



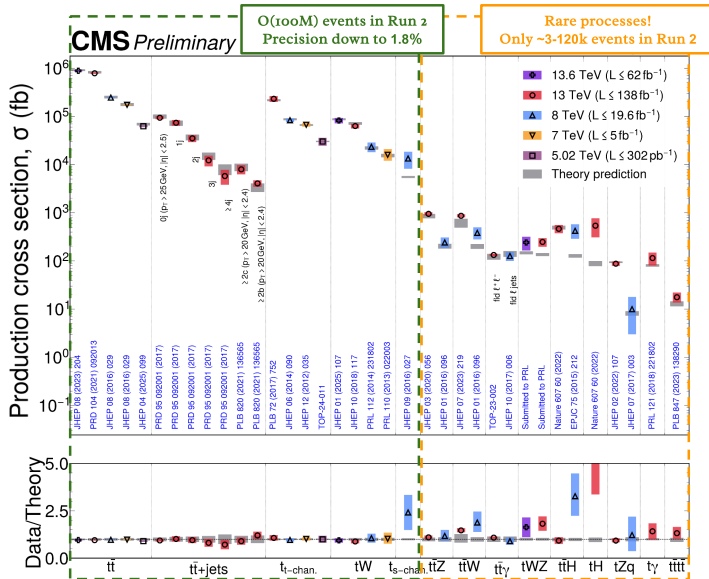
# Measurements of top quark associated production and rare processes

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DIS2026: 33rd International Workshop on Deep Inelastic Scattering and Related Subjects, Bologna (Italy)

# Rare top quark production at CMS:



**Javier's previous talk:** [\[link\]](#)

- $t\bar{t}$  production
- single-top production
- measurements of top properties...

**This talk:**

Overview of rare production processes involving top quarks:  $t\bar{t}X$ ,  $tX$ ,  $t\bar{t}\bar{t}$

(<1 pb)

# Rare top quark production at CMS:

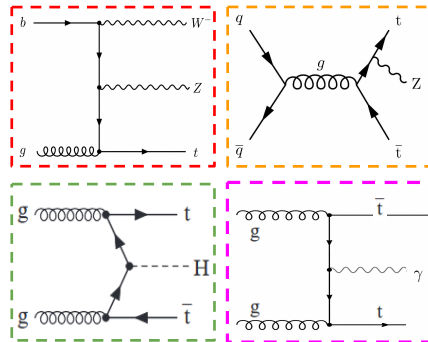
## Why Study Rare Processes Involving the Top Quark?

- Direct access to top couplings

- $tWZ \rightarrow$  top-boson EW coupling
- $t\bar{t}Z \rightarrow$  top-Z interaction
- $t\bar{t}H \rightarrow$  top Yukawa coupling
- $t\bar{t}\gamma(\gamma) \rightarrow$  electromagnetic coupling

- Sensitivity to new physics

- deviations from SM predictions could signal:
  - anomalous couplings
  - heavy new particles
  - higher-dimensional operators



But an important challenge... **very small Standard Model cross sections**

**→ require high luminosity and advanced analysis techniques**

# Rare top quark production at CMS:

## Covered in this talk:



tWZ production

13 + 13.6 TeV; 200 fb<sup>-1</sup>

[Phys. Rev. Lett. 136 \(2026\) 081802](#)



CP violation in  $t\bar{t}Z/tZq$

13 + 13.6 TeV; 173 fb<sup>-1</sup>

[Phys. Lett. B 869 \(2025\) 139857](#)



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

13 TeV; 138 fb<sup>-1</sup>

[JHEP 03 \(2026\) 083](#)



$t\bar{t}\gamma$  and  $tq\gamma$  measurement

13 TeV; 138 fb<sup>-1</sup>

[CMS-PAS-TOP-25-003](#)



3-top production

13 TeV; 138 fb<sup>-1</sup>

[CMS-PAS-TOP-24-006](#)

## More results in:

- [CMS TOP Public Results](#)
- [LHC Top Working Group](#)





# CMS: $tWZ$ observation

Phys. Rev. Lett. 136 (2026) 081802

200 fb<sup>-1</sup>

## Signal regions:

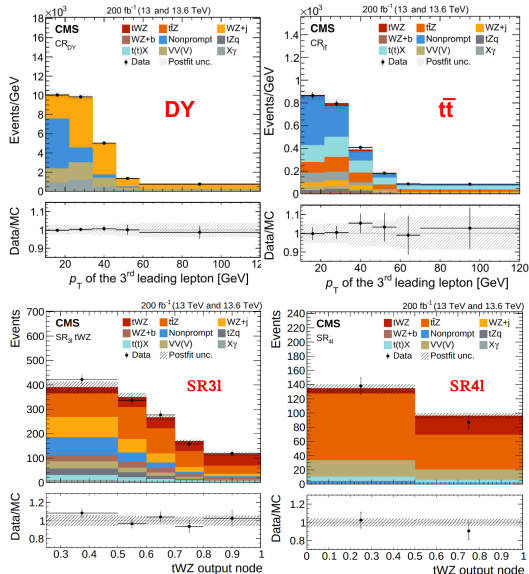
- **SR3l** - 3 leptons (e or  $\mu$ ), one OSSF (opposite-sign same-flavour) lepton pair inside 15 GeV Z-mass window, at least 2 jets (at least 1 b-tag)
- **SR4l** - 4 leptons, exactly one OSSF lepton pair inside Z window, at least 1 b-tagged jet

