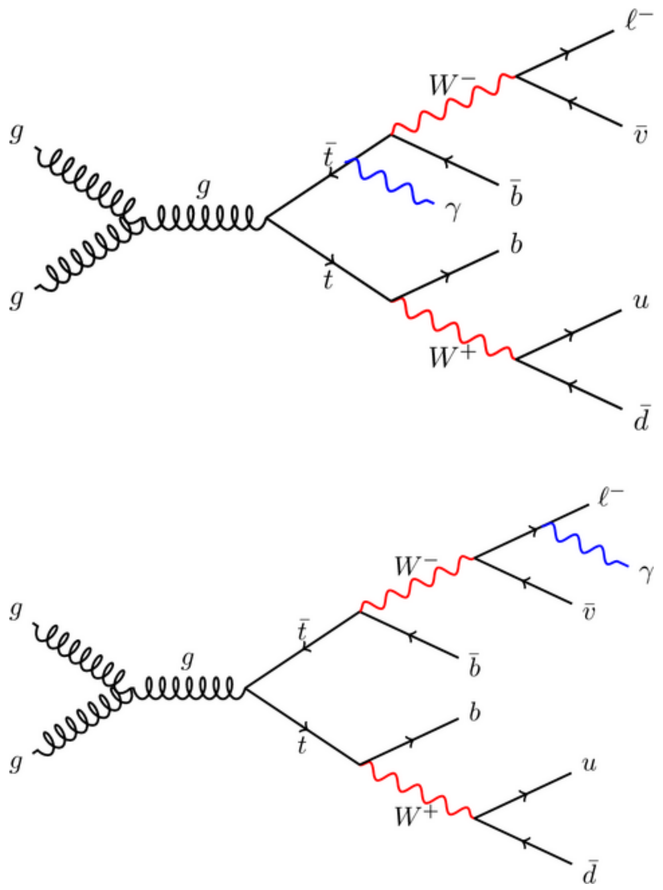
$\sigma(t\bar{t}W) = 868 \pm 40\,(\text{stat}) \pm 51\,(\text{syst})\,\text{fb}$

Overview of ATLAS and CMS ttV measurements



$t\bar{t}\gamma$ production

- **Probing $t\gamma$ Electroweak Coupling**
- **First evidence of $t\bar{t}\gamma$ production** by the CDF Collaboration. Several inclusive/differential cross-sections at LHC.
- **EFT interpretations** allow for constraining of Wilson parameters. Sensitive to potential anomalous dipole moments of the top quark.
- **Asymmetry in top quark production**: differences in rapidity distributions between top quarks and antiquarks. Enhanced in $t\bar{t}\gamma$ production due to the larger fraction of quark–antiquark-initiated events.



ATLAS EXPERIMENT

arXiv:2403.09452 (2024) **NEW!**

Phys. Lett. B 843 (2023)

