

**Associated top quark productions by
ATLAS and CMS**

**Dominik Babál (Slovak Academy of Sciences)
on behalf of the ATLAS and CMS Collaborations**



La Thuile (05.03.2026)

Overview



$t\bar{t}l^*l$ inclusive + EFT

13 TeV; 140 fb⁻¹

[EPJC 85 \(2025\) 1434](#)



$t\bar{t}\gamma\gamma$ production

13 TeV; 140 fb⁻¹

[Phys. Lett. B 8xx \(2026\) 140195](#)



$t\bar{t}Wj$ EW production

13 TeV; 140 fb⁻¹

[Submitted to Phys. Rev. D](#)



$t\bar{t}j$ charge asymmetry

13 TeV; 138 fb⁻¹

[CMS-PAS-TOP-24-015](#)



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

13 + 13.6 TeV; 173 fb⁻¹

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



tWZ production

13 + 13.6 TeV; 200 fb⁻¹

[Accepted by Phys. Rev. Lett.](#)

ATLAS+CMS Preliminary LHC top WG

$\sqrt{s} = 13$ TeV

May 2025

$t\bar{t}W$

$t\bar{t}Z$

$t\bar{t}Z+tWZ$

$t\bar{t}\gamma$ prod. $l+jets$ & dilepton

$t\bar{t}\gamma+tW\gamma_{e\mu}$

$t\bar{t}\gamma$ dilepton

$t\bar{t}\gamma$ $l+jets$

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

$0.88 \pm 0.05 \pm 0.07$ pb

$0.87 \pm 0.04 \pm 0.05$ pb

$0.86 \pm 0.04 \pm 0.04$ pb

$0.95 \pm 0.05 \pm 0.06$ pb

$1.14 \pm 0.05 \pm 0.04$ pb

$0.319 \pm 0.004^{+0.015}_{-0.014}$ pb $\times 3$

$0.0396 \pm 0.0008^{+0.0026}_{-0.0022}$ pb $\times 20$

$0.175 \pm 0.003 \pm 0.006$ pb $\times 5$

$0.798 \pm 0.007 \pm 0.048$ pb

$\sigma_{tW} = 0.75 \pm 0.05(\text{scale}) \pm 0.01(\text{PDF})$ pb
PRL 131 (2023) 231901
NNLO(QCD)+NLO(EW)

$\sigma_{t\bar{t}\gamma} \times 3 = 0.30^{+0.03}_{-0.03}(\text{tot.})$ pb $\times 3$
MadGraph5_aMC@NLO
NLO QCD

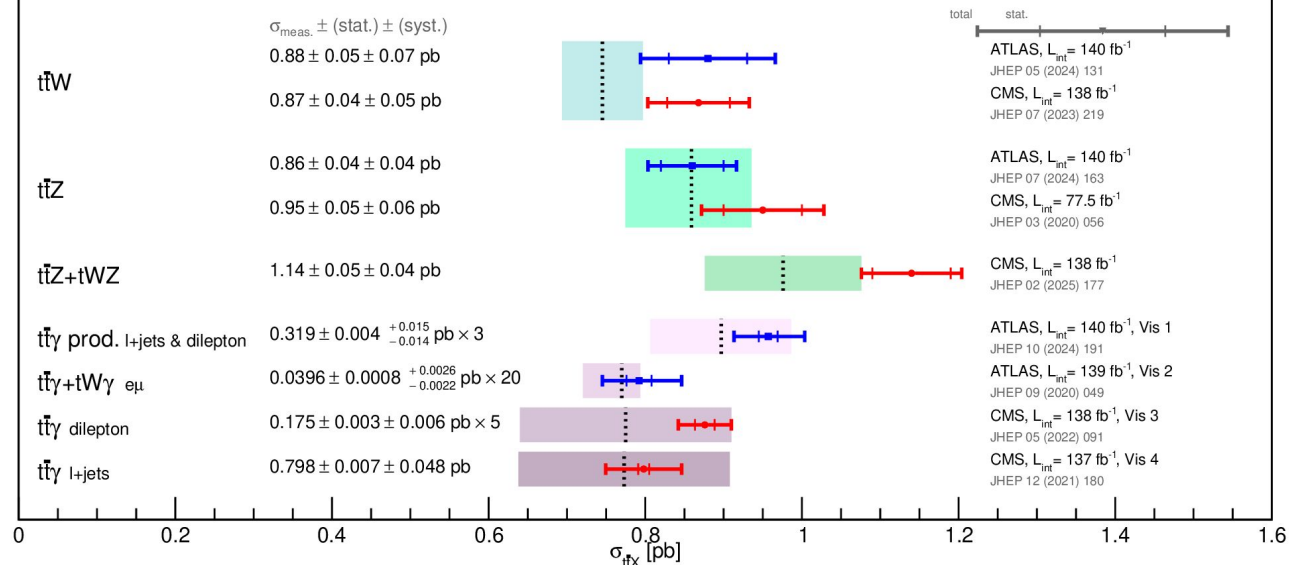
$\sigma_{t\bar{t}\gamma} \times 20 = 0.038^{+0.001}_{-0.002}(\text{tot.})$ pb $\times 20$
JHEP 10 (2018) 158
NLO QCD

$\sigma_{tZ} = 0.86^{+0.07}_{-0.08}(\text{scale}) \pm 0.02(\text{PDF})$ pb
EPJC 80 (2020) 428
NLO(QCD+EW)+NNLL

$\sigma_{t\bar{t}\gamma} \times 5 = 0.15 \pm 0.03(\text{tot.})$ pb $\times 5$
MadGraph5_aMC@NLO
NLO QCD

$\sigma_{tZ+WZ} = 0.98 \pm 0.10(\text{tot.})$ pb
MadGraph5_aMC@NLO
NLO QCD

$\sigma_{t\bar{t}\gamma} = 0.77 \pm 0.14(\text{tot.})$ pb
MadGraph5_aMC@NLO
NLO QCD



ATLAS: High-mass $t\bar{t}l^+l^-$ and LFU-inspired EFT

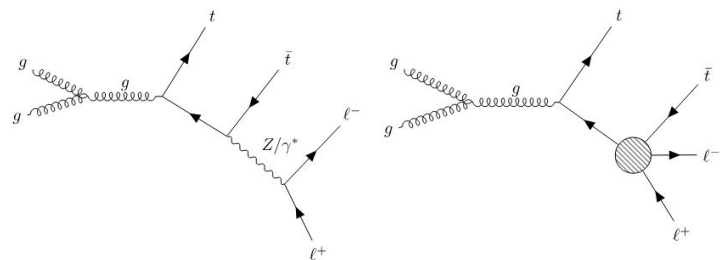
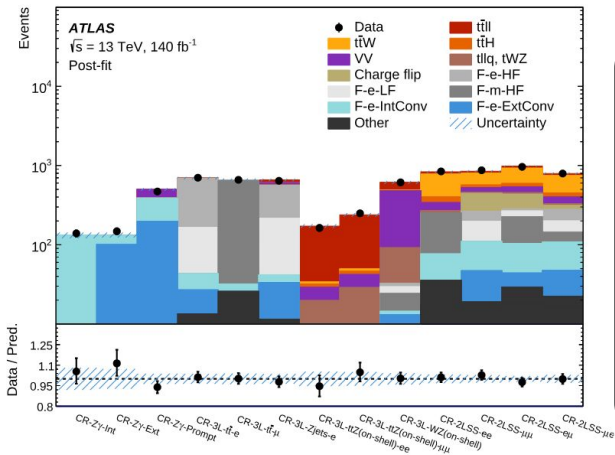
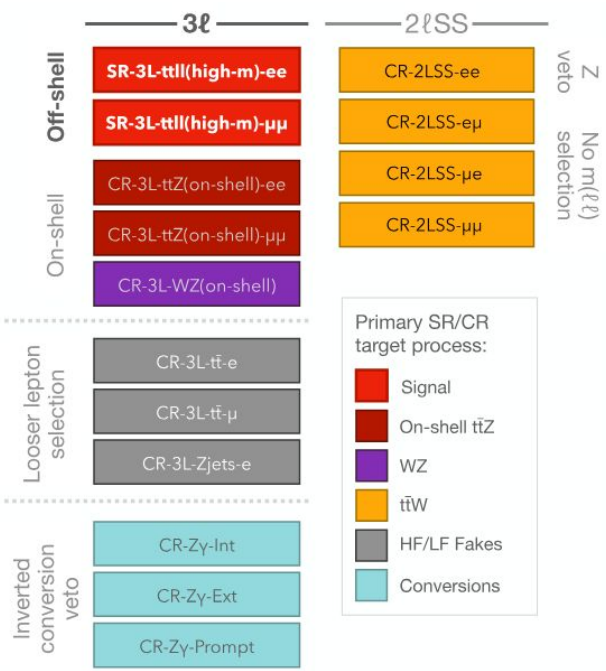
- First ATLAS study targeting **off-shell $t\bar{t}l^+l^-$ production**
- $Z/\gamma^* \rightarrow$ OSSF lepton pair
- Probe **BSM effective $t\bar{t}ll$ coupling** - high mass region enhances EFT sensitivity
- Goal: inclusive xs, EFT interpretation
- **LFU violation**
 - SM assumes same decay rate of W to e and μ
 - Here from difference between flavor-split ee and $\mu\mu$ WCs

Signal selection:

- **3 leptons** for high $t\bar{t}l^+l^-$ purity
- At least **one OSSF (opposite-sign-same-flavour) lepton pair** with $m_{ll} > 10$ GeV
- At least **3 jets** (1 *b* tagged)
- m_{ll} of Z pair higher than **101,2 GeV**

Backgrounds

- 13 CRs for main bckgs
- **$t\bar{t}W$**
 - 2 same-sign leptons
- **$t\bar{t}Z, WZ + jets$**
 - Lepton pair within Z peak
 - 3-class DNN ($t\bar{t}l^+l^-$, $t\bar{t}Z$, $WZ+jet$)
- **Non-prompt leptons**
 - Heavy+light flavour fakes, Conversion and charge-flip fakes