## Backgrounds:

- CR(ZZ), CR(WZ) to constrain main backgrounds
- CR(Drell-Yan), CR( $t\bar{t}$ ) to control non-prompt leptons, mis-ID rates free parameters

## ML algorithm to separate signal vs backgrounds:

- Transformer based ParT algorithm





# CMS: tWZ observation

Phys. Rev. Lett. 136 (2026) 081802

200 fb<sup>-1</sup>

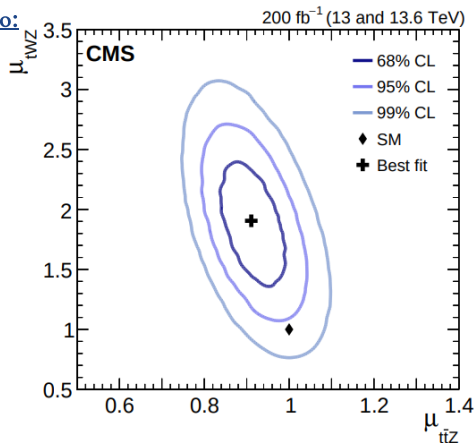
## Signal strength extracted in simultaneous profile likelihood fit to:

- 3 classifier outputs (tWZ, ttZ, other) in SR3l
  - Binary classifier in SR4l
- Separate fits for 13 and 13.6 TeV
- $\mu$  extracted also per year and lepton flavour composition

## Combined result:

$$\mu_{tWZ} = 1.77 + 0.23 \text{ (stat)} + 0.22 \text{ (syst)} \text{ fb}$$

- Observed significance  $5.8\sigma$  ( $3.5\sigma$  expected)
- $2.3\sigma$  larger than SM expectation, consistent with ‘evidence’ analysis. Corresponding xs:
  - $\sqrt{s} = 13 \text{ TeV}$ :  $\sigma_{tWZ} = 248 + 38 \text{ (stat)} + 35 \text{ (syst)} \text{ fb}$
  - $\sqrt{s} = 13.6 \text{ TeV}$ :  $\sigma_{tWZ} = 242 + 62 \text{ (stat)} + 46 \text{ (syst)} \text{ fb}$

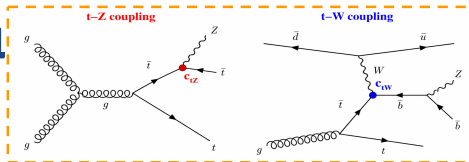




# CMS: CP violation in $t\bar{t}Z/tZq$

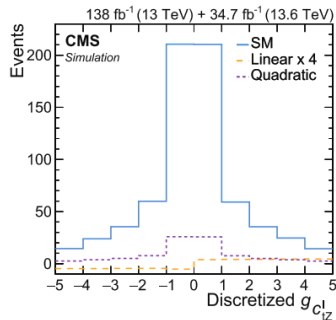
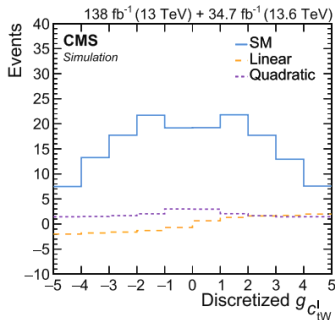
Phys. Lett. B 869 (2025) 139857

173 fb<sup>-1</sup>  
Run 2 + 2022



- Search for CP violation in  $t\bar{t}Z / tZq$
- Needed to explain **baryon asymmetry** → SM sources insufficient, motivating searches for **BSM effects**
- EFT operators  $O_{tW}^I, O_{tZ}^I$  (CP sensitive)
- Setting EFT limits for ML-based **CP-odd** observables
- **Key idea:**

