Associated top quark production including EFT interpretations with ATLAS+CMS

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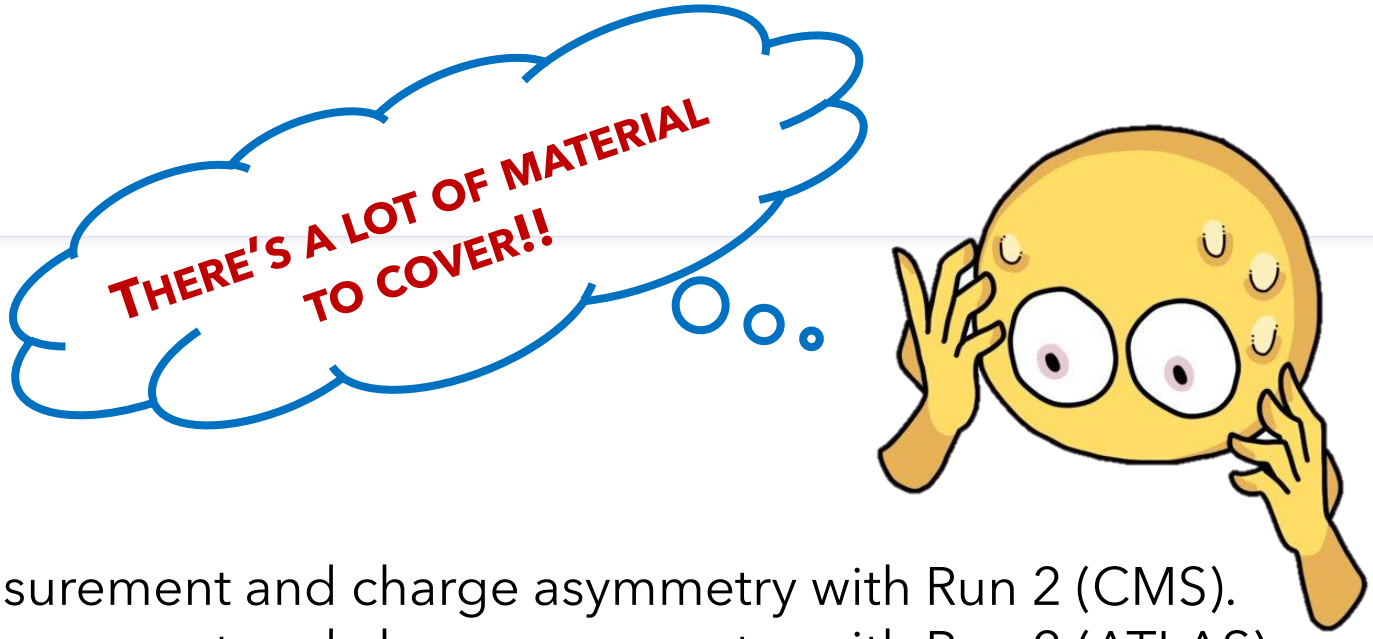
CMS

ATLAS EXPERIMENT

WiN 25

In this talk…



- <u>Top quark productions analysis:</u>
  - ttW differential cross section measurement and charge asymmetry with Run 2 (CMS).
  - ttW differential cross section measurement and charge asymmetry with Run 2 (ATLAS).
  - ttγ inclusive+differential cross section measurement (CMS).
  - ttγ differential cross section measurement (ATLAS).
  - tWZ observation (CMS).
  - tt$\gamma\gamma$ observation (ATLAS – NEW!).

More top physics and analysis in Markus Cristinziani's talk!!

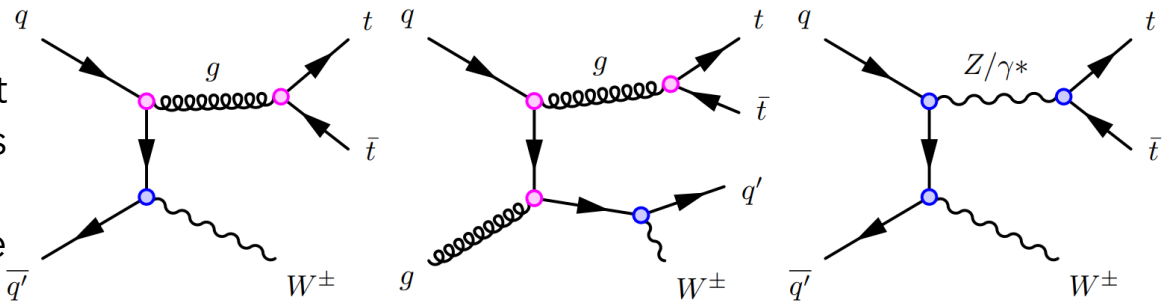
- <u>EFT interpretation analysis:</u>
  - Measurement of ttll at high-mass with EFT (ATLAS).
  - Search for CP violation in events with top quarks and Z bosons (CMS).

Measurement of ttW cross section with Run 2 data

ttW inclusive, differential and charge asymmetry measurement with full Run 2

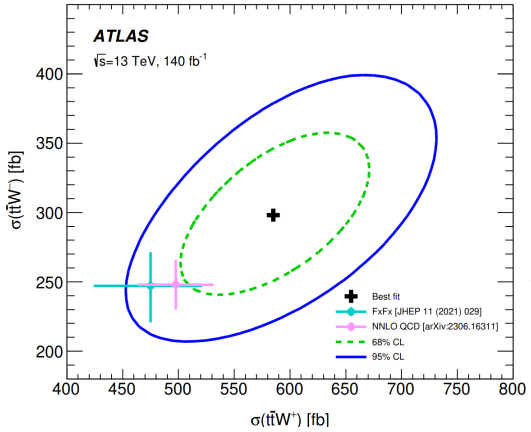
JHEP05(2024)131

- Limitations/difficulty in signal modeling are a big challenge.
- Two final states (2lss and 3l leptons) splitted in different categories based on: lepton charge, lepton flavor, jets multiplicity and b-tags multiplicity.
- Also 10 CRs are used in the measurements to study the normalisation of the leading backgrounds.