CMS

JHEP 12 (2021) 180

JHEP 05 (2022) 091

$t\bar{t}\gamma$ production

JHEP 05 (2022) 091

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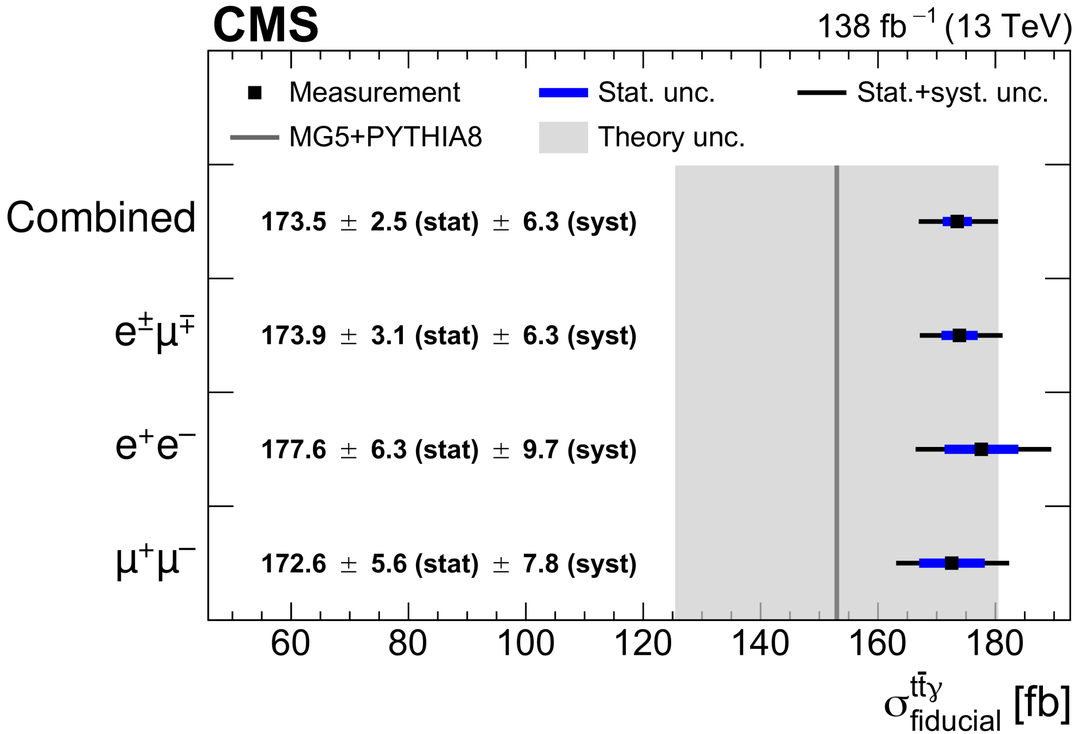


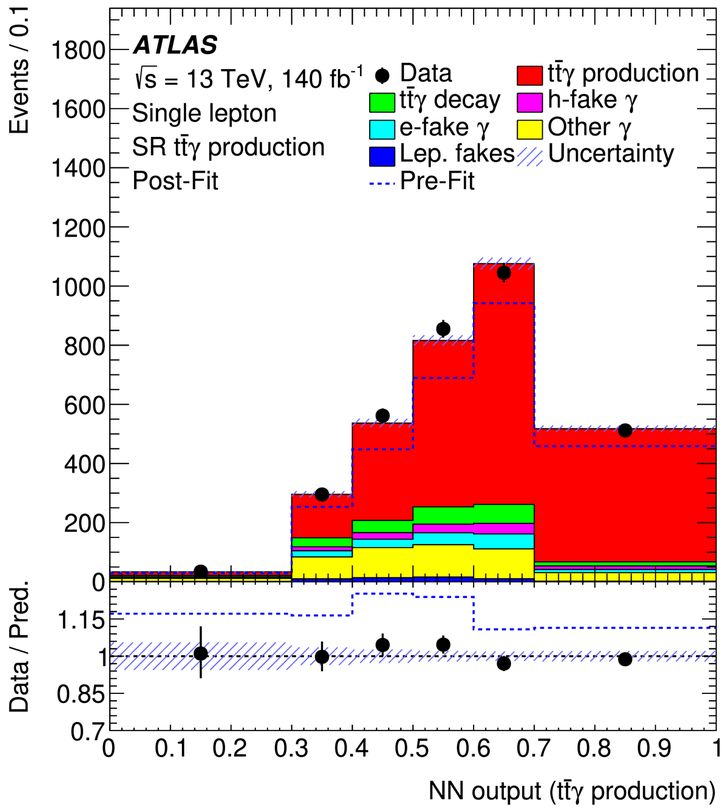
$$\sigma_{\text{fid}}(\text{pp} \to \text{t}\bar{\text{t}}\gamma) = 175.2 \pm 2.5\,(\text{stat}) \pm 6.3\,(\text{syst})\,\text{fb}$$
$$\sigma_{\text{SM}}(\text{pp} \to \text{t}\bar{\text{t}}\gamma) = 155 \pm 27\,\text{fb}.$$

Measurement of fiducial cross-section in agreement with SM predictions

$t\bar{t}\gamma$ production

arXiv:2403.09452 (2024) **NEW!**

- **Signature:** 1ℓ and 2ℓ.
- **Control regions** to account for misidentified photons.
- **Employment of NN classification:** multiclass in 1ℓ and binary in 2ℓ
- **Inclusive cross-section measured for:**
  - $t\bar{t}\gamma$ production (with $t\gamma$ coupling)
  - total $t\bar{t}\gamma$ production (regardless from γ origin)
- **Differential cross-sections measured for** several variables
- **Limits set on EFT parameters** related to EW dipole moment of the top quark. Combination with $t\bar{t}Z$ measurement.