CP-odd observables:  
 symmetric around 0 → **SM**  
 asymmetric → **BSM**



## EFT interpretation:

$$w = w_{\text{SM}} + \sum_i c_i^I l_i + \sum_{ij} c_i^I c_j^I q_{ij}$$

Linear (interference between SM and BSM) - **CP odd**

Quadratic (pure BSM effects) - **CP even**



# CMS: CP violation in $t\bar{t}Z/tZq$

Phys. Lett. B 869 (2025) 139857

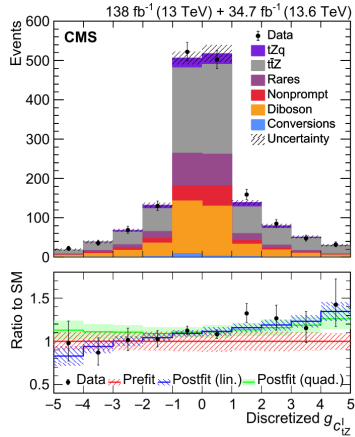
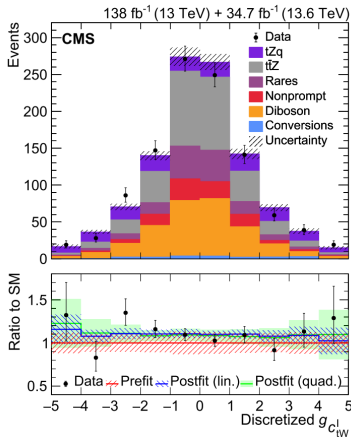
173 fb<sup>-1</sup>

## Signal region selection:

- 3 charged leptons
- At least 1 OSSF lepton pair inside 15 GeV Z-mass window
- At least 2 jets (at least 1 b-tag)

## Backgrounds:

- WZ, ZZ dominant - from MC
- Non-prompt leptons from data-driven mis-ID probability method



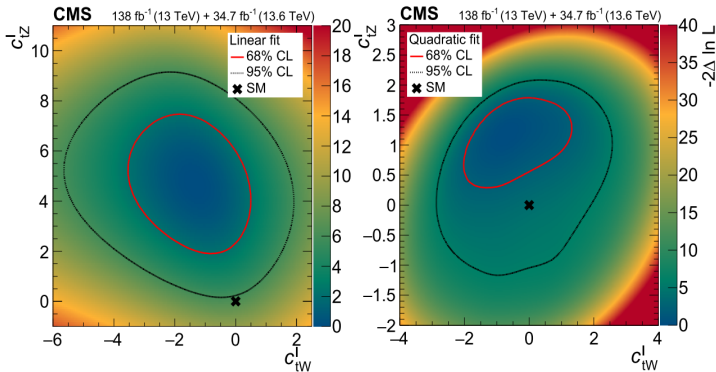


# CMS: CP violation in $t\bar{t}Z/tZq$

Phys. Lett. B 869 (2025) 139857

173 fb<sup>-1</sup>

- EFT limits from maximum likelihood fit to NN discriminants
- 2 fitting scenarios:**
  - Linear** (considering only linear terms)
  - Quadratic** (linear + quadratic terms)
- Overall good compatibility of observed limits with SM predictions (within  $2\sigma$ )
- In individual fits:**  
largest discrepancy for  $c_{tZ}^I$  ( $1.9-2.5\sigma$ )



**Results consistent with SM expectations within  $2\sigma$**



# CMS: $t\bar{t}W$ differential cross-section

IHEP o3 (2026) o83

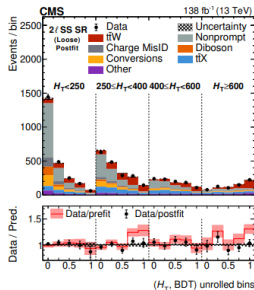
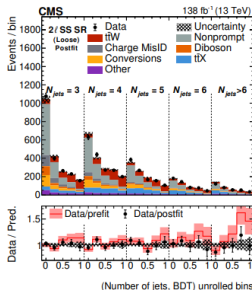
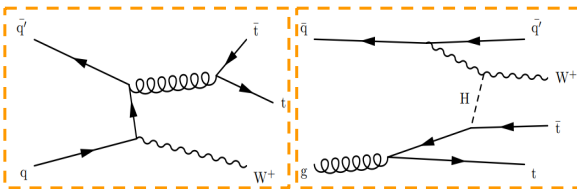
138 fb<sup>-1</sup>

- Both [ATLAS](#) and [CMS](#) have reported a **higher cross-section** than the current MC predictions
- $t\bar{t}W$  is an important uncertainty in  $t\bar{t}t$ ,  $t\bar{t}H$ , ...
- Goal:**
  - First differential cross sections** by CMS in 2l and 3l channels
  - First leptonic charge asymmetry** of tops by CMS in 3l channel

## 2 strategies:

- Counting strategy:**
  - focus on purity, tight lepton selection
  - lower signal acceptance
- MVA strategy:**
  - focus on signal acceptance, loose lepton selection
  - more background

➔ **2D binning of the BDT and the variable of interest**  
 - separate signal from backgrounds