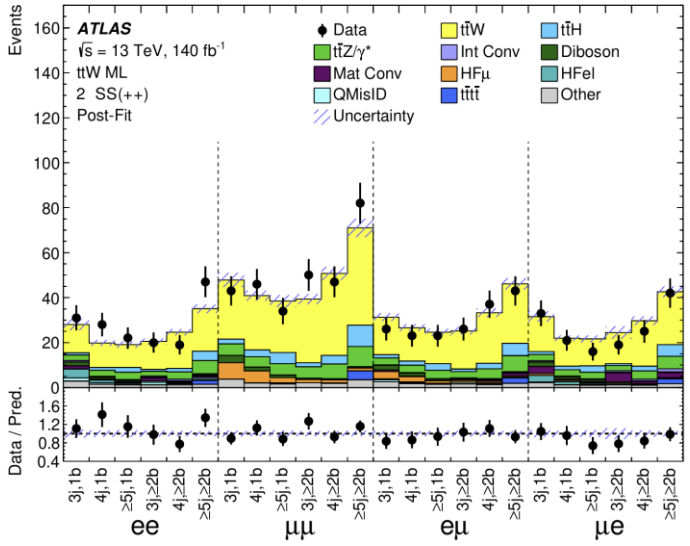
Inclusive measurement: 48 regions for 2lss channel and 8 regions for 3l channel.

$$\sigma = 880 \pm 50\,(stat) \pm 70\,(syst)$$



Tension between the predictions and the data remains.

Agreement of 1.4σ

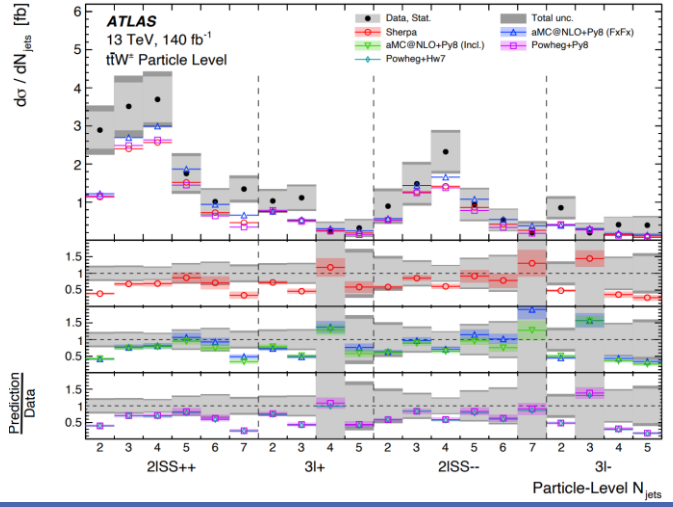


Charge asymmetry: Consistent with SM predictions.

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

Differential measurement:

- Using 2 regions for 2lss and 6 regions for 3l.
- Used 6 variables based on previously observed discrepancies

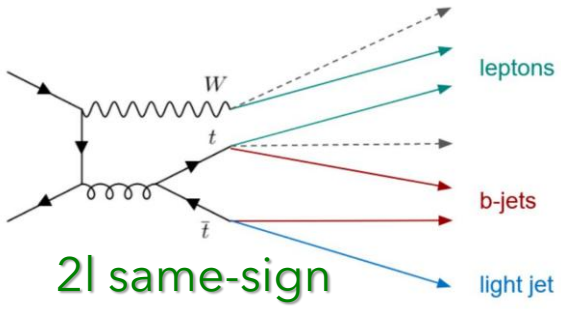


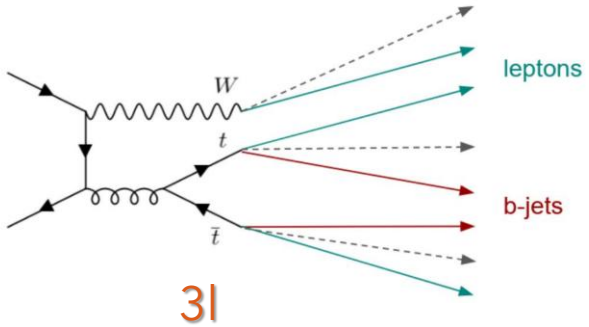
Used 6 observables!

ttW differential and charge asymmetry measurement with full Run 2

CMS-PAS-TOP-24-003

- Tensions between previous inclusive measurements and SM predictions at NNLO.
- Signal is modelled using aMC@NLO with multijet merging up to 1 jet.
- Two regions of measurement: 2 lepton same-sign (2lss) and 3 leptons (3l). Also, validation and control regions to study the backgrounds.