Measurement of incl. cross-section in agreement with SM predictions

$t\bar{t}\gamma$ production

arXiv:2403.09452 (2024) **NEW!**

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- **Employment of NN classification:** multiclass in 1ℓ and binary in 2ℓ
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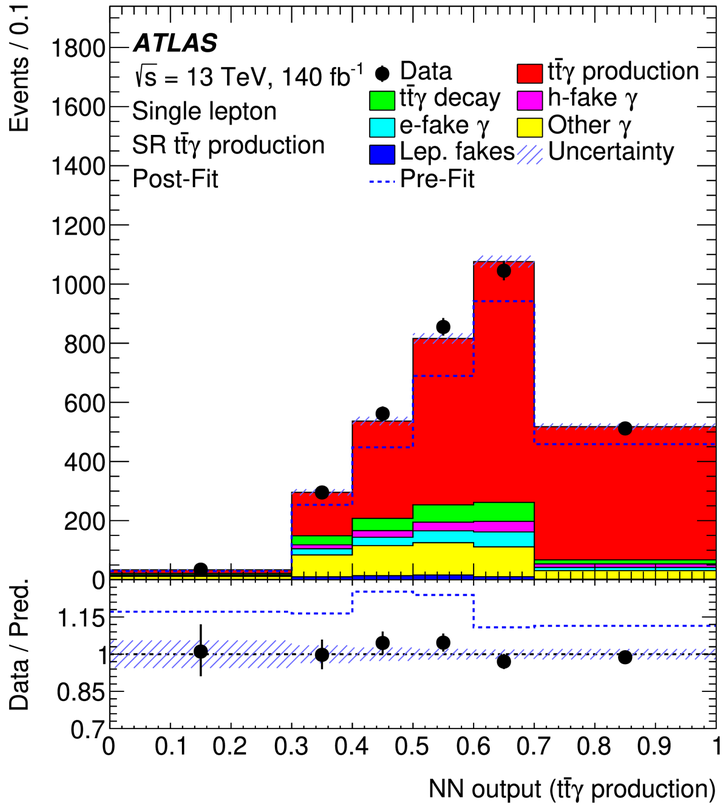

$$\sigma_{t\bar{t}\gamma \text{ production}} = 322^{+16}_{-15}\ \text{fb} = 322 \pm 5\ (\text{stat}) \pm 15(\text{syst})\ \text{fb}.$$

NLO MG5: $299^{+29}_{-30}(\text{scale})^{+7}_{-4}(\text{PDF})\ \text{fb}$

Measurement of incl. cross-section in agreement with SM predictions

$t\bar{t}\gamma$ production

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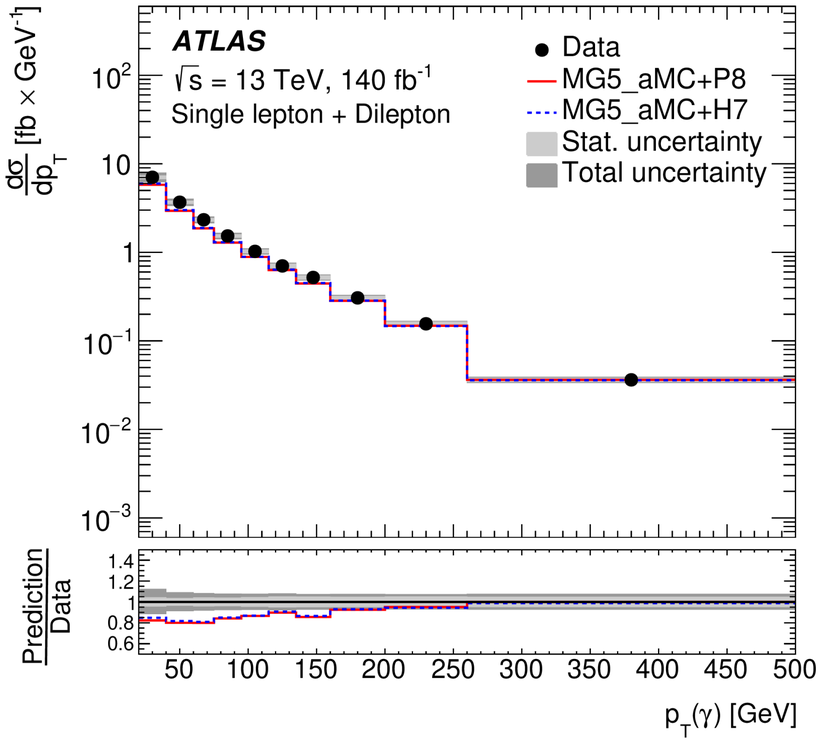