# CMS: $t\bar{t}W$ differential cross-section

IHEP o3 (2026) o83

138 fb<sup>-1</sup>

## Signal region selection:

### $2\ell$ SS (Same-Sign Dilepton SR):

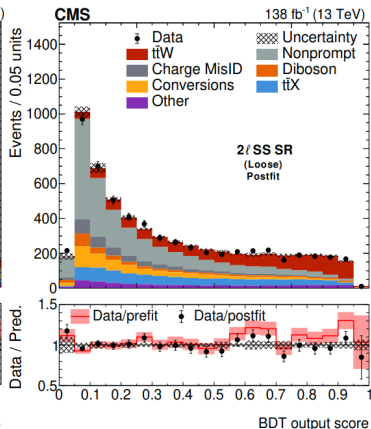
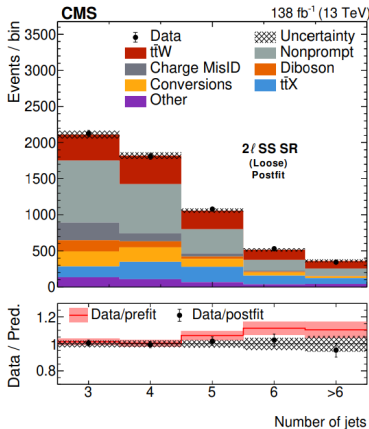
- Exactly 2 SS leptons
- $m_{\ell\ell} > 30$  GeV
- Z veto ( $|m_{ll} - m_Z| > 10$  GeV)
- $\geq 3$  jets,  $\geq 2$  b-tagged
- Optional:  
 $p_T^{\text{miss}} > 30$  GeV (MVA strategy)

### $3\ell$ SR:

- Exactly 3 leptons
- $\geq 1$  opposite-sign pair
- $m_{\ell\ell} > 30$  GeV
- Z veto on OSSF pair
- $\geq 2$  jets,  $\geq 2$  b-tagged

## Backgrounds:

- non-prompt, charge misID leptons, conversions, ...
- Irreducible backgrounds:  $t\bar{t}H$ ,  $t\bar{t}Z$





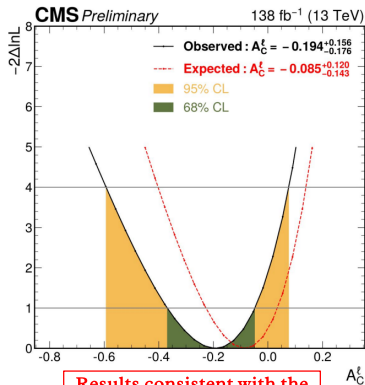
# CMS: $t\bar{t}W$ differential cross-section

IHEP o3 (2026) o83

138 fb<sup>-1</sup>

## Charge asymmetry

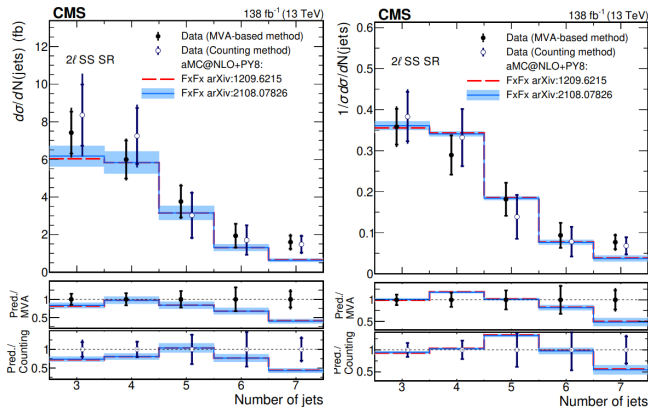
$$A_c^\ell = \frac{N(\Delta y^\ell > 0) - N(\Delta y^\ell < 0)}{N(\Delta y^\ell > 0) + N(\Delta y^\ell < 0)}$$



Results consistent with the SM are observed

## Differential cross-section

- Normalized cross section measurements consistent
- Absolute cross section with larger values compared to the SM expectations



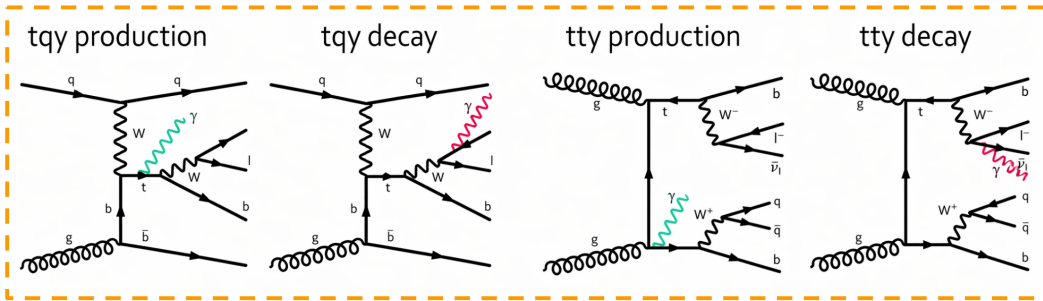


# CMS: $t\bar{t}\gamma$ and $tq\gamma$ measurement

CMS-PAS-TOP-25-003

138 fb<sup>-1</sup>

- Complementary to the dedicated analysis on  $tq\gamma$  by ATLAS ([PRL 131, \(2023\) 181901](#))
- **First observation of  $tq\gamma$  by CMS and first differential measurement ever!**