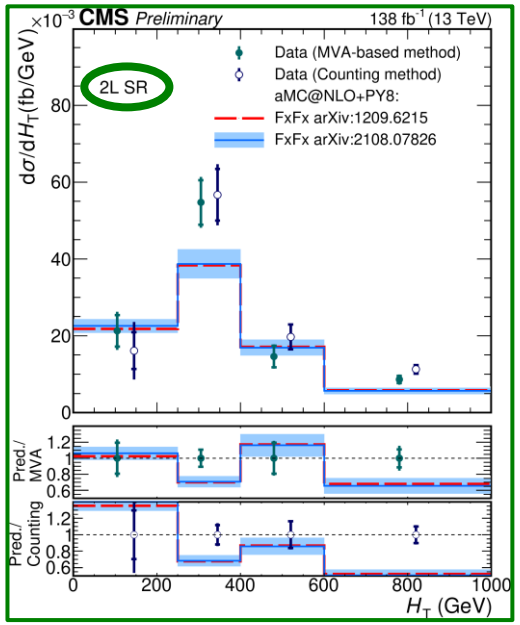
Methodology

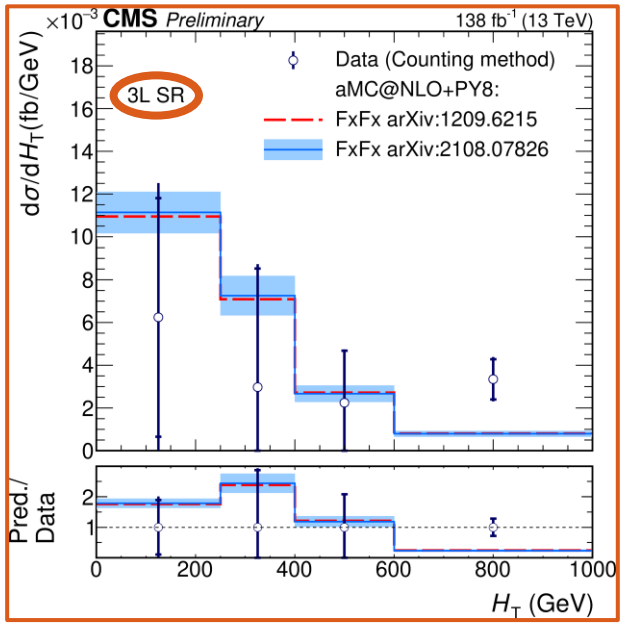
MVA method:

- In 2lss.
- Looser lepton selection.
- Purity of signal achieved with a MVA (36 input variables).

Counting method:

- 3l and 2lss as complementary
- Tighter lepton selection.
- Less purity
- Direct unfolding.

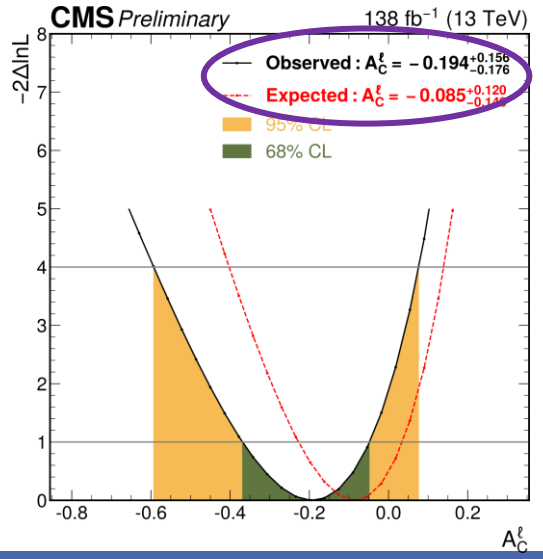




+other 13 variables!

Charge asymmetry:

Consistent with SM predictions.

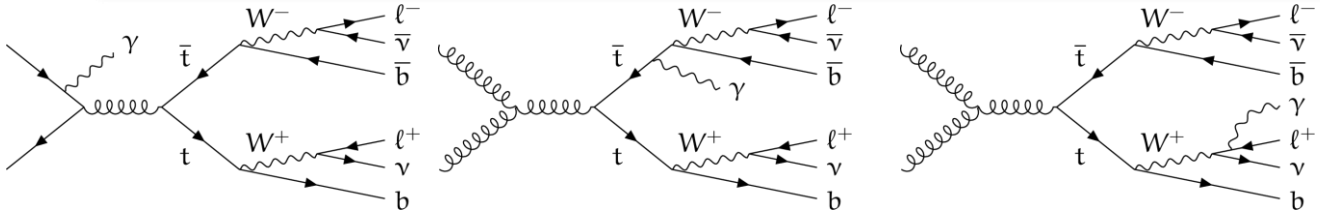


Results compatible within uncertainties → Slight tension with SM predictions

Measurement of $tt\gamma$ cross section with Run 2 data

$t\bar{t}\gamma$ inclusive and differential measurement with full Run 2

CMS-PAS-TOP-23-002



- Two sources of the process: production or decay.
- Simulated separately at NLO and LO using aMC@NLO.
- Overlap with tWγ removed with a diagram removal method (DR1).

Production + decay:

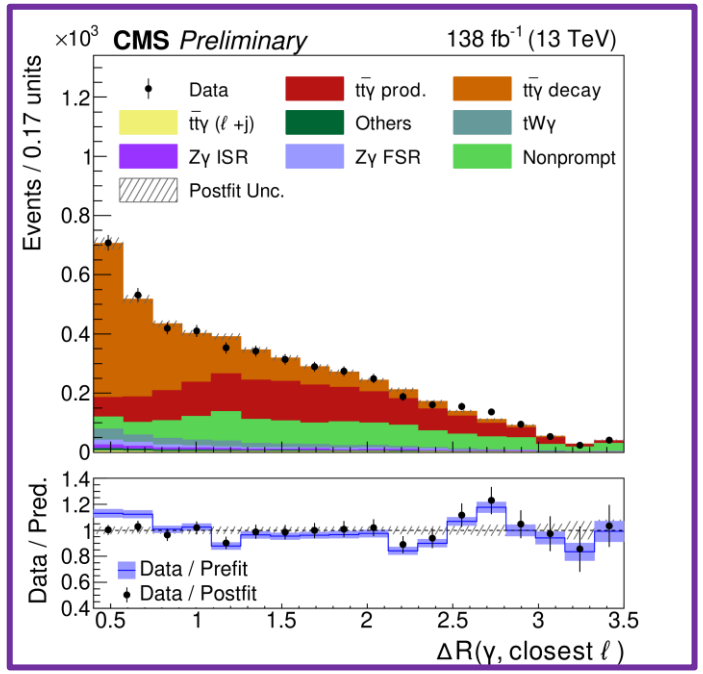
$$\sigma_{t\bar{t}\gamma} = 134 \pm 7\,(syst) \pm 3(stat)\,fb$$

$$\sigma^{pred}_{t\bar{t}\gamma} = 123 \pm 16\,fb$$

Only production:

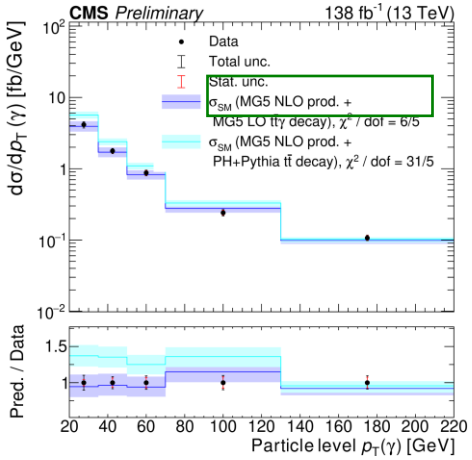
$$\sigma_{t\bar{t}\gamma} = 54 \pm 4\,(syst) \pm 2\,(stat)\,fb$$

$$\sigma^{pred}_{t\bar{t}\gamma} = 55 \pm 5\,fb$$

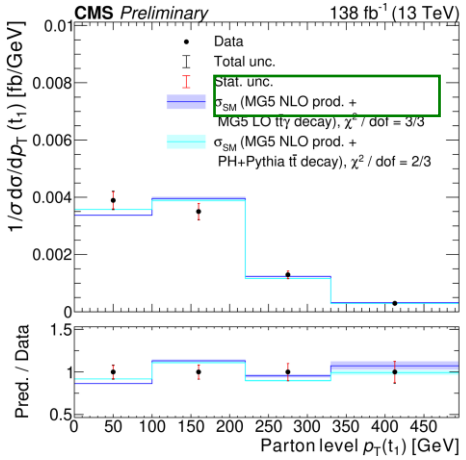


Differential measurement:

PARTICLE LEVEL



PARTON LEVEL



+other 6 variables!

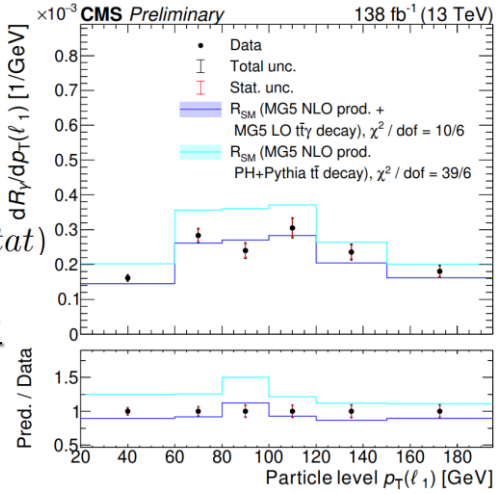
Good agreement with the SM prediction!!

$t\bar{t}\gamma/t\bar{t}$ ratio: Measured both inclusively and differetially:

$$R = 0.0125 \pm 0.0005\,(syst) \pm 0,0002(stat)$$

Top quark charge asymmetry:

$$A_C = (-1.2 \pm 4.2)$$



ttγ differential and asymmetry measurement with full Run 2

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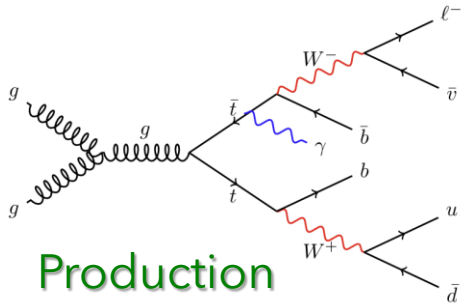
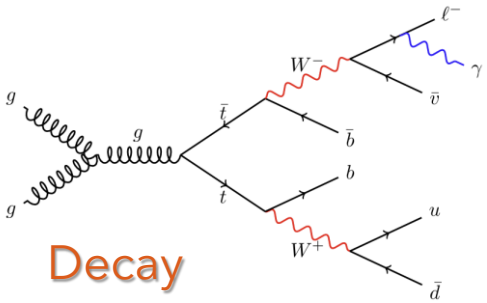




- Two sources of the process: production or decay. Simulated with aMC@NLO generator.
- Study two different channels (single lepton and dilepton channel) with two different approaches.
- Also control regions to study the backgrounds

Single lepton:

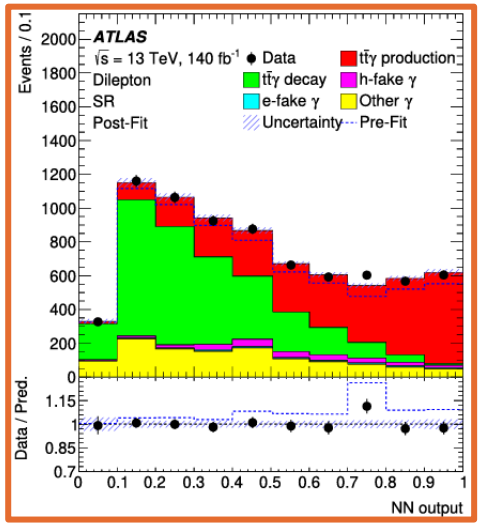
Use of a NN with 40 variables to separate signal (ttγ production) and backgrounds (ttγ decays, photon fakes processes and other processes with prompt photons).