Unfolded cross-sections as a function of:
Photon, lepton, jet kinematics and separation

Observables in good agreement with Monte Carlo predictions

$t\bar{t}\gamma$ production

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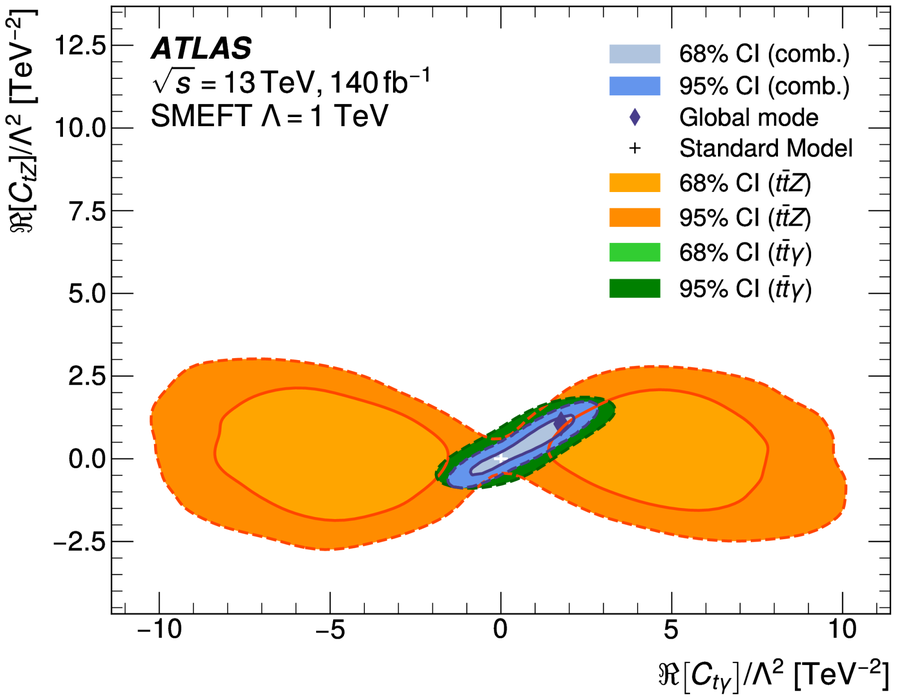


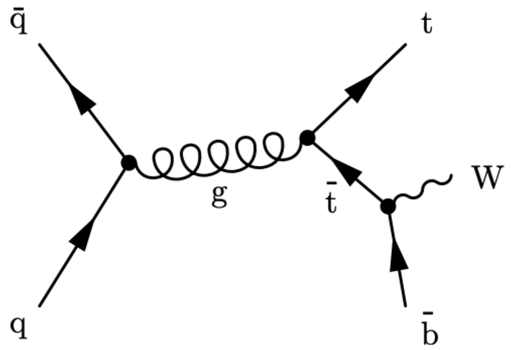
$t\bar{t}\gamma$ and $t\bar{t}Z$ combined fit of a pair of EFT operators

▸ cf. Mark Owen's talk on EFT

tW production

NEW! CMS-PAS-TOP-23-008 (2024)

- **First on Run 3** dataset ($34.7\,\mathrm{fb}^{-1}$) at $\sqrt{s} = 13.6\,\mathrm{TeV}$
- **Signature:** 2 opposite charge leptons.
- **Main irreducible background** $t\bar{t}$
- **Diagram removal** 2 to avoid double counting with $t\bar{t}$.
- **Inclusive cross-section measured** using jet multiplicity-based random forest discriminant and sub-leading jet kinematics.
- **Differential cross-sections measured for** six variables
- **Standard Model** aN^{3}LO cross-section
  $87.9^{+2.0}_{-1.9}\,(\mathrm{scale}) \pm 2.4(\mathrm{PDF}, \alpha_s)\,\mathrm{pb}$