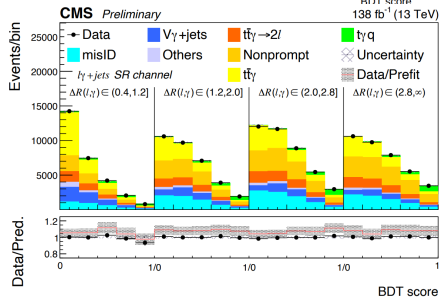
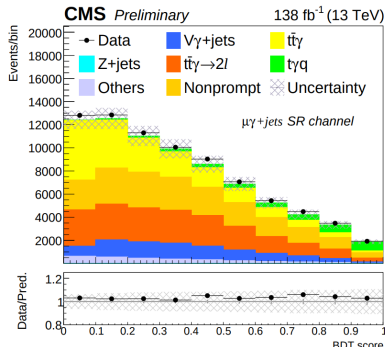


# CMS: $t\bar{t}\gamma$ and $tq\gamma$ measurement

CMS-PAS-TOP-25-003

138 fb<sup>-1</sup>

- Topology of the events characterized by:
  - 1 lepton
  - 1 b-tagged jet
  - 1 spectator jet
- Backgrounds due to different processes, constrained in dedicated control regions:
  - Non-prompt photons and leptons
  - Electrons misidentified as photons
  - $W\gamma$ ,  $Z\gamma$  production
  - Dileptonic  $t\bar{t}\gamma$
- **Dedicated BDT trained to separate  $t\bar{t}\gamma$  and  $tq\gamma$**





# CMS: $t\bar{t}\gamma$ and $tq\gamma$ measurements

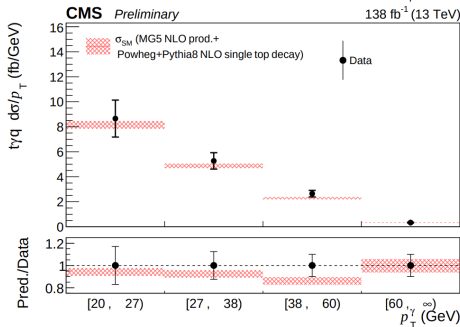
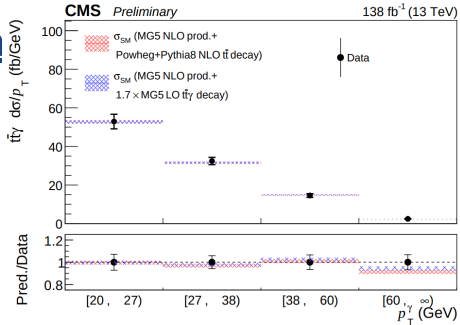
CMS-PAS-TOP-25-003

138 fb<sup>-1</sup>

- Simultaneous measurement of  $t\bar{t}\gamma$  and  $tq\gamma$  inclusively and differentially

$\sigma_{t\bar{t}q} = 237 \pm 17 \text{ fb}$	$\sigma_{t\bar{t}q}(\text{SM}) = 207.6 \pm 8.5 \text{ fb}$
$\sigma_{t\bar{t}\gamma} = 1445 \pm 81 \text{ fb}$	$\sigma_{t\bar{t}\gamma}(\text{SM}) = 1370 \pm 23 \text{ fb}$

- Results consistent with the SM predictions



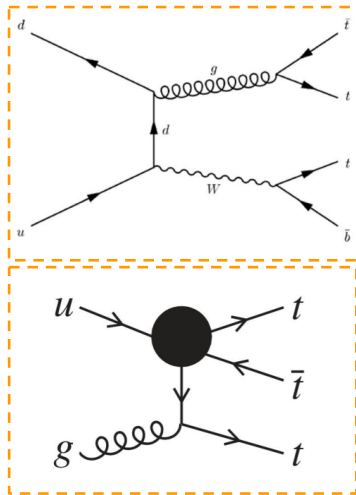


# CMS: 3-top production

CMS-PAS-TOP-24-006

138 fb<sup>-1</sup>

- **Very rare production mode** O(2 fb)
  - sensitive to FCNCs and BSM effects
- Employing two channels:
  - **Single-lepton (SL):**
    - $\geq 1$  lepton + jets
    - typically  $\geq 6$  jets and  $\geq 2$  b-tagged jets in signal region
  - **Multilepton (SSDL + ML):**
    - 2 same-sign leptons or  $\geq 3$  leptons
    - additional jets and b-tagged jets
- largest backgrounds:  $t\bar{t}W/Z$  and non-prompt leptons