ATLAS: High-mass $t\bar{t}l^+l^-$ and LFU-inspired EFT

- Simultaneous PLF to event yields in SRs and CRs
- Extracted **signal strength $\mu(\bar{t}\bar{t}l^+l^-)$** in full m_{ll} range and **95% CL upper limit** for BSM contribution in high mass bin (>550 GeV) - **all compatible with SM**

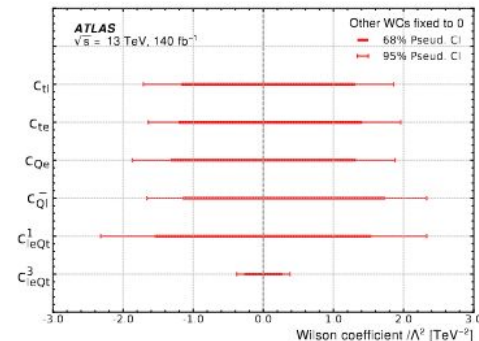
SM results

	$m(l^+l^-) > m_Z + 10$ GeV		$m(l^+l^-) > 550$ GeV	
	$\mu(\bar{t}\bar{t}l^+l^-)$	Significance	Exp. 95% CL upper limit	Obs. 95% CL upper limit
$\bar{t}\bar{t}e^+e^-$	$0.8^{+0.6}_{-0.6}$	1.4σ	25.4 ab	26.9 ab
$\bar{t}\bar{t}\mu^+\mu^-$	$1.1^{+0.5}_{-0.5}$	2.5σ	27.5 ab	26.0 ab
$\bar{t}\bar{t}l^+l^-$	$1.0^{+0.4}_{-0.4}$	2.9σ	30.5 ab	30.8 ab

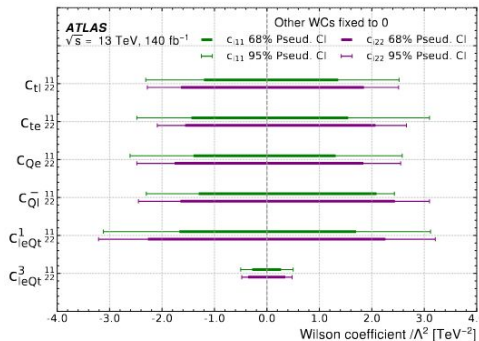
EFT results

- EFT max likelihood fits performed for single operator
- **Fits for all WCs confirm compatibility with the SM**
- **Flavour-inclusive:**
 - Provides most stringent limits
- **Flavour-split:**
 - Sensitivity diluted, but still significant constraining power
- **LFU-violation:**
 - Less sensitive than flavour-split fits
 - Limited by Run 2 statistical precision, but cancellation of systematics promising

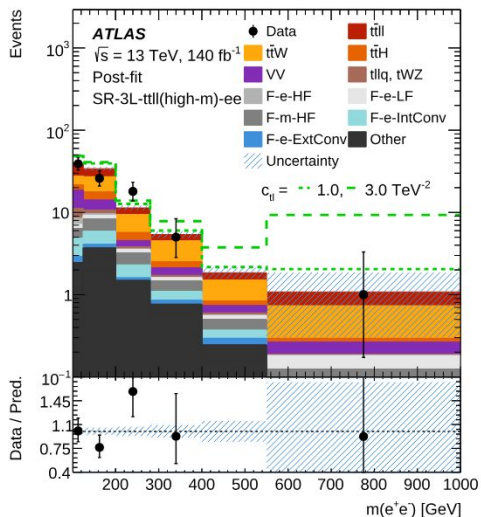
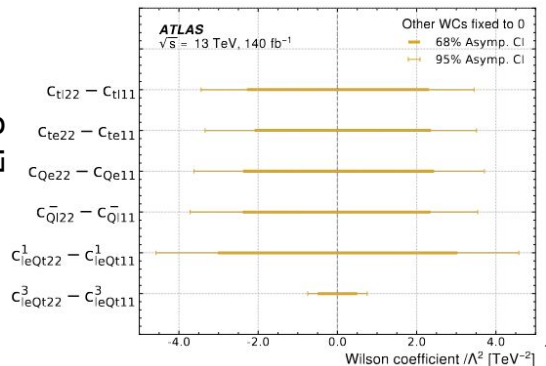
Flavour-inclusive



Flavour-split

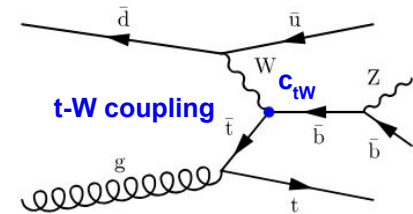
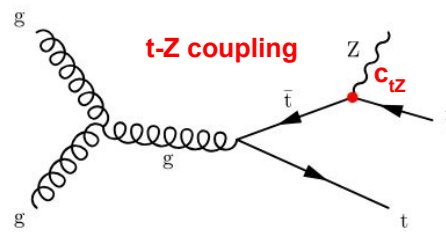


LFU



CMS: CP violation in ttZ/tZq

- Search for CP violation in $t\bar{t}Z$ / tZq
- CP violation necessary to explain baryon asymmetry in universe → SM sources insufficient, motivating searches for BSM effects
- Operators O_{tW}^I, O_{tZ}^I sensitive to CP
- Setting EFT limits for **ML-based CP-odd observables**
- Data from **full Run 2 + Run 3** (only 2022)

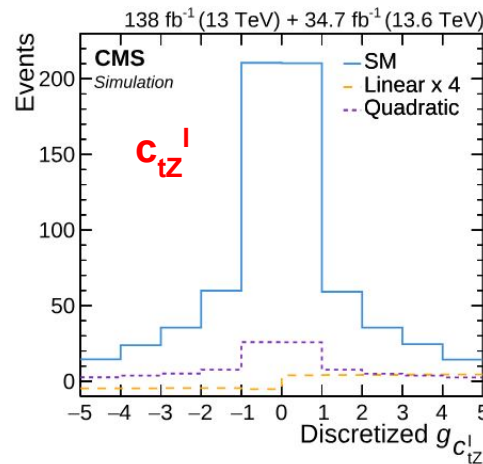
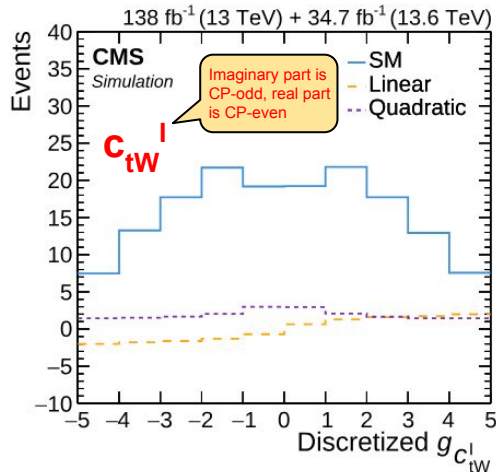


Signal selection:

- **3 charged leptons**
- At least **1 OSSF** (opposite-sign-same-flavour) **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



- **CP-odd observables** symmetric around 0 for SM, asymmetric for BSM
- **EFT reweighting:**

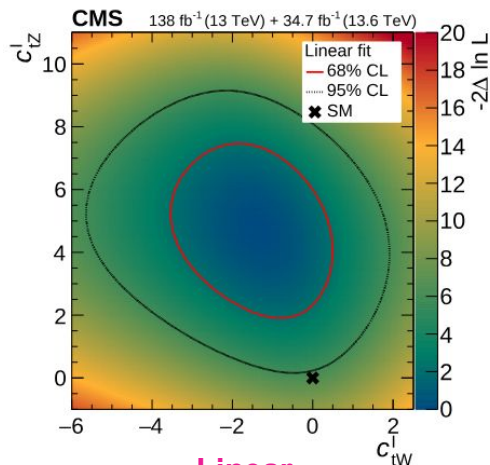
$$w = w_{SM} + \sum_i c_i^I l_i + \sum_{ij} c_i^I c_j^I q_{ij}$$

Linear (interference between SM and BSM) - CP odd

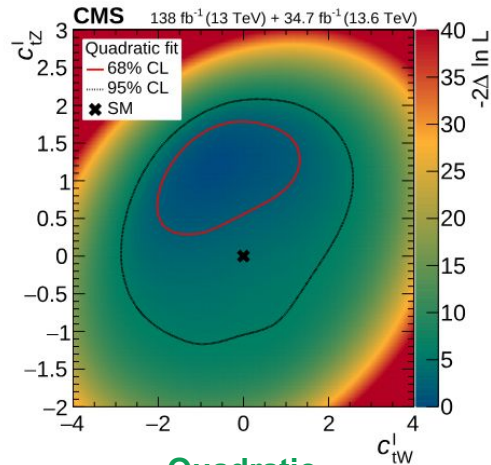
Quadratic (pure BSM effects) - CP even

CMS: CP violation in ttZ/tZq

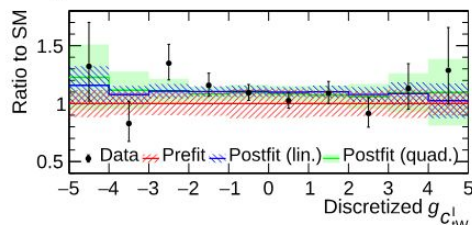
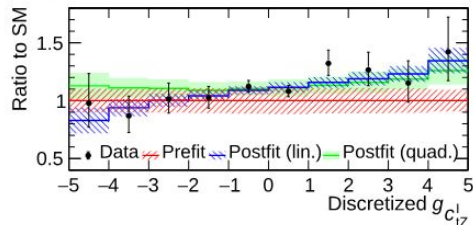
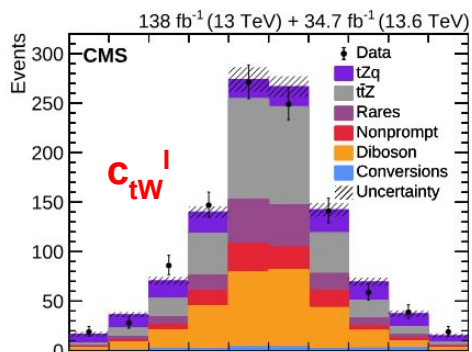
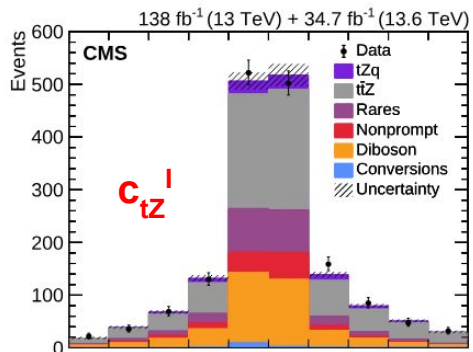
- **2 equivariant Neural Networks** (separately for c_{tZ}^I, c_{tW}^I)
- **WZ included in training** - separation of signal from main bckg (enhanced sensitivity)