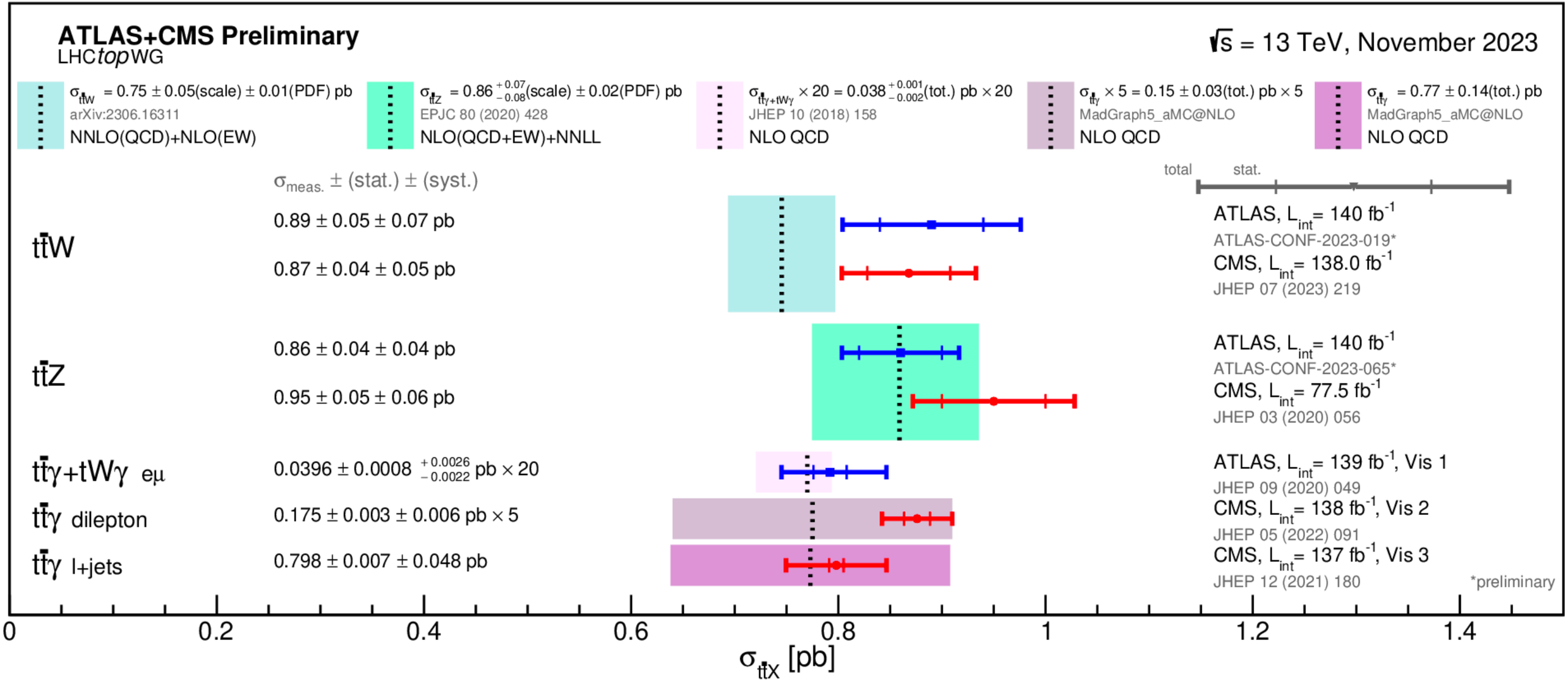
a removed diagram

$$\sigma(tW) = 84.1 \pm 2.1\,(\mathrm{stat})^{+9.8}_{-10.2}\,(\mathrm{syst}) \pm 3.3\,(\mathrm{lumi})\,\mathrm{pb}$$