# CMS: 3-top production

CMS-PAS-TOP-24-006

138 fb<sup>-1</sup>

## Single lepton channel

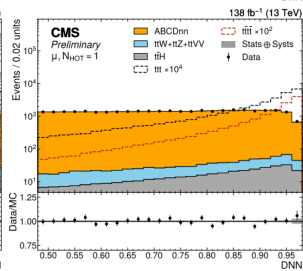
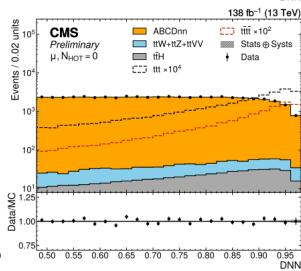
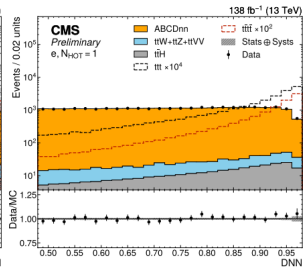
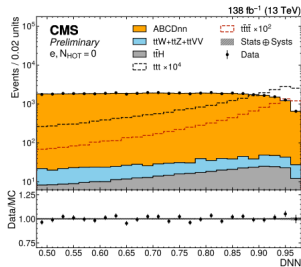
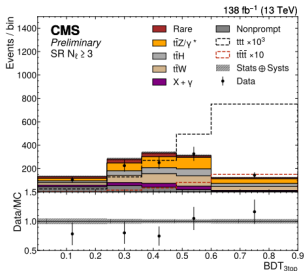
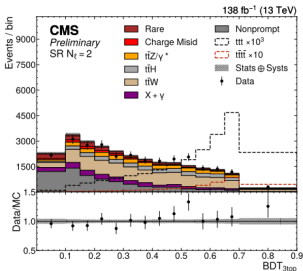
### Single-lepton:

- DNN classifier trained to separate 3-top signal vs  $t\bar{t}$

### Multilepton:

- BDT to discriminate 4tops from background+3top
- BDT to discriminate 3tops from background

## Multilepton





# CMS: 3-top production

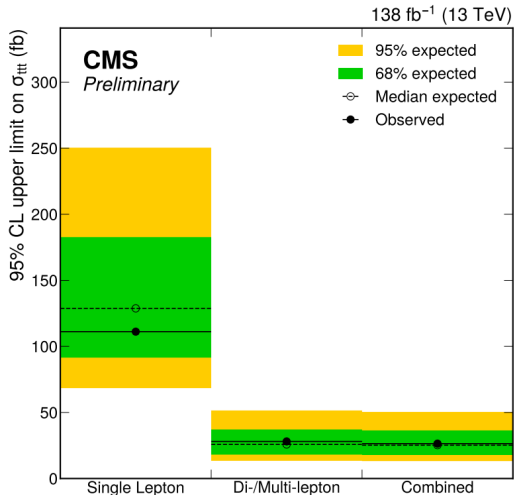
CMS-PAS-TOP-24-006

138 fb<sup>-1</sup>

- Upper limit on signal strength at 95% CL:

$$\sigma_{\text{ttt}} < 25 \text{ fb (26 fb exp)}$$

- $\sigma_{\text{ttt}} \text{ (SM)} = 2 \text{ fb}$
- Measurement limited by statistical uncertainty



## Summary:

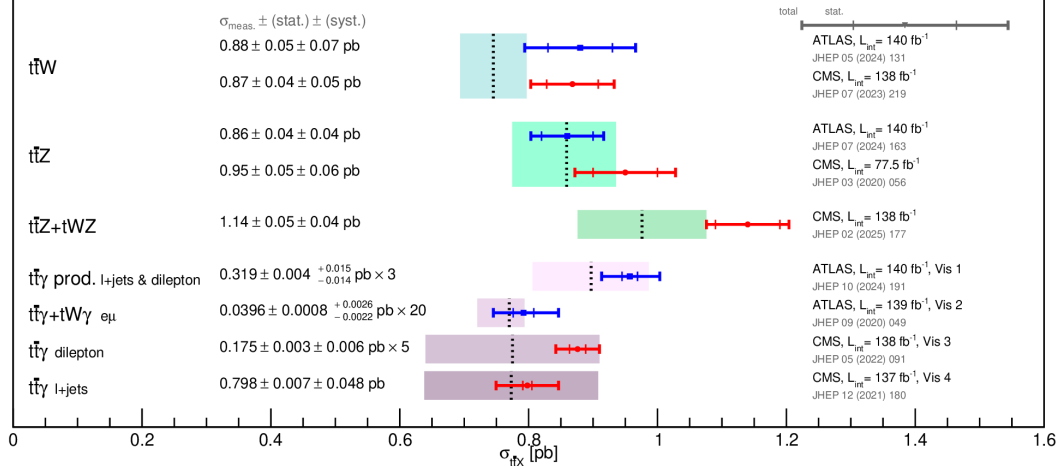
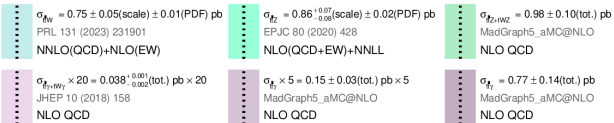
- Presented the most recent results on rare top quark production by the CMS Collaboration
- CMS making **really good progress** in understanding rare top quark processes
- New observations:
  - **tWZ**: advanced ML techniques and combination with Run 3 data finally achieve observation
  - **tq $\gamma$** : first observation achieved, including the first differential measurement, consistent with SM expectations
- No significant deviations from SM:
  - $t\bar{t}\gamma$  / tq $\gamma$  results consistent with predictions
  - CP violation limits compatible with SM
  - $t\bar{t}W$  differential cross-section within expectations