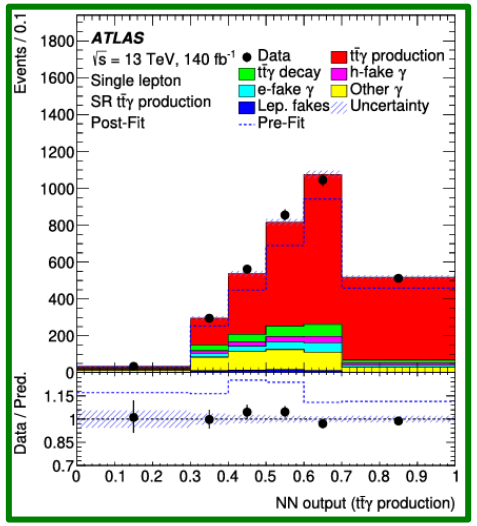
$$\sigma_{single\ lep.} = 704 \pm 5\,(stat) \pm 49\,(syst)\ fb$$

Two leptons:

Binary classification NN (signal-backgrounds) with 16 variables.

$$\sigma_{single\ lep.} = 116.1 \pm 1.7\,(stat) \pm 8.0\,(syst)\ fb$$





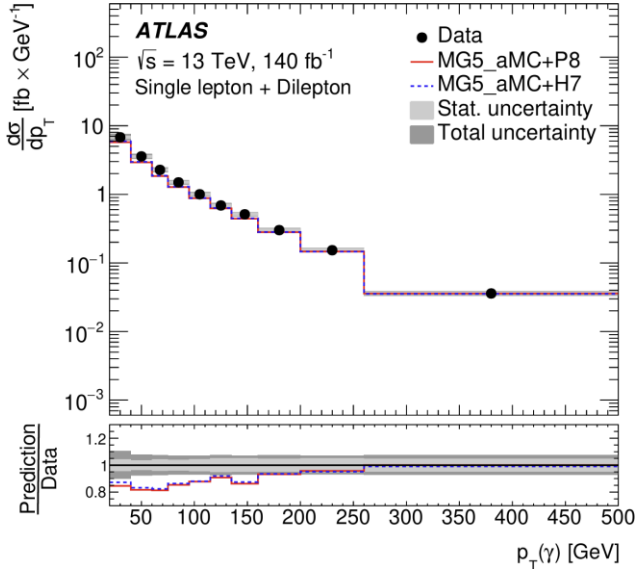
Combined measurement in agreement with SM:

$$\sigma_{production} = 319 \pm 4\,(stat) \pm 15\,(syst)\ fb$$

Differential measurement:

- Separate channels and combined.
- MADGRAPH prediction understimate ttγ.

+other 16 variables!

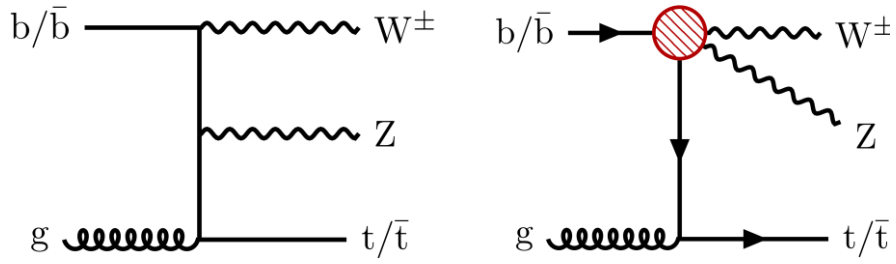


The EFT interpretation is discussed later!!!

Observation of tWZ production

Observation of tWZ production at the CMS experiment (Run 2 + Run 3)

CMS-PAS-TOP-24-009



Improve of the previous measurement:

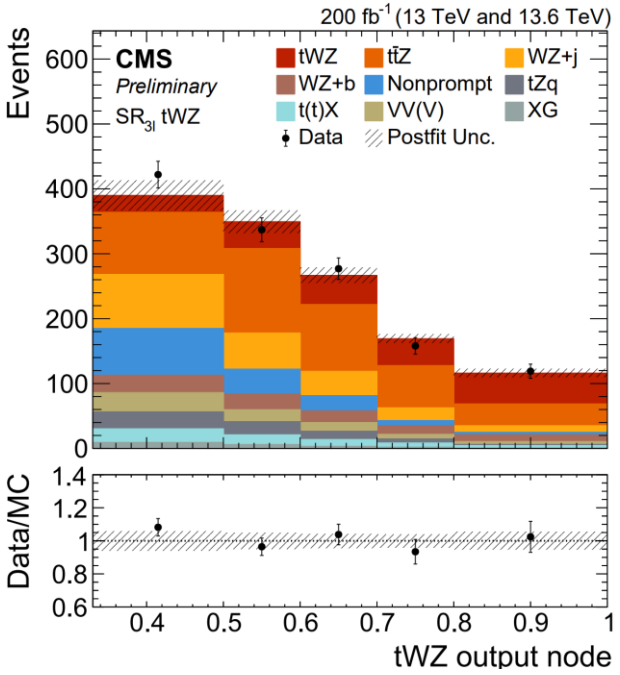
- Adding Run 3 data (previous used only Run 2 data).
- State-of-art of ML techniques and reconstruction methods to achieve unprecedented sensitivity.