Measurement in agreement with SM predictions

cf. Alejandro Soto Rodriguez's talk for more details

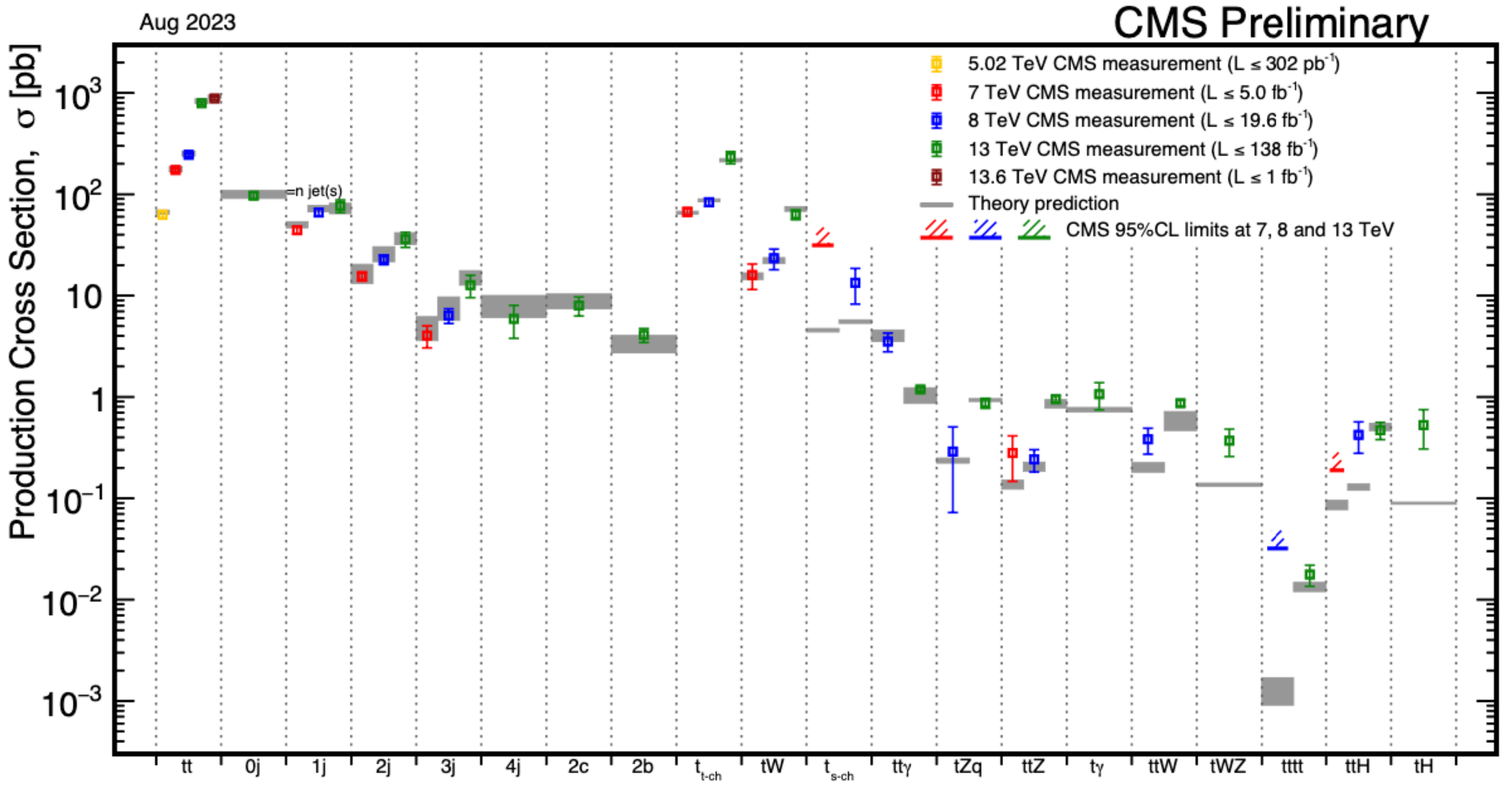
Conclusion


ATLAS+CMS Preliminary
LHCtopWG
√s = 13 TeV, November 2023
σtt̄W = 0.75 ± 0.05(scale) ± 0.01(PDF) pb
arXiv:2306.16311
NNLO(QCD)+NLO(EW)
σtt̄Z = 0.86 +0.07 −0.08 (scale) ± 0.02(PDF) pb
EPJC 80 (2020) 428
NLO(QCD+EW)+NNLL
σtt̄γ+tWγ × 20 = 0.038 +0.001 −0.002 (tot.) pb × 20
JHEP 10 (2018) 158
NLO QCD
σtt̄γ × 5 = 0.15 ± 0.03(tot.) pb × 5
MadGraph5_aMC@NLO
NLO QCD
σtt̄γ = 0.77 ± 0.14(tot.) pb
MadGraph5_aMC@NLO
NLO QCD
σmeas. ± (stat.) ± (syst.)
total
stat.
tt̄W
0.89 ± 0.05 ± 0.07 pb
ATLAS, Lint = 140 fb-1
ATLAS-CONF-2023-019*
0.87 ± 0.04 ± 0.05 pb
CMS, Lint = 138.0 fb-1
JHEP 07 (2023) 219
tt̄Z
0.86 ± 0.04 ± 0.04 pb
ATLAS, Lint = 140 fb-1
ATLAS-CONF-2023-065*
0.95 ± 0.05 ± 0.06 pb
CMS, Lint = 77.5 fb-1