**Backup**

**ATLAS+CMS Preliminary**  
LHC *top*WG

$\sqrt{s} = 13$  TeV

May 2025



**ATLAS+CMS Preliminary**  
LHCtopWG

$\sqrt{s} = 13 \text{ TeV}$ , May 2025

$\sigma_{tZq} \times 5 = 102^{+5}_{-2}(\text{tot.}) \text{ fb} \times 5$   
MadGraph5\_aMC@NLO  
NLO QCD

$\sigma_{tZq} \times 5 = 94^{+3}_{-3}(\text{tot.}) \text{ fb} \times 5$   
MadGraph5\_aMC@NLO  
NLO QCD

$\sigma_{tq\gamma} = 515^{+36}_{-42}(\text{tot.}) \text{ fb}$   
MadGraph5\_aMC@NLO  
NLO QCD

$\sigma_{tq\gamma} \times 5 = 81 \pm 4(\text{tot.}) \text{ fb} \times 5$   
MadGraph5\_aMC@NLO  
NLO QCD

$\sigma_{tWZ} \times 2 = 136^{+9}_{-8}(\text{tot.}) \text{ fb} \times 2$   
MadGraph5\_aMC@NLO  
NLO QCD

$\sigma_{\text{meas.}} \pm (\text{stat.}) \pm (\text{syst.})$



tZq

$97 \pm 13 \pm 7 \text{ fb} \times 5$



ATLAS,  $L_{\text{int}} = 139 \text{ fb}^{-1}$   
JHEP 07 (2020) 124

$88^{+8}_{-7} \text{ }^{+7}_{-6} \text{ fb} \times 5$



CMS,  $L_{\text{int}} = 138 \text{ fb}^{-1}$   
JHEP 02 (2022) 107

tq $\gamma$

$688 \pm 23^{+75}_{-71} \text{ fb}$



ATLAS,  $L_{\text{int}} = 139 \text{ fb}^{-1}$ , Vis 1  
PRL 131 (2023) 181901

$115 \pm 17 \pm 30 \text{ fb} \times 5$



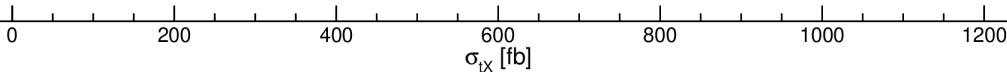
CMS,  $L_{\text{int}} = 36 \text{ fb}^{-1}$ , Vis 2  
PRL 121 (2018) 221801