Linear



Quadratic



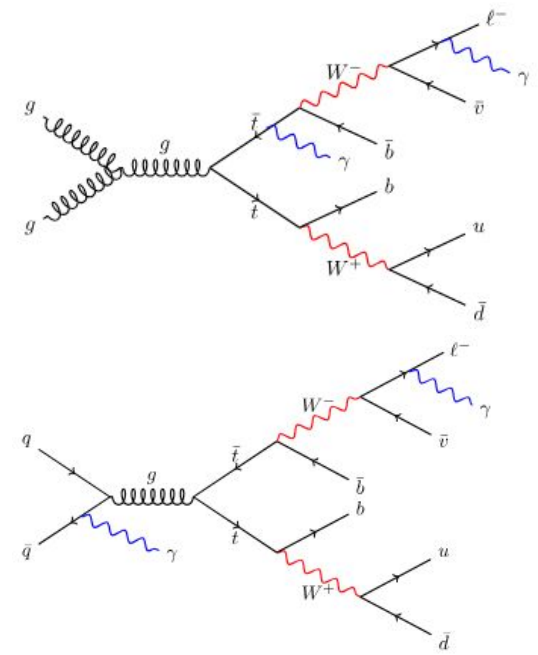
- EFT limits from maximum likelihood fit to NN discriminants
- **2 fitting scenarios:**
 - **Linear** (considering only linear terms)
 - **Quadratic** (linear + quadratic terms)
- Wilson coefficients fitted **individually** and **simultaneously**

• Overall **good compatibility of observed limits with SM predictions** (within 2σ)

• In individual fits **largest discrepancy for c_{tZ}^I** ($1.9-2.5\sigma$ in positive values), due to slight asymmetry in $g(c_{tZ}^I)$ and excess of observed data (compatible with recent ttZ measurements)

ATLAS: Observation of $t\bar{t}\gamma\gamma$ production

- $t\bar{t}\gamma\gamma$ directly probe $t\bar{t}\gamma$ EW coupling
- Sensitivity to **anomalous dipole moments** via $t\bar{t}\gamma\gamma/t\bar{t}\gamma$ xs ratio
- $t\bar{t}\gamma\gamma$ important irreducible **background for $t\bar{t}H$** ($H \rightarrow \gamma\gamma$)
- **Goal: provide first reference fiducial xs measurement for future theoretical developments** - current generators cannot simulate processes with irradiated γ from charged particles at high-order accuracy



Signal selection:

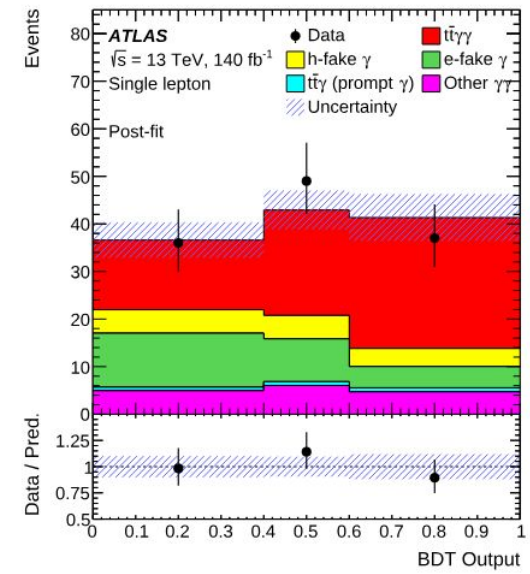
- SR inspired by **previous $t\bar{t}\gamma$ analysis** ([JHEP 10 \(2024\) 191](#))
 - Exactly **2 isolated γ**
 - **1 isolated lepton** (e or μ)
 - At least **4 jets** (at least 1 b jet)
 - Event rejected if $86.19 < m_{e\gamma} < 96.19$ GeV to suppress $Z \rightarrow ee$

Backgrounds:

- **Prompt γ bckg (15 %):**
 - Dominant source $V\gamma\gamma$, $t\bar{t}H$
 - Estimated from MC
- **Fake γ bckg:**
 - ***e-fake*** (20 %) - from dilepton $t\bar{t}\gamma$, estimated in data from fraction of $Z \rightarrow ee$ reconstructed as $e\gamma$ pairs
 - ***h-fake*** (10 %) - estimated from data using ABCD method

ATLAS: Observation of $t\bar{t}\gamma\gamma$ production

- **BDT to separate signal from main bckgs** - 19 variables related to γ kinematics
- Cross section measured in fiducial phase space via PLF to BDT discriminant
- **Fiducial PS** defined at *particle level*, following $t\bar{t}\gamma$ analysis:
 - Selection analogous to reco level
- $t\bar{t}\gamma\gamma/t\bar{t}\gamma$ xs ratio extracted at particle level using inputs from $t\bar{t}\gamma$ analysis



Source	$\Delta\sigma_{t\bar{t}\gamma\gamma}/\sigma_{t\bar{t}\gamma\gamma}$ [%]	$\Delta R_{t\bar{t}\gamma\gamma/t\bar{t}\gamma}/R_{t\bar{t}\gamma\gamma/t\bar{t}\gamma}$ [%]
$t\bar{t}\gamma\gamma$ modelling	1.4	1.3
Prompt-photon background norm. & modelling	4.4	5.8
Fake-photon background estimates	6.5	0.5
Fake-lepton background estimate	-	0.9
Jet	9.7	5.9
Photon	6.5	4.0
b -tagging	3.4	1.0
Leptons	1.5	0.3
Luminosity	1.4	0.1
E_T^{miss}	0.4	1.1
Pile-up	1.6	1.4
MC statistical uncertainties	2.5	2.8
Total systematic uncertainty	15.0	10.0

Measured fiducial xs:

$$\sigma_{t\bar{t}\gamma\gamma} = 2.42^{+0.58}_{-0.53} \text{ fb} = 2.42^{+0.46}_{-0.38} \text{ (stat)}^{+0.35}_{-0.38} \text{ (syst)} \text{ fb.}$$

- **23 % relative uncert.** - syst. dominated by jet + γ and fake γ
- No published theory prediction for xs
- **Observed significance 5.2 σ**

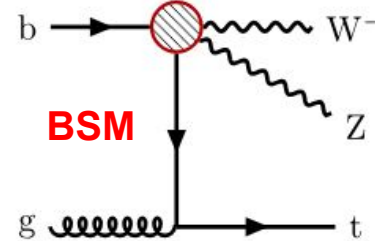
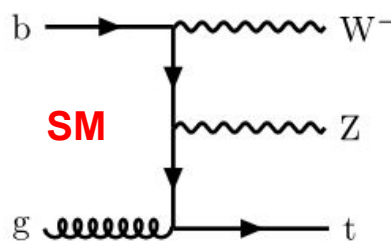
Fiducial xs ratio:

$$R_{t\bar{t}\gamma\gamma/t\bar{t}\gamma} = (3.30^{+0.63}_{-0.55} \text{ (stat)}^{+0.32}_{-0.34} \text{ (syst)}) \times 10^{-3}$$

- **20 % relative uncert.** - correlated systs. (jets, γ , fake γ , lumi) partially cancelled out

CMS: tWZ production

- **tWZ very rare process**, never observed before
- Provides direct access to **top-boson EW couplings**
- Sensitive **probe to BSM effects** (e.g. anomalous couplings)
- Evidence (3.4σ) by CMS in 2024 ([Phys. Lett. B 855 \(2024\) 138815](#))
- Combination of **Run 2** (2016-18) and **Run 3** (2022-23) data
- Sensitivity increased by **advanced ML and reconstruction techniques**

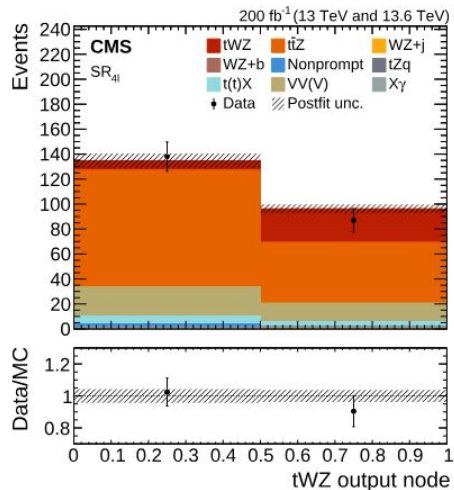
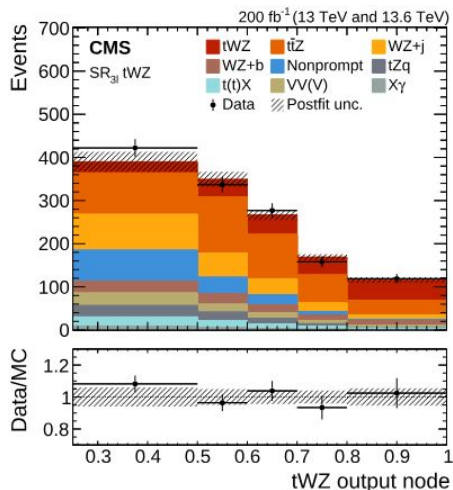


Signal regions:

- **SR_{3l}** - 3 leptons (e or μ), one OSSF lepton pair inside 15 GeV Z-mass window, at least 2 jets (at least 1 b-tag)
- **SR_{4l}** - 4 leptons, exactly one OSSF lepton pair inside Z window, at least 1 b-tagged jet

Backgrounds:

- **CR(ZZ), CR(WZ)** to constrain main bckgs
- **CR(Drell-Yan), CR(tt̄)** to control non-prompt leptons, mis-ID rates free parameters of the PLF

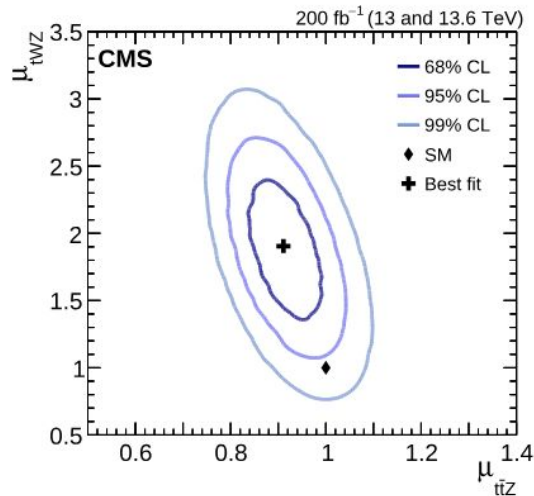
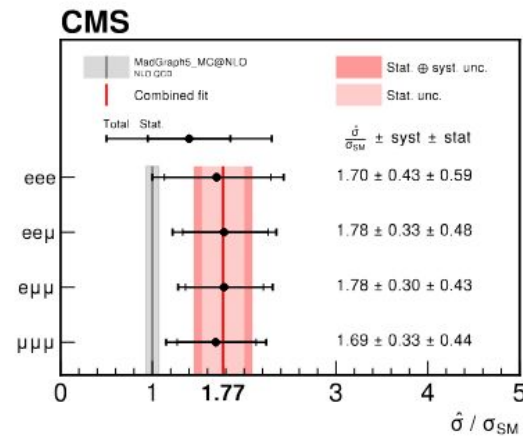
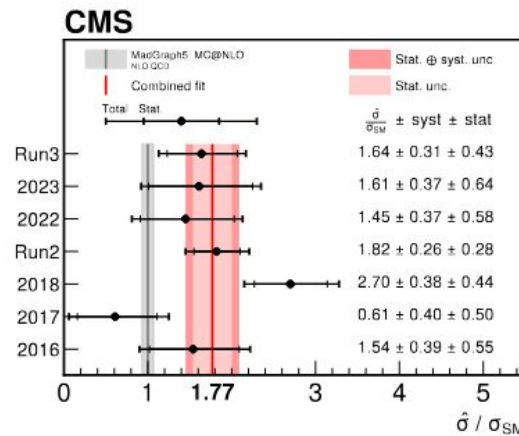


ML algorithm to separate signal from backgrounds

- Transformer based **PART** algorithm
- **Particle** (kinematics of lepton and jets, b-tag info, lepton flavour) and **interaction** (correlation between pairs of particles) variables

CMS: tWZ production

- Signal strength extracted in **simultaneous PLF** to:
 - 3 classifier outputs (tWZ, ttZ, other) in **SR₃₁**
 - Binary classifier in **SR₄₁**
- **Separate fits** for 13 and 13.6 TeV
- μ extracted also **per year and lepton flavour** composition



Combined result:

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

- Observed significance **5.8 σ** (3.5 σ expected)
- **2.3 σ larger than SM expectation**, consistent with 'evidence' analysis

Corresponding xs:

$$\sqrt{s} = 13 \text{ TeV: } \sigma_{tWZ} = 248 \pm 38 \text{ (stat)} \pm 35 \text{ (syst) fb}$$

$$\sqrt{s} = 13.6 \text{ TeV: } \sigma_{tWZ} = 242 \pm 62 \text{ (stat)} \pm 46 \text{ (syst) fb}$$

- Uncertainty **dominated by statistics**, major systematics:
 - Normalisations of **ttZ (14%)**, WZ+b (9%) and jet energy corrections (6%)
- Signal strengths of tWZ and ttZ determined in simultaneous fit without constraints on ttZ xs → consistent with dedicated measurement

ATLAS: A search for EW ttWj production

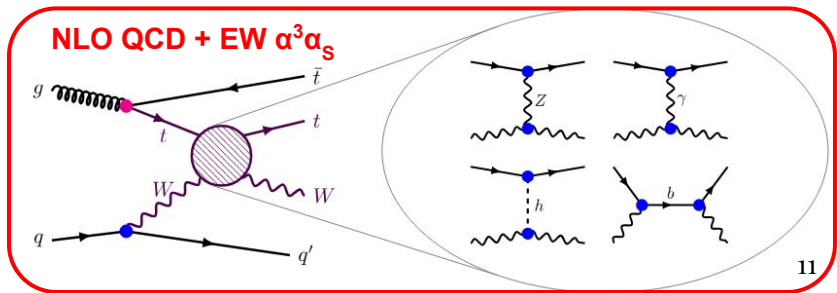
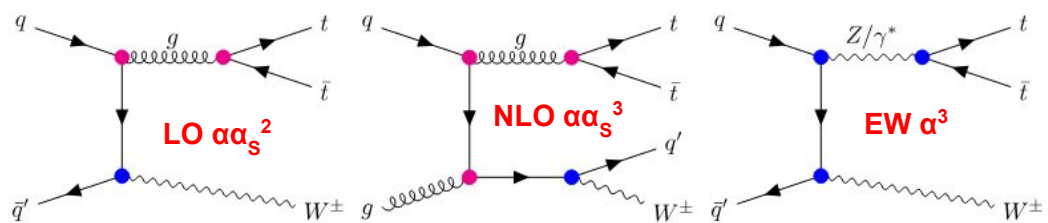
- **t \bar{t} W** already **extensively studied** - at 8 TeV in agreement with SM, at 13 TeV see some tension after including higher-order EW corrections
- **t \bar{t} W** **important bckg** for **t \bar{t} H**, **t \bar{t} t \bar{t}** - crucial to **study modelling at high orders**
- **t \bar{t} Wj EW**
 - probes **tW scattering vertex** - never studied at LHC
 - strong sensitivity to BSM effects
- **Goal:**
 - Measure **95% CL upper limit** on xs
 - **EFT** for 2 operators:

$$\frac{c_{Ht}}{\Lambda^2} O_{Ht} = \frac{c_{Ht}}{\Lambda^2} (H^\dagger i \overleftrightarrow{D}_\mu H) (\bar{t}_R \gamma^\mu t_R)$$

$$\frac{c_{HQ}^{(1)}}{\Lambda^2} O_{HQ}^{(1)} = \frac{c_{HQ}^{(1)}}{\Lambda^2} (H^\dagger \overleftrightarrow{D}_\mu H) (\bar{Q}_L \gamma^\mu Q_L)$$

- Signal selection:**
- **2l topology** with **leptonic decay of t and W** (t \rightarrow lvb, W \rightarrow lv), and **hadronic decay of second t** (t \rightarrow qqb)
 - **2 same-charge leptons** to suppress VV bckg
 - **|\Delta\eta_l| > 2.0** (difference in pseudorapidity between most forward non-b jet and the jet with highest m_j)

- Backgrounds:**
- **t \bar{t} W QCD** - 3 CRs for overall normalisation and low and high \Delta\eta_l
 - **VV, t \bar{t} Z, photon conversions** - dedicated CRs
 - **Charge-flips** - events with mis ID charge, estimated from Z \rightarrow ee events
 - **Fake leptons** - from data using matrix method (parametrised in terms of t \bar{t} W xs)



ATLAS: A search for EW ttWj production

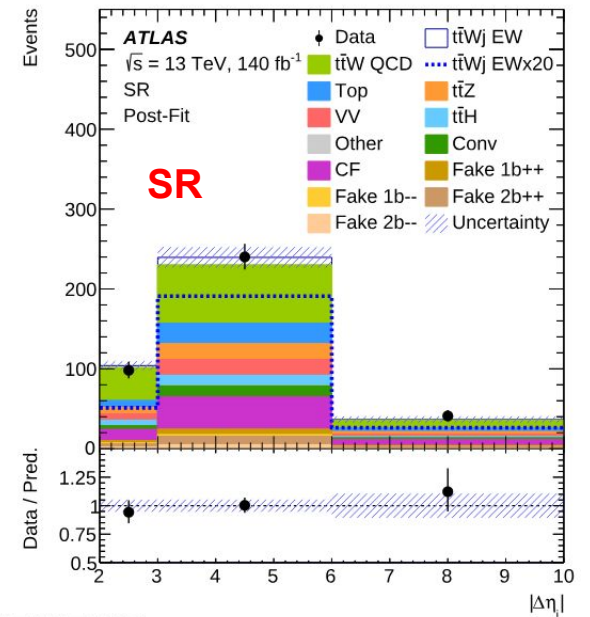
- Profile likelihood fit to SR and 7 CRs
- Free floating normalisation of ttZ, ttW QCD, VV, photon conversions and charge-flip backgrounds
- Extracted signal strength:

$$\mu_{t\bar{t}Wj_{EW}} = 0.9^{+2.4}_{-3.0}$$

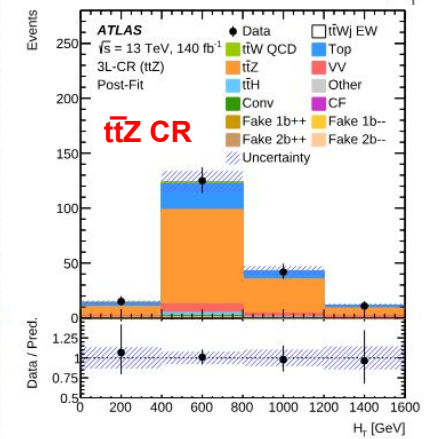
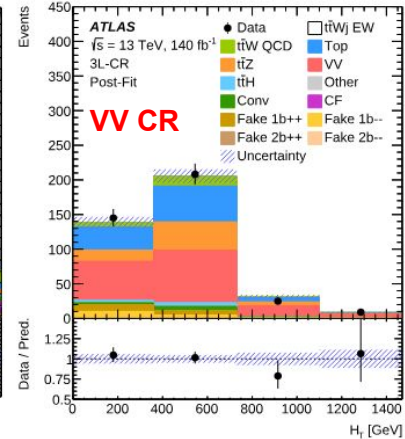
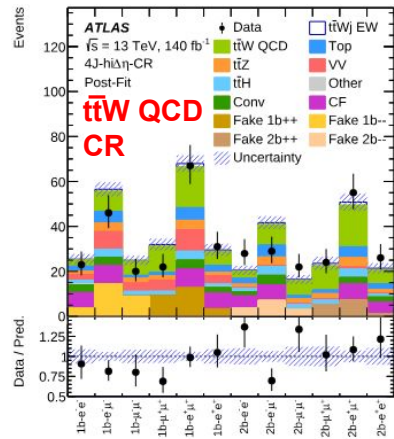
- Corresponding 95% CL_s upper limit for the xs:

$$\sigma_{t\bar{t}Wj_{EW}} < 251 \text{ fb} \quad \text{SM prediction: 47.7 fb}$$