JHEP 03 (2020) 056
tt̄γ+tWγ eμ
0.0396 ± 0.0008 +0.0026 −0.0022 pb × 20
ATLAS, Lint = 139 fb-1, Vis 1
JHEP 09 (2020) 049
tt̄γ dilepton
0.175 ± 0.003 ± 0.006 pb × 5
CMS, Lint = 138 fb-1, Vis 2
JHEP 05 (2022) 091
tt̄γ l+jets
0.798 ± 0.007 ± 0.048 pb
CMS, Lint = 137 fb-1, Vis 3
JHEP 12 (2021) 180
*preliminary
0
0.2
0.4
0.6
0.8
1
1.2
1.4
σttX [pb]

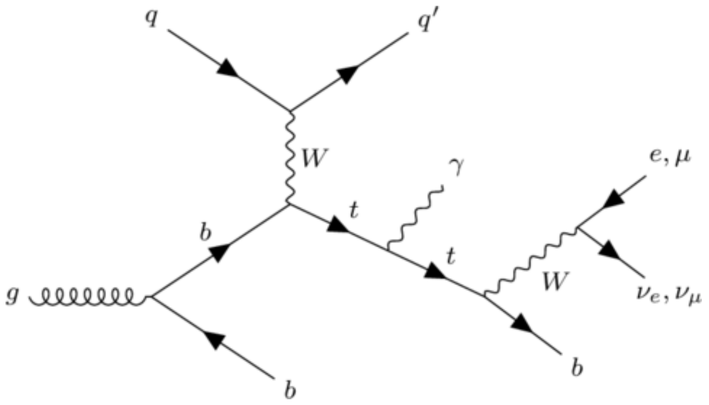
Conclusion

- **A variety of processes** where top quark is produced in association are explored at the LHC with **new results** since Moriond 2023
- **New results with increasing precision** despite often small cross-sections:
  - Thanks to optimised selections, improved analysis techniques
  - Several analyses designed for differential cross-section measurements
  - Strengthening constraints on anomalous couplings interpreted in the context of EFT