tWZ

$354 \pm 54 \pm 95 \text{ fb} \times 2$

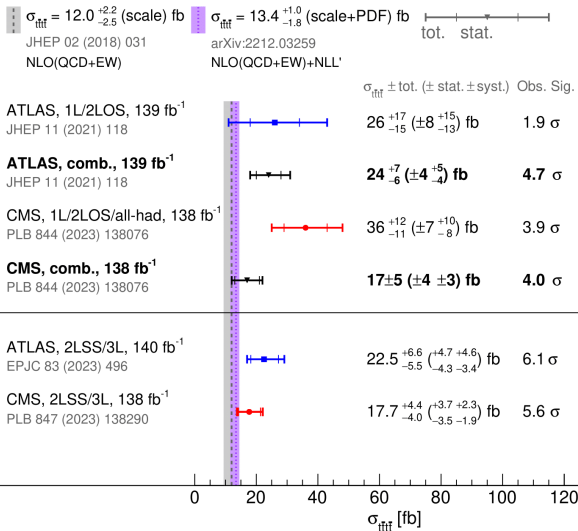


CMS,  $L_{\text{int}} = 138 \text{ fb}^{-1}$   
PLB 855 (2024) 138815



**ATLAS+CMS Preliminary**  
**LHCtopWG**

$\sqrt{s} = 13$  TeV, November 2023

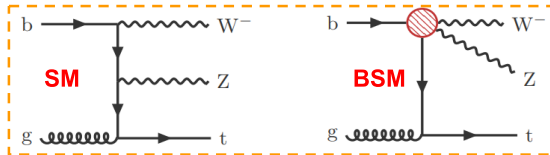




# CMS: tWZ observation

Phys. Rev. Lett. 136 (2026) 081802

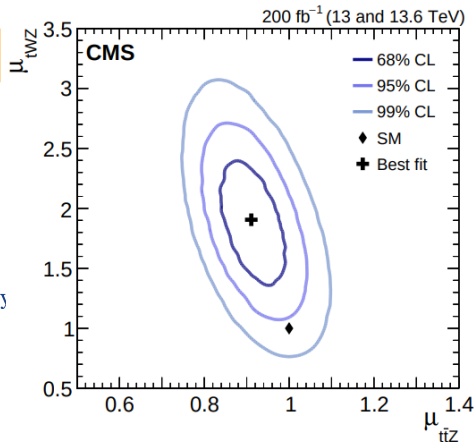
200 fb<sup>-1</sup>



## Combined result:

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- Observed significance  $5.8\sigma$  ( $3.5\sigma$  expected)
- $2.3\sigma$  larger than SM expectation, consistent with ‘evidence’ analysis. Corresponding xs:
  - $\sqrt{s} = 13 \text{ TeV}$ :  $\sigma_{tWZ} = 248 + 38 \text{ (stat)} + 35 \text{ (syst)} \text{ fb}$
  - $\sqrt{s} = 13.6 \text{ TeV}$ :  $\sigma_{tWZ} = 242 + 62 \text{ (stat)} + 46 \text{ (syst)} \text{ fb}$
- Uncertainty dominated by statistics, major systematics:
  - Normalizations of  $t\bar{t}Z$  (14%),  $WZ+b$  (9%) and jet energy corrections (6%)
- Signal strengths of  $tWZ$  and  $t\bar{t}Z$  determined in simultaneous fit without constraints on  $t\bar{t}Z$  xs → consistent with dedicated measurement



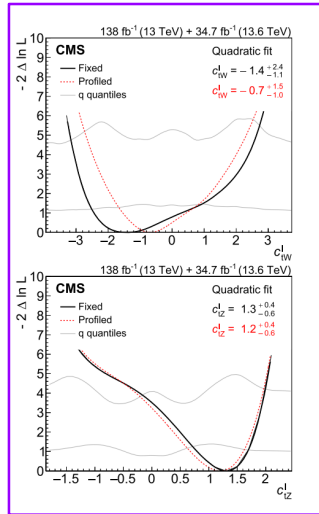
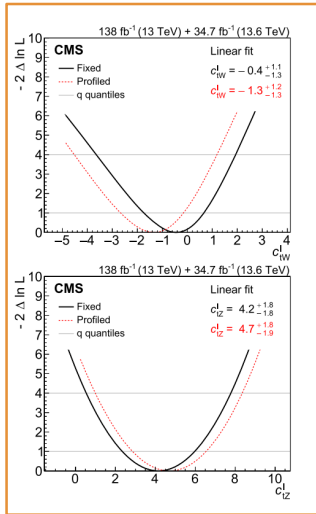


# CMS: CP violation in $t\bar{t}Z/tZq$

Phys. Lett. B 869 (2025) 139857

173 fb<sup>-1</sup>

- **2 equivariant Neural Networks** (separately for  $c_{tZ}^I, c_{tW}^I$ )
- WZ included in NN training - separation of signal from main background (enhanced sensitivity)
- EFT limits from maximum likelihood fit to NN discriminants
- **2 fitting scenarios:**
  - **Linear** (considering only linear terms)
  - **Quadratic** (linear + quadratic terms)



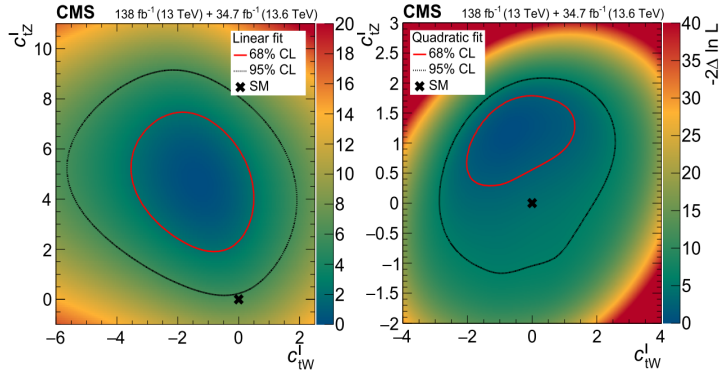


# CMS: CP violation in $t\bar{t}Z/tZq$

Phys. Lett. B 869 (2025) 139857

173 fb<sup>-1</sup>

- Wilson coefficients fitted individually and simultaneously
- Overall **good compatibility of observed limits with SM predictions** (within  $2\sigma$ )
- **In individual fits:** **largest discrepancy for  $c_{tZ}^I$**  ( $1.9\text{-}2.5\sigma$  in positive values), due to slight asymmetry in  $g(c_{tZ}^I)$  and excess of observed data (compatible with recent  $t\bar{t}Z$  measurements)



**Results consistent with SM expectations within  $2\sigma$**