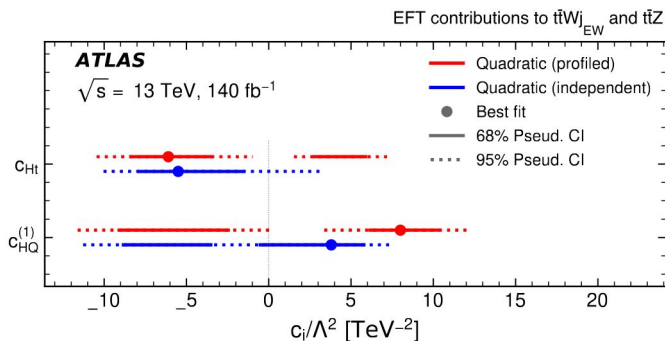
- Uncertainty dominated by systematics (ttW QCD norm., jets + E_T^{miss})



Uncertainty Source	$\Delta\mu_{t\bar{t}Wj_{EW}}$
Total Statistical and Systematic	+2.4 / -3.0
Total Systematic	+2.2 / -2.8
Total Statistical	+0.9 / -0.9
<i>t</i> tW _{QCD} normalization	+1.6 / -2.2
Jets and E _T ^{miss}	+1.6 / -2.2
<i>t</i> tW _{jEW} modeling	+0.4 / -1.5
<i>t</i> tW _{QCD} modeling	+0.6 / -1.2
MC statistical	+0.7 / -0.9
Fake leptons	+0.5 / -0.7

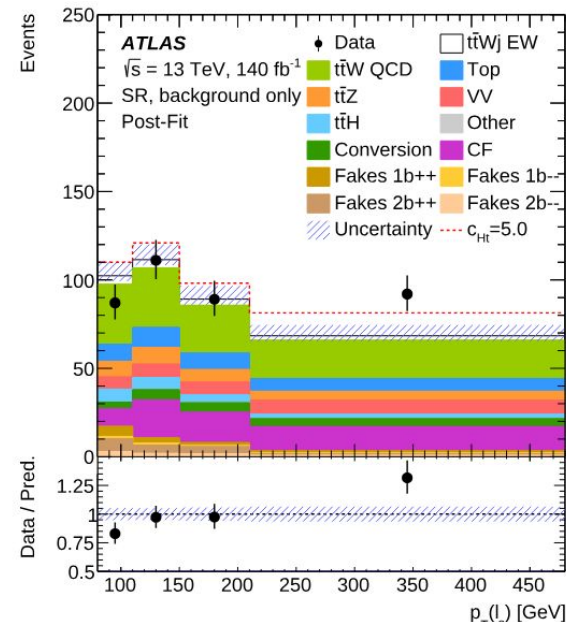
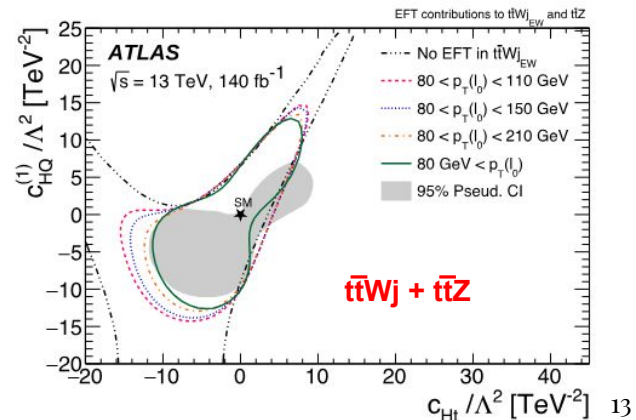
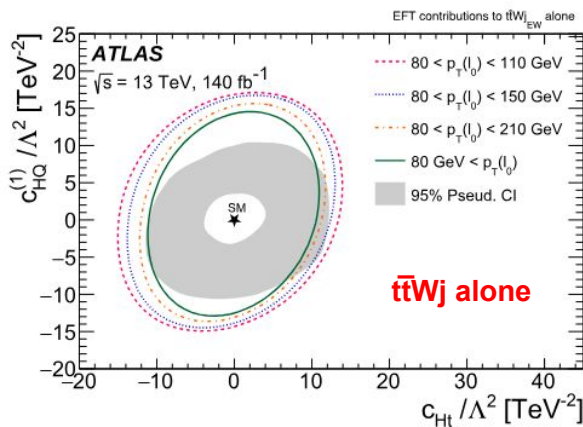


ATLAS: A search for EW ttWj production



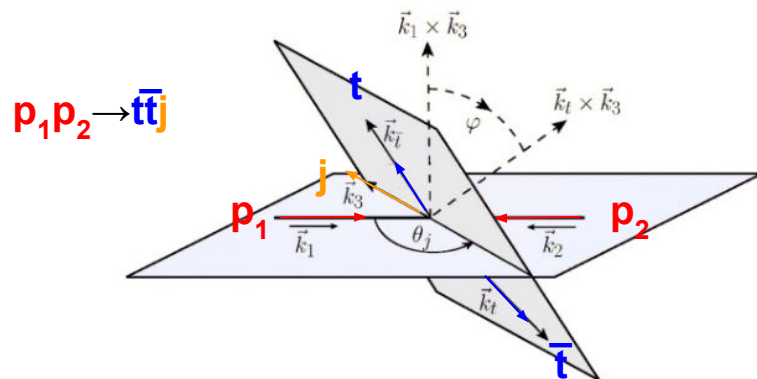
- Operators fitted **individually (1D)** and also **simultaneously (2D)**
- Non-0 best fit values** due to data/MC disagreement in highest p_T bin
- Energy growth dependency confirmed by excluding high- p_T bins

- EFT effects enhanced with increasing energy scale \rightarrow SR binned in *leading lepton* p_T
- Considering EFT effects for **both $ttWj$ alone and with ttZ**
- Profile likelihood EFT fits for **2 most sensitive EFT operators** - $O_{Ht}, O_{HQ}^{(1)}$
- All fits consider **linear** (dominant for ttZ) and **quadratic** (dominant for $ttWj$) terms



CMS: tt̄ charge asymmetry

- Asymmetries in angular distributions between t and t̄ quark studied at LHC → here **focus on energy A_E** (already studied by ATLAS in [EPJC 82 \(2022\) 374](#)) and **incline A_I** (never measured before)
- Interference effects at NLO** → source of asymmetries in SM
- Asymmetries **sensitive to numerous BSM models**
- In **t̄t̄** real gluon contributions induce asymmetry at tree level (enhanced when jet emitted perpendicular to the beam axis)



Incline asymmetry probes **qq̄** channel

- Angular correlation between t and j in t̄t̄ frame

$$A_I \equiv \frac{\sigma^\varphi(y_{t\bar{t}j} > 0) - \sigma^\varphi(y_{t\bar{t}j} < 0)}{\sigma_{\text{tot}}},$$

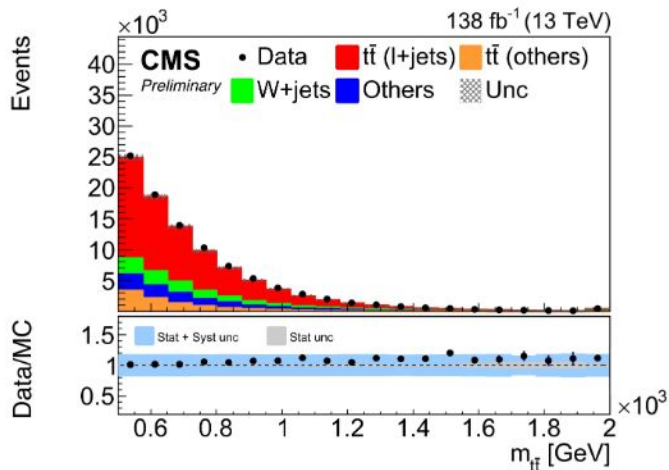
Energy asymmetry probes **qq** channel

- Energy difference of t and t̄ in partonic CM frame

$$A_E = \frac{\sigma(\Delta E > 0) - \sigma(\Delta E < 0)}{\sigma_{\text{tot}}},$$

Signal selection:

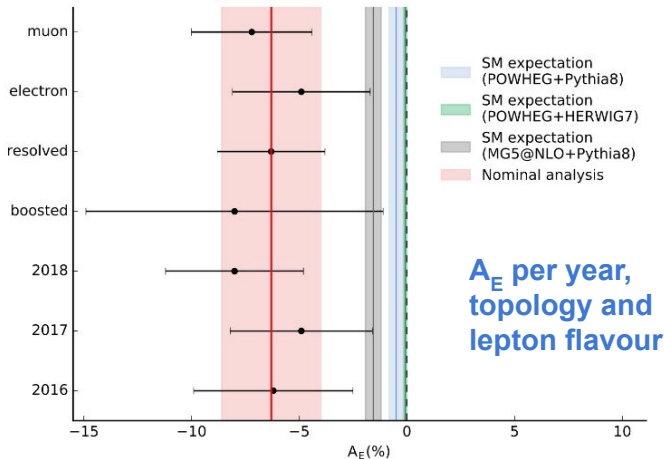
- l+jets** decay of t̄t̄ pair
- 3 topologies**
 - resolved (all jets as separate objects),
 - semi-resolved (1 W-tagged large R jet),
 - boosted (1 t-tagged large R jet)
- Jet assignment based on **χ² mass discriminator**
- Additional jet: p_T^{j-add} > 100 Gev, isolated from t quarks