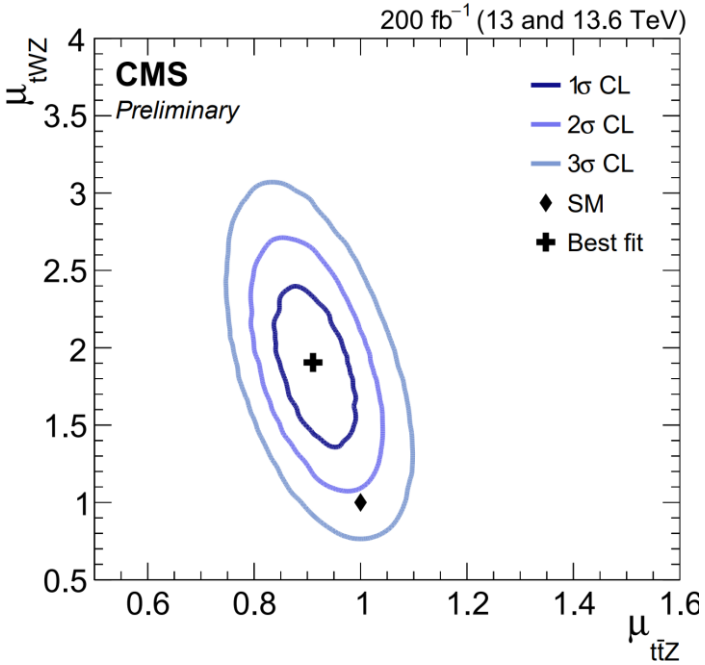
- Two regions of measurement: 3 lepton and 4 leptons. Also control regions to study the backgrounds.

- Four control regions: 2 achieve control of WZ/ZZ backgrounds & two to help to improve the modelling of nonprompt leptons (mainly DY and ttbar).
- Multivariate analysis approach: Discriminate between signal (tWZ) and main backgrounds (ttZ+WZ).

$$\sigma_{13\ TeV} = 248 \pm 38\,(stat) \pm 35\,(syst)\ fb$$
$$\sigma_{13.6\ TeV} = 242 \pm 62\,(stat) \pm 46\,(syst)\ fb$$

Agrees with the standard model (SM) prediction within 2.3 standard deviations.

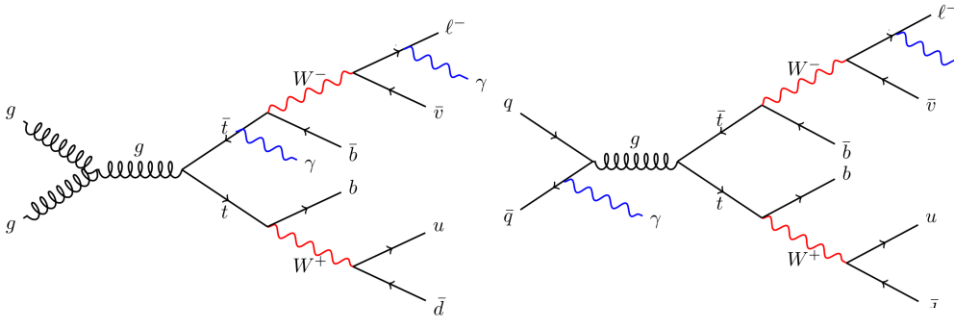




Observation of $tt\gamma\gamma$ production

Observation of ttγγ production

https://arxiv.org/abs/2506.05018



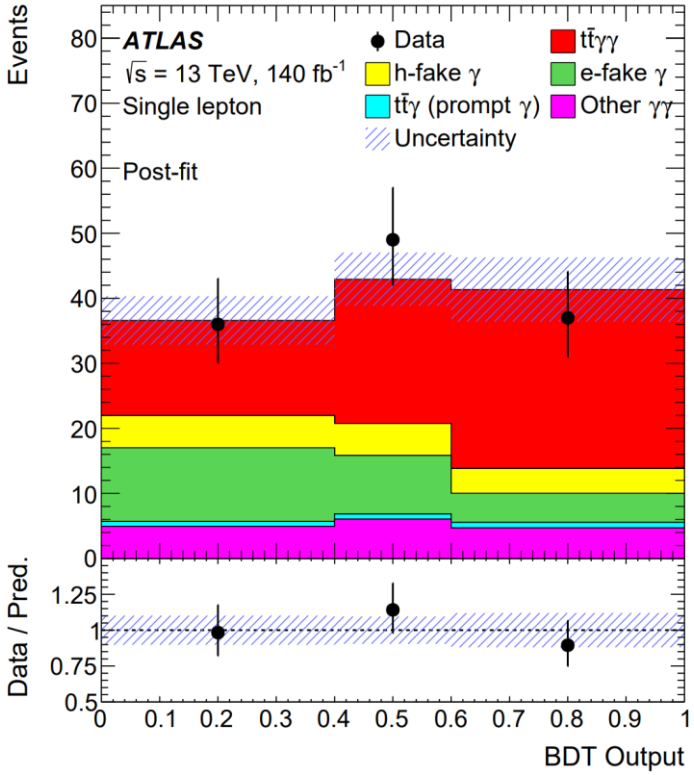
- Using full Run 2 data in a single lepton region.
- The signal cannot be simulated at high-order accuracy using ME generators interfaced with parton shower.

Cross section

- A multivariate analysis using a BDT is performed to separate the signal and background.
- 19 variables (properties of the photons, such as photon conversion type, p_T and η, invariant masses and angular separations of different objects).

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

Good agreement between data and MC predictions



tttγγ/ttγ cross section ratio

- ttg production and decay in the single lepton channel.
- A four-class NN is used to define a region enriched in production events and three control regions enriched in decay.

$$R_{t\bar{t}\gamma\gamma/t\bar{t}\gamma} = (3.30^{+0.70}_{-0.65}) \times 10^{-3} = (3.30^{+0.63}_{-0.55}\ (\text{stat})^{+0.32}_{-0.34}\ (\text{syst})) \times 10^{-3}$$

- No available calculations of the ratio that would allow for a direct comparison.