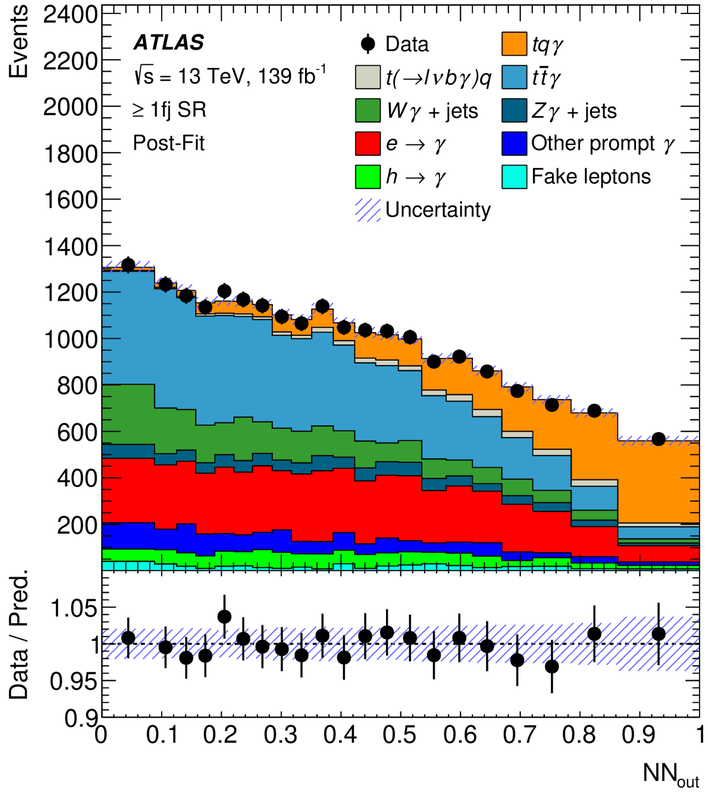
Additional Material


Aug 2023
CMS Preliminary
Production Cross Section, σ [pb]
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
=n jet(s)
5.02 TeV CMS measurement (L ≤ 302 pb^{-1})
7 TeV CMS measurement (L ≤ 5.0 fb^{-1})
8 TeV CMS measurement (L ≤ 19.6 fb^{-1})
13 TeV CMS measurement (L ≤ 138 fb^{-1})
13.6 TeV CMS measurement (L ≤ 1 fb^{-1})
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
tt
0j
1j
2j
3j
4j
2c
2b
$t_{t\text{-ch}}$
tW
$t_{s\text{-ch}}$
ttγ
tZq
ttZ
tγ
ttW
tWZ
tttt
ttH
tH

Observation of $tq\gamma$ production



- **Probing $t\gamma$ Electroweak Coupling**
- **Signature** includes 1 lepton.
- **Cross-section** at particle and parton levels
- **Main background $t\bar{t}\gamma$**



$$\sigma = 688 \pm 23(\text{stat})^{+75}_{-71}(\text{syst})\ \text{fb}$$
$$\sigma(\text{SM}) = 515^{+36}_{-42}\ \text{fb}$$

ATLAS EXPERIMENT

Phys. Rev. Lett. 131, (2023)

CMS

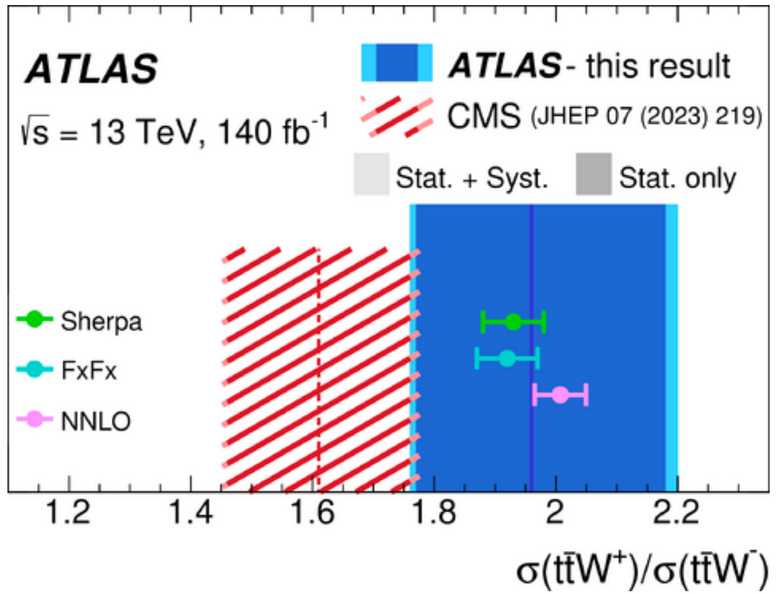
PRL 121 (2018) 221802

Observation of $tq\gamma$ production with a cross-section compatible with SM predictions at NLO within 2 standard deviations.

ttW production

arXiv:2401.05299

- **Signature:** same-charge 2ℓ and 3ℓ.
- **Main irreducible backgrounds** $t\bar{t}Z/\gamma^*$, WZ and $t\bar{t}H$
- **Control regions for background normalisation:** diboson, $t\bar{t}Z$, electron-from-photon conversions and leptons from hadron decays.
- **Subcategories for measurement:** events in SRs are further subdivided for inclusive or differential $t\bar{t}W$ cross-section measurements, with **48** 2ℓ and **8** 3ℓ categories.
- **Measurement:** multiclass neural network (2ℓ) and $m_{\ell\ell\ell}$ (3ℓ) for best precision on cross-section
- **Standard Model** NNLO cross-section
  $745 \pm 50\,(\text{scale}) \pm 13(2\text{ loop app.}) \pm 19(\text{PDF}, \alpha_s)\,\text{fb}$



Measurement of $\sigma(t\bar{t}W^+)/\sigma(t\bar{t}W^-)$ in agreement with SM predictions