CMS: ttj charge asymmetry

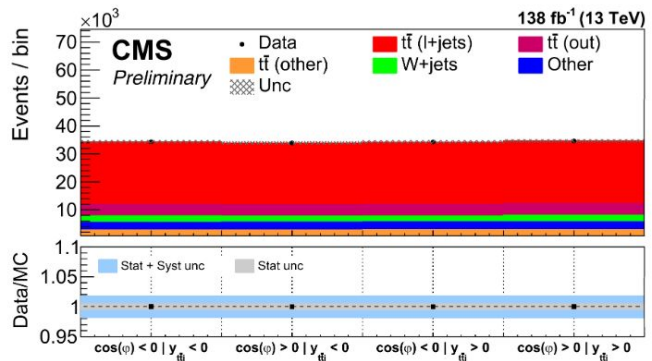
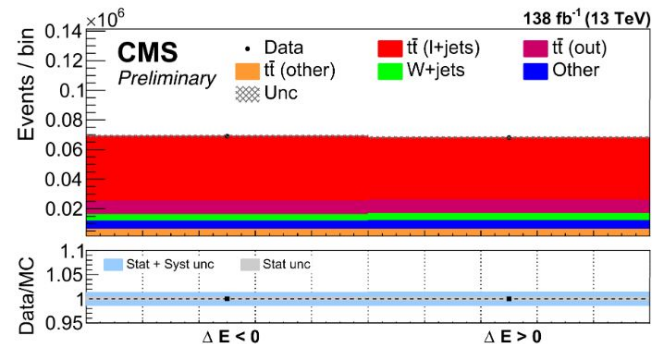
- **BDT to separate signal from main bckgs (W+jets)** - score used to define SR
- **Profile likelihood unfolding to particle level fiducial phase space**
- Results **compared to reference (MG5_aMC@NLO + Pythia 8), and alternative predictions**
- No significant deviation from SM prediction (A_E within 2σ)
- A_E deviates by **2.7 σ** from 0-asymmetry hypothesis

CMS Preliminary









- Uncertainty **dominated by statistics**
- Systematic contribution comparable (dominant W+jets modelling, limited MC size)

Scenario	A_E (%)	A_I (%)
	$\frac{\pi}{4} \leq \theta_1^{\text{opt}} \leq \frac{3\pi}{5}$	$\frac{\pi}{4} \leq \theta_1^{\text{opt}} \leq \frac{3\pi}{5}$
Data	-6.3 ± 2.3	2.5 ± 2.3
SM (MG5_aMC@NLO+PYTHIA8)	-1.6 ± 0.3	-0.5 ± 0.5
SM (POWHEG+PYTHIA8)	-0.5 ± 0.3	-0.1 ± 0.1
SM (POWHEG+HERWIG7)	-0.1 ± 0.1	-0.4 ± 0.3



Summary

- ATLAS and CMS making good progress in understanding rare top quark processes
- Presented two new observations:
 - $t\bar{t}\gamma\gamma$: reference measurement for future theoretical developments 
 - tWZ : advanced ML techniques and combination with Run 3 data finally achieve observation 
- Advancements in testing lepton-flavour  and CP violations  in lepton associated $t\bar{t}$ productions via **sensitive EFT fits**
- New phenomena probed - tW scattering vertex in $t\bar{t}Wj$ by  , incline asymmetry in $t\bar{t}j$ by 



top top
quark

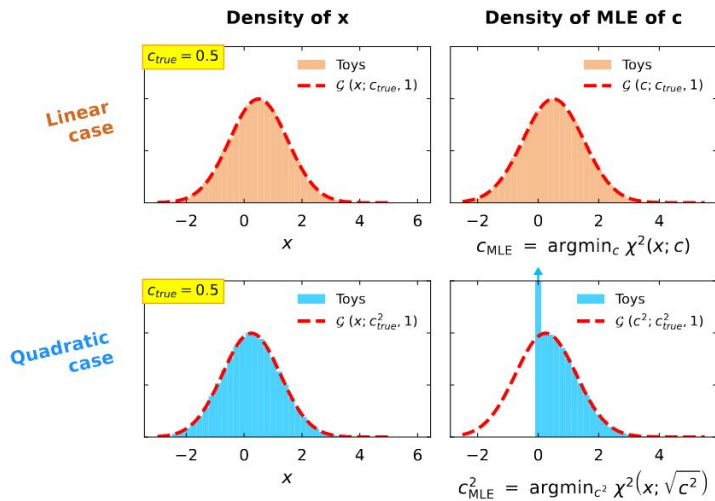
antitop
quark

Thank you for your attention!

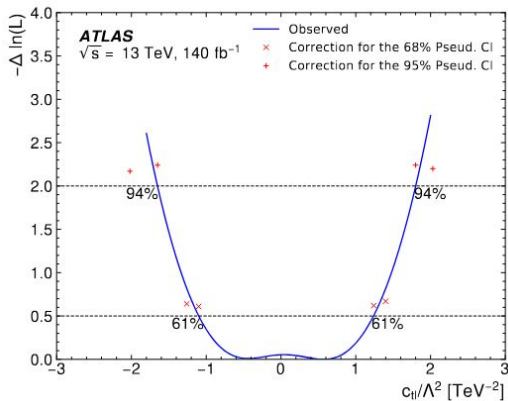
BACKUP

Violation of the Wilks' theorem

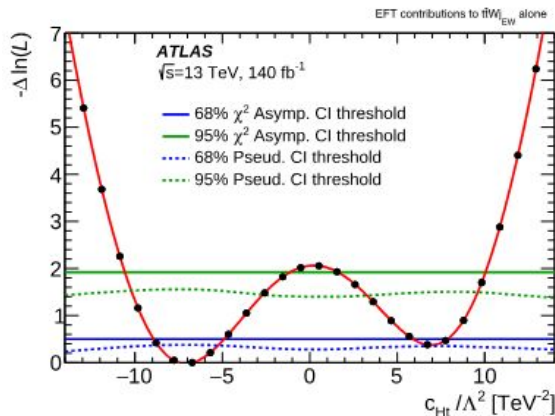
- As demonstrated in [SciPost Phys. Core 6 \(2023\) 013](#) Wilks' theorem is often violated in quadratic EFT fits
- Asymptotic distribution of the profile likelihood ratio is not a χ^2 distribution when the EFT parametrisation is not dominated by the linear component
 - The key condition for Wilks' theorem is that the best-fit statistical models lies in the bulk of the function space profiled, not near its boundaries
- For quadratic EFT fits will always occur at the SM hypothesis - expected density Gaussian-distributed for $c_{\text{MLE}}^2 > 0$, while delta function at $c_{\text{MLE}}^2 = 0$
- As a consequence, in case of quadratic EFT fits in some presented analyses, the alternative approach based on fitting toy pseudodata test statistics is employed to determine 68 and 95 % confidence levels



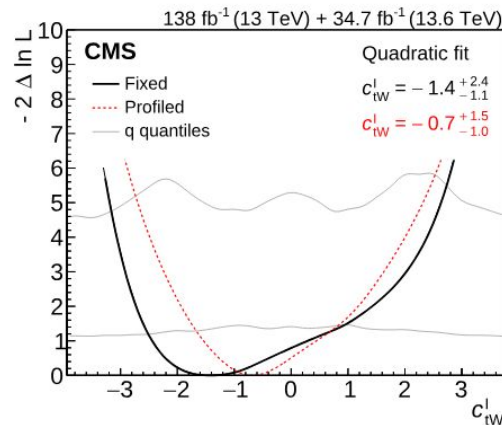
ATLAS High mass $t\bar{t}l^+l^-$



ATLAS Search for EW $t\bar{t}W$



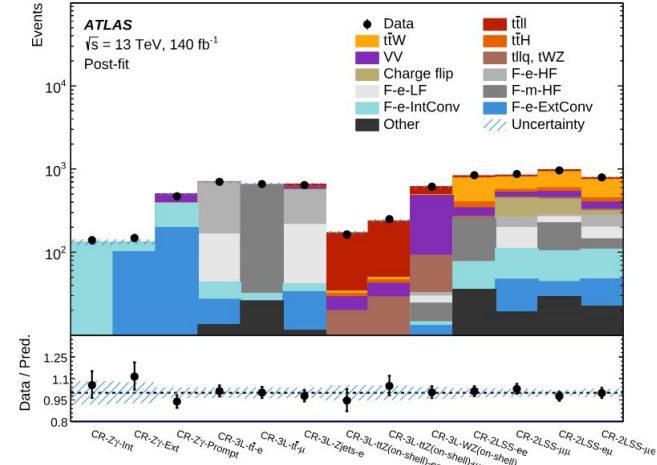
CMS CP violation in $t\bar{t}Z/tZq$



ATLAS: High-mass $t\bar{t}l^+l^-$ and LFU-inspired EFT

Backgrounds

- 13 CRs for main bckgs
- $t\bar{t}W$
 - 2 same-sign leptons ($p_T > 27, 20$ GeV)
 - At least 3 jets (at least 1 b-tagged at 85% WP)
 - Splitted by lepton flavours (e (leading in p_T) e (sub-leading in p_T), $\mu\mu$, $e\mu$, μe)
 - Binned in leading lepton p_T
- $t\bar{t}Z, WZ$ + jets
 - OSSF pair within Z peak (± 10 GeV)
 - 3-class DNN ($t\bar{t}l^+l^-$, $t\bar{t}Z$, WZ +jet) used for splitting (inspired by most recent $t\bar{t}Z$ analysis)
- Non-prompt leptons
 - Looser lepton selection (one loose + 2 tight)
 - HF+LF, Conversion and charge-flip fakes
 - Charge-flip fakes from data-driven method in 2L-SS CR ($Z \rightarrow ee$, one with OS e and one with SS e , bckg is subtracted in region outside Z peak)
 - Binned in lepton p_T and $\eta \rightarrow$ free parameters of the PLF



EFT fits

- 6 four-fermion top quark-lepton EFT operators in the SMEFT formalism
- Constraints on the O_{leQt}^3 tighter due to tensor structure
- Dominant systs: $t\bar{t}l^+l^-$ and $t\bar{t}W$ modelling and limited MC