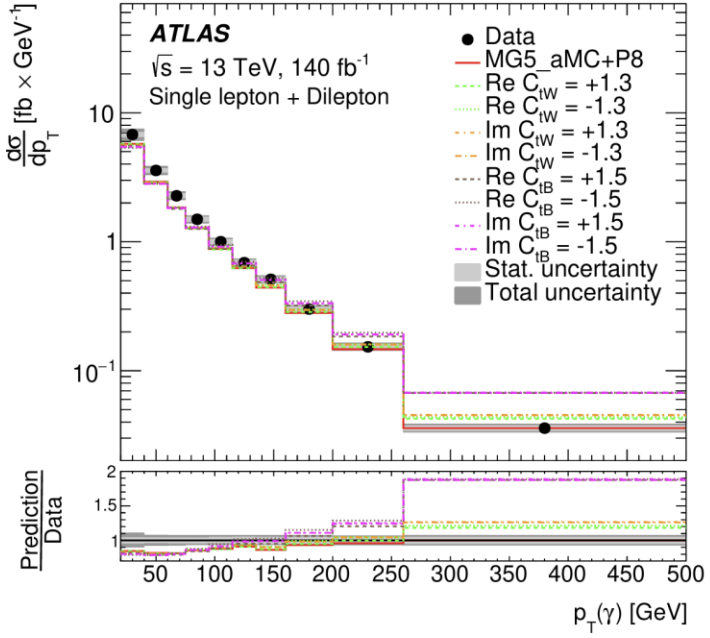
Dominated by statistical uncertainties in both measurement

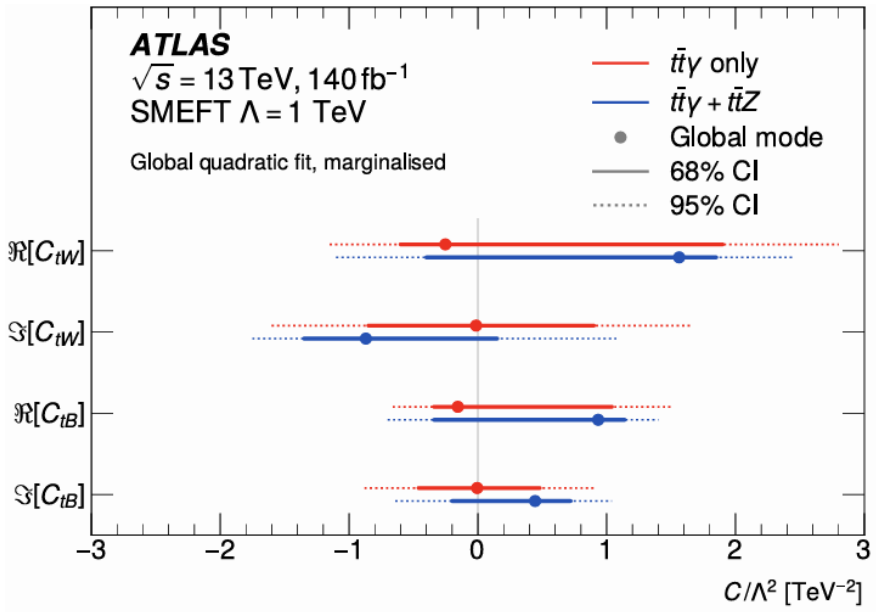
EFT interpretations

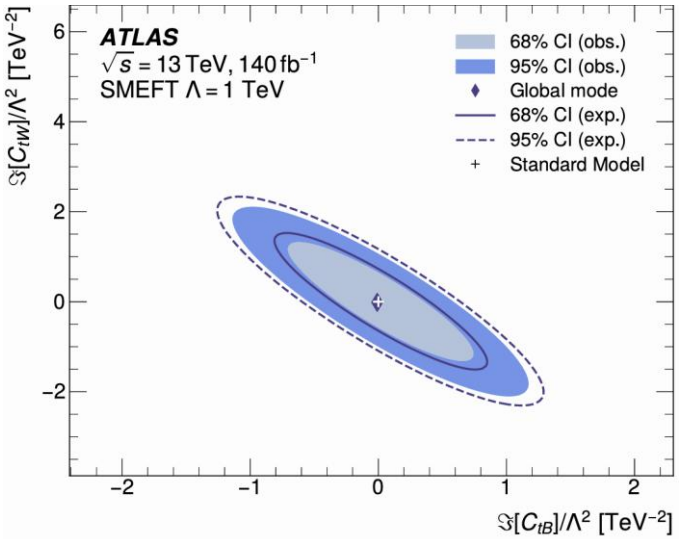
EFT interpretation in ttγ process

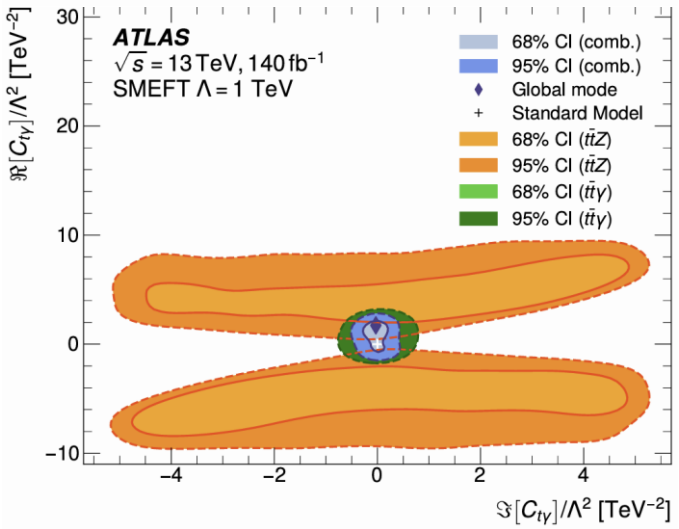
JHEP10(2024)191

- The differential cross-sections as a function of the photon p_T are interpreted in the framework of the SMEFT. The ttγ production process is expected to be sensitive to several EFT operators (highest sensitivity to C_{tB} and C_{tW}).
- A combined measurement with ttZ slightly improves the limits, in the credible intervals for C_{tW} obtained with the independent quadratic fits are reduced by up to 20%.