LFU

- Anomalies observed in LFU tests in B-hadron decays into D^* and lepton-neutrino pair
- Importance of probing LFU in general - commonality in couplings which means anomalies in B-sector could also be manifest in top sector

Operator	Definition	Description
O_{te}	$(\bar{e}_p \gamma_\mu e_r)(\bar{l}_i \gamma^\mu t_j)$	R-handed leptons and R-handed quarks in the $i\bar{l}l^+l^-$ vertex
O_{Qe}	$(\bar{Q} \gamma_\mu Q)(\bar{e}_p \gamma^\mu e_r)$	R-handed leptons and L-handed quarks in the $i\bar{l}l^+l^-$ and $b\bar{b}l^+l^-$ vertices
O_{tl}	$(\bar{l}_p \gamma_\mu l_r)(\bar{t}_i \gamma^\mu t_j)$	L-handed leptons and R-handed quarks in the $i\bar{l}l^+l^-$ vertex
O_{Ql}^1	$(\bar{l}_p \gamma_\mu l_r)(\bar{Q} \gamma^\mu Q)$	L-handed leptons and L-handed quarks in the $i\bar{l}l^+l^-$ and $b\bar{b}l^+l^-$ vertices, weak-singlet
O_{Ql}^3	$(\bar{l}_p \sigma^i \gamma_\mu l_r)(\bar{Q} \sigma^i \gamma^\mu Q)$	L-handed leptons and L-handed quarks in the $i\bar{l}l^+l^-$ and $b\bar{b}l^+l^-$ vertices, weak-triplet
O_{leQt}^1	$(\bar{l}_p^j e_r) \epsilon_{jk} (\bar{Q}^k t_i)$	Mixed L-/R-handed quarks and leptons in the $i\bar{l}l^+l^-$, $i\bar{b}l^+l^-$ and $b\bar{b}l^+l^-$ vertices, scalar
O_{leQt}^3	$(\bar{l}_p^j \sigma_{\mu\nu} e_r) \epsilon_{jk} (\bar{Q}^k \sigma^{\mu\nu} t_i)$	Mixed L-/R-handed quarks and leptons in the $i\bar{l}l^+l^-$, $i\bar{b}l^+l^-$, $i\bar{b}l^+l^-$ and $b\bar{b}l^+l^-$ vertices, tensor

CMS: CP violation in ttZ/tZq

- In SM, CP violation occurs thanks to the imaginary phases in q and ν mixing matrices of the weak interaction
 - But magnitude insufficient to explain baryon asymmetry - motivating searches for BSM sources

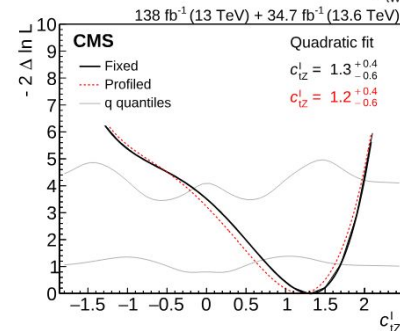
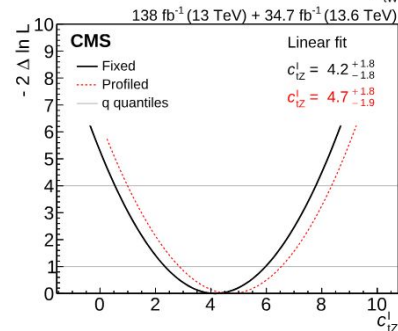
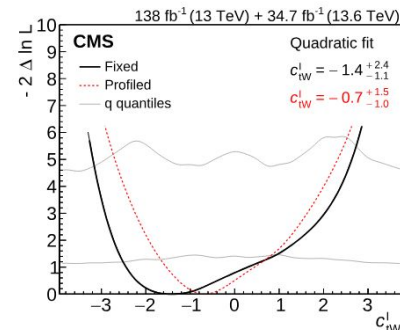
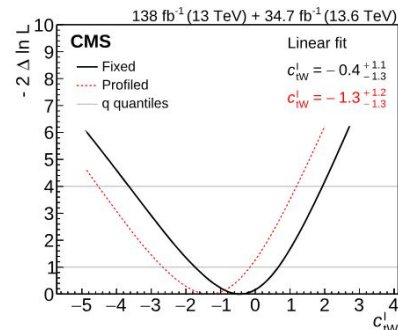
Backgrounds

- All estimated from MC but fakes from mis ID probability method:
 - As SR, but one lepton is loose (fails nominal lepton selection criteria)
 - Accuracy checked in VR where b-jet selection criteria and OSSF are inverted

Construction of CP-odd observables

- ttZ is CP eigenstate - linear effects cancel out for CP-even observables because CP transformation changes the sign of linear contribution -> for CP-odd introduce asymmetries
- tZq is not CP eigenstate but verified that asymmetries are present
- Equivariant NNs:**

- Models g with set of variables x where $g(\mathbf{CP}(x)) = -g(x)$
- Training variables:** 3-momenta of leptons and 5 leading jets, b-tagging score, $\mathbf{p}_T^{\text{miss}}$, W lepton charge sign, data taking period (0-5 integer values, account for differences in detector conditions and COM energy)
- 4 hidden layers, leaky RELU activation function (PYTORCH)
- Likelihood scores as a function of WCs minimize loss function and ensures that models converge to optimal observables
- Dataset splitted: 50% (training), 25% (hyperparameters), 25% (testing)



$$L_i = \sum w_{\text{SM}} \left(\frac{l_i}{w_{\text{SM}}} - g_i(x) \right)^2$$

ATLAS: Observation of $t\bar{t}\gamma\gamma$ production

BDT:

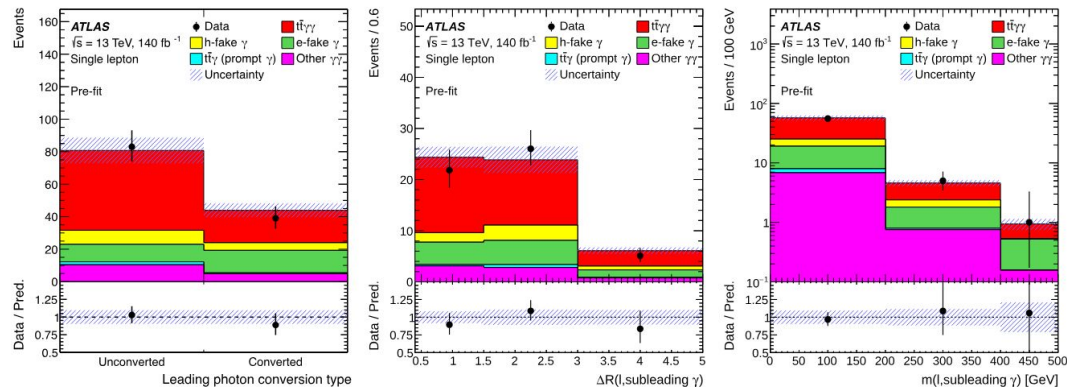
- 19 variables related to γ kinematics:
 - Conversion type, p_T , η , invariant masses, angular separations ($m_{\gamma\gamma}$, $\Delta R(\gamma,\gamma)$, $\Delta R(\gamma,l)$, $\Delta R(\gamma,b)$, E_T^{miss} , jet properties)
- 4 folds (3 for training, 1 for testing)

Fiducial PS following $t\bar{t}\gamma$ analysis:

- γ from hadron decay ($p_T > 20$ GeV), p_T sum of all objects surrounding γ smaller than γp_T
- $\Delta R(\gamma,\gamma / j / l) > 0.4$
- 2 γ , 1 lepton, at least 4 jets (1 ghost matched to B hadron)
- Rejected if additional lepton with $p_T > 7$ GeV
- Pass reco/ Pass fiducial = 19 %

Fit:

- $t\bar{t}\gamma\gamma/t\bar{t}\gamma$ **xs ratio** extracted at particle level using inputs from $t\bar{t}\gamma$ analysis (NN output for SR and 3 CRs - $t\bar{t}\gamma$ decay, fake γ , other prompt γ bckgs)
- For $t\bar{t}\gamma$ **exactly 1 γ** , otherwise same selection



Modelling

- No available comparison for xs (inclusive and also ratio)
 - **Only at LO:**

$$\sigma_{t\bar{t}\gamma\gamma}^{\text{MG5_aMC}} = 1.53^{+0.40}_{-0.52} (\text{scale})^{+0.05}_{-0.03} (\text{PDF}) \text{ fb}$$
- Samples used:
 - $t\bar{t}\gamma\gamma$ - 2 -> 8 process MG5_aMC@NLO + Pythia 8 **at LO** in QCD ($\gamma\gamma$ at ME) - k factor from 2 -> 4 process at NLO
 - $t\bar{t}\gamma$ - 2 -> 3 process where γ from ISR, off-shell t **at NLO**; 2 -> 2 process where γ from on-shell t at LO

CMS: tWZ production

- SM prediction at NLO in QCD:
 $\sqrt{s} = 13 \text{ TeV: } \sigma_{tWZ} = 136_{-8}^{+9} \text{ fb}$
 $\sqrt{s} = 13.6 \text{ TeV: } \sigma_{tWZ} = 148_{-9}^{+10} \text{ fb}$

Theoretical uncertainties considered:

- For signal DR1 vs. DR2 (DS diff. not included as already covered by DR diff.)
- Modelling uncertainty derived for WZ in CR(WZ):
 - Leptonic decay of WZ - at most 1 jet from ME at NLO -> additional jet emissions simulated by PS -> mismodelling in N_{jet} distribution
 - Applied simulation-to-data reweighting

ML algorithm to separate signal from background (4 nodes - tWZ, tZ, WZ+jets, other)

- Particle** variables:
 - 4 momenta of leptons and jets, $\mathbf{p}_T^{\text{miss}}$, $\log(p_T)$, $\log(E)$, η , ϕ , b-tagging info, lepton flavours
- Interaction** variables:

$$\Delta = \sqrt{(y_a - y_b)^2 + (\phi_a - \phi_b)^2},$$

$$k_T = \min(p_{T,a}, p_{T,b})\Delta,$$

$$z = \min(p_{T,a}, p_{T,b}) / (p_{T,a} + p_{T,b}),$$

$$m^2 = (E_a + E_b)^2 - |\mathbf{p}_a + \mathbf{p}_b|^2,$$

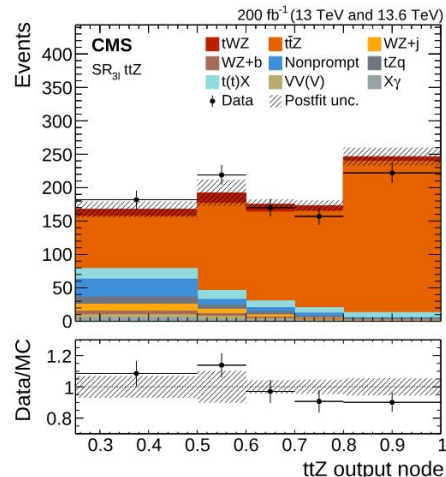
- 4 different trainings (per SR and COM energy) - 50:50% split for training and testing
- WZ+jets and other merged together ("other" region)
- Data/MC agreement for features verified also in CR(tZ) for SR_{3l} and CR(ZZ) for SR_{4l}

Signal regions:

- $p_T(l_0) > 25 \text{ GeV}$, $p_T(l_1) > 15 \text{ GeV}$

Backgrounds:

- CR(ZZ)** - At least 1 jet, exactly 4 leptons, 2 OSSF lepton pairs compatible with Z peak
- CR(WZ)** - At least 2 jets (no b-jet), 3 leptons (1 OSSF inside Z window), $p_T^{\text{miss}} > 40 \text{ GeV}$
- CR(Drell-Yan)** - Same as WZ but inverted cut on p_T^{miss} and no N_j requirement
- CR(tt)** - At least 2 jets (1b), 3 leptons (no OSSF)
- Variables used in the fit:**
 - CR(ZZ)** - event yield,
 - CR(WZ)** - jet multiplicity to constrain diboson modelling,
 - CR(DY)/CR(tt)** - trailing lepton p_T to constrain the fakes lepton rates (3 categories of fakes - from y (50% uncert.), from b-jets (20% uncert.), from light q and gluon jets (50% uncert.), there is about 30% fakes in CR(DY) + CR(tt))



Results of simultaneous tWZ + tZ fit

$$\mu_{tWZ} = 1.88 \pm 0.30 \text{ (stat)} \pm 0.15 \text{ (syst)}$$

$$\mu_{tZ} = 0.91 \pm 0.04 \text{ (stat)} \pm 0.03 \text{ (syst)}$$

ATLAS: A search for EW ttWj production

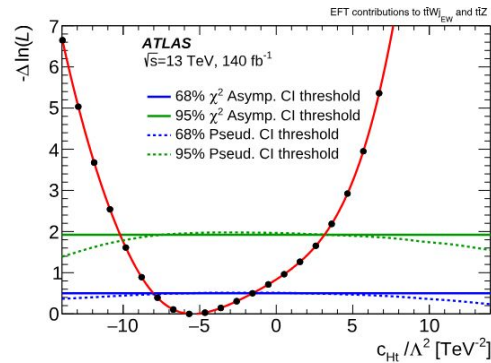
- ttWj EW produces a forward jet with greater η than ttW QCD production -> experimental separation using $|\Delta\eta_j|$
- ttWj EW probes various SM couplings - significant quadratic E dependence due to scattering topology (linear E dependence for ttZ, ttH)
- For ttWj EW linear terms in EFT suppressed, quadratic dominates due to 2 longitudinally polarised gauge bosons in the tW scattering vertex
- $O_{Ht}, O_{HQ}^{(1)}$ modify EW couplings of the top quark via contributions to the tW scattering vertex

Modelling:

- ttWj EW modelled at LO with Sherpa 2.2.10, rescaled to NLO (k=1.13)
- Fake leptons estimated with matrix method - parameters are determined as a function of ttW xs to reduce modelling dependence

EFT fit:

- Violation of the Wilks' theorem is not so prominent when adding ttZ effects because linear terms dominant for this process
- When considering only ttZ EFT effects, degeneracy occurs in 2D fits, which is diluted when adding also ttWj effects



Signal selection:

	Signal Region
Leptons	2 same-charge leptons
$p_T(l_0)$	> 80 GeV
$p_T(l_1)$	> 40 GeV
$ \eta(e) $	< 2.0
$ \eta(\mu) $	< 2.5
N (jets)	≥ 4
N (b-jets)	≥ 1
$p_T(j_0)$	> 60 GeV
m_{ll}	> 125 GeV
m_{ee}	∉ [81.1, 101.1] GeV
$ \Delta\eta_j $	> 2.0
$\sum p_T(j)$	> 250 GeV
Conversion radius (e)	≥ 50 mm

Backgrounds:

- 7 CRs:
 - **Photon conversion** - single bin
 - **Charge flips** - mis ID electron charge
 - **ttZ** - at least 1 OSSF lepton pair inside 10 GeV Z mass window, at least 4 jets (at least 2 b), 3 leptons
 - **3L CR** - targeting dibosons, exactly 3 jets (1 b), 3leptons
 - **4J-low- $\Delta\eta_j$** - targeting normalisation of ttW QCD at low $\Delta\eta_j$
 - **4J-high- $\Delta\eta_j$** - targeting normalisation of ttW QCD and fake leptons at high $\Delta\eta_j$ (same as in SR but with orthogonal $H_T, p_{T(l_{0/1})}$ and m_{ll})
 - **3J CR** - constraining overall non-ttW QCD at high m_{ll} in a PS close to SR

CMS: tt̄ charge asymmetry

- Charge asymmetry in tt̄ already measured at LHC and in agreement with SM
- y asymmetry **diluted at LHC** (arises from qq̄ while tt̄ dominantly produced in gg)

Source	Uncertainty A _E (%)	Uncertainty A _I (%)
Data statistical uncertainty	±1.6	±1.5
MC modeling	±1.3	-1.4, +1.3
Size of MC samples	±0.7	±0.6
Theory	±0.4	-0.6, +0.9
Jet energy corrections	±0.3	-0.2, +0.3
Other experimental uncertainties	±0.4	±0.3
Total	±2.3	±2.3

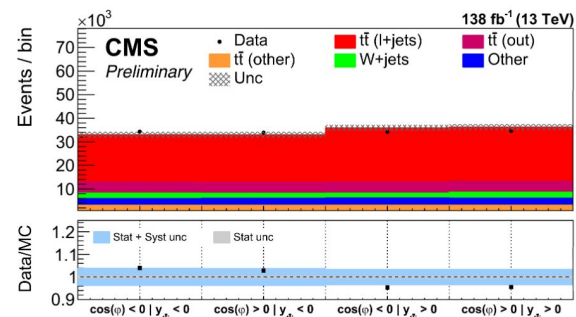
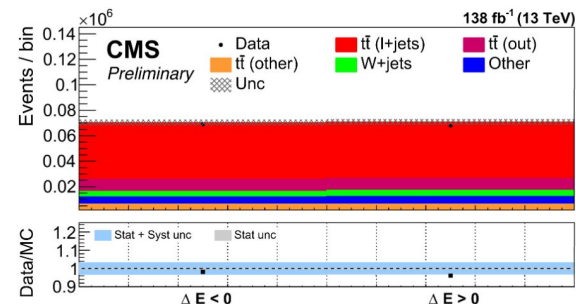
BDT

- **10 input variables:** p_T(l), η(l), p_T(j₁), η(j₁), p_T(j₂), η(j₂), m_{tt̄}, χ², N_{jets}, p_T^{miss}
- Training with XGBoost (80% training, 20% validation), events with negative weight removed
- Only events with **BDT > 0.6** considered in the measurement

Signal selection

- **l+jets decay** of tt̄ pair → single isolated e or μ (p_T > 55 GeV)
- At least **2 jets** (at least 1 b-tag) - p_T^{j1} > 150 GeV, p_T^{j2} > 150 GeV
- p_T^l + p_T^{miss} > 150 GeV, p_T^{miss} > 50 (80) GeV (μ (e))
- **m_{tt̄} > 450 GeV**
- p_{z,v} determined from quadratic equation
- Large R jets for tW tagging with R = 0.8 and ΔR(j^{AK8}, l) > 0.8
- Jet assignment based on **χ² mass discriminator** (χ² > 30):

$$\chi^2 = \chi_{\text{lep}}^2 + \chi_{\text{had}}^2 = \left(\frac{m_{\text{lep}} - \bar{m}_{\text{lep}}}{\sigma_{\bar{m}_{\text{lep}}}} \right)^2 + \left(\frac{m_{\text{had}} - \bar{m}_{\text{had}}}{\sigma_{\bar{m}_{\text{had}}}} \right)^2$$



$$A_I \equiv \frac{\sigma^\varphi(y_{\text{tt}\bar{t}} > 0) - \sigma^\varphi(y_{\text{tt}\bar{t}} < 0)}{\sigma_{\text{tot}}}$$

$$\sigma^\varphi(y_{\text{tt}\bar{t}} > 0) = \sigma(y_{\text{tt}\bar{t}} > 0, \cos \varphi > 0) - \sigma(y_{\text{tt}\bar{t}} > 0, \cos \varphi < 0)$$

$$\sigma^\varphi(y_{\text{tt}\bar{t}} < 0) = \sigma(y_{\text{tt}\bar{t}} < 0, \cos \varphi > 0) - \sigma(y_{\text{tt}\bar{t}} < 0, \cos \varphi < 0)$$

$$A_E = \frac{\sigma(\Delta E > 0) - \sigma(\Delta E < 0)}{\sigma_{\text{tot}}}$$

$$\Delta E = E_t - E_{\bar{t}}$$

$$\theta_j^{\text{opt}} = \begin{cases} \theta_j & \text{if } y_{\text{tt}\bar{t}} > 0 \\ \pi - \theta_j & \text{if } y_{\text{tt}\bar{t}} < 0 \end{cases}$$

- **Jet produced centrally to tt̄ system** and perpendicular to beam axis