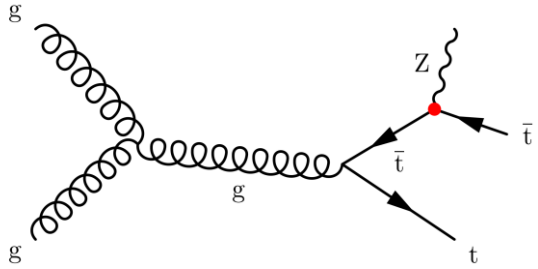


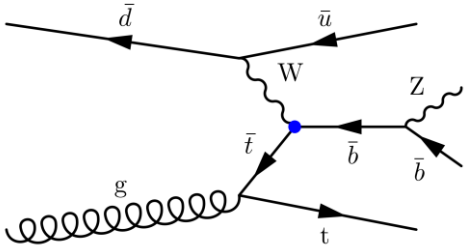




Search for CP violation in events with top quarks and Z bosons

https://arxiv.org/abs/2505.21206





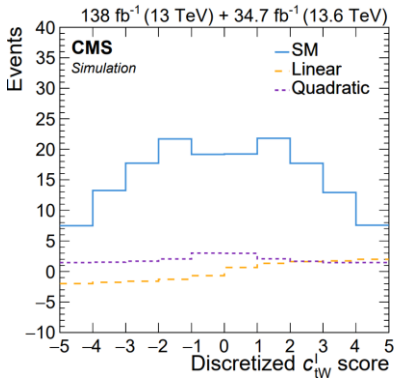
- This search targets dimension-6 CP-odd EFT operators using combined Run 2 and Run 3 data.
- C^{I}_{tZ} and C^{I}_{tW} modifies ttZ and tZq (via tW coupling) respectively.

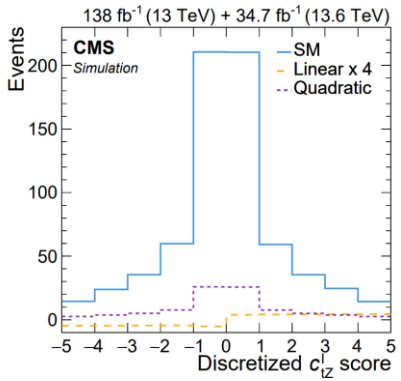
- Use of CP-odd observables constructed via CP-equivariant function:

$$g_i(x) = f_i(x) - f_i(CP(x))$$

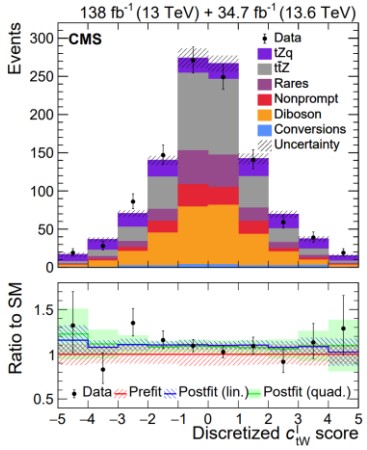
CPV observables as a new key of EFT tests.

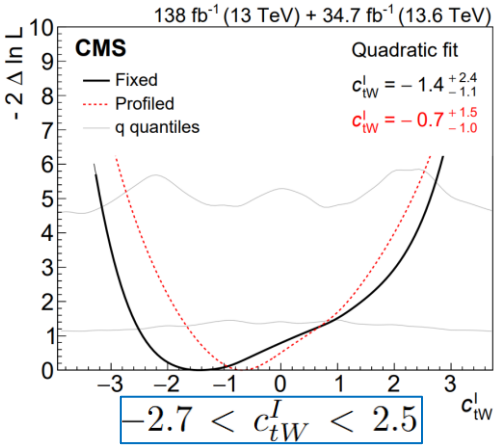
- Two CP-equivariant neural networks separately to be sensitive to C^{I}_{tZ} and C^{I}_{tW}. The output is a CP-odd score.
- If shows asymmetry under SM, it means new CPV signatures.

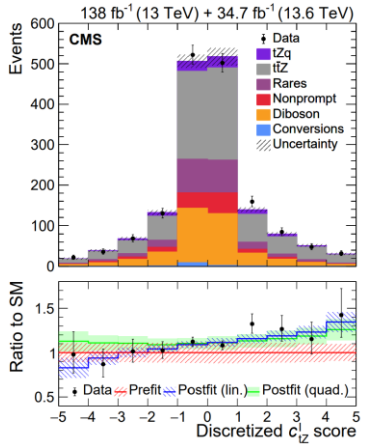


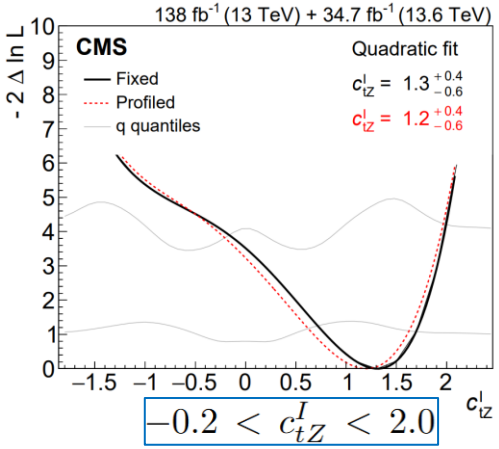


- Results are consistent (mostly) with the SM.
- CP violation sensitivity is mostly driven by the linear term.
- First limits on the linear term of C^{I}_{tZ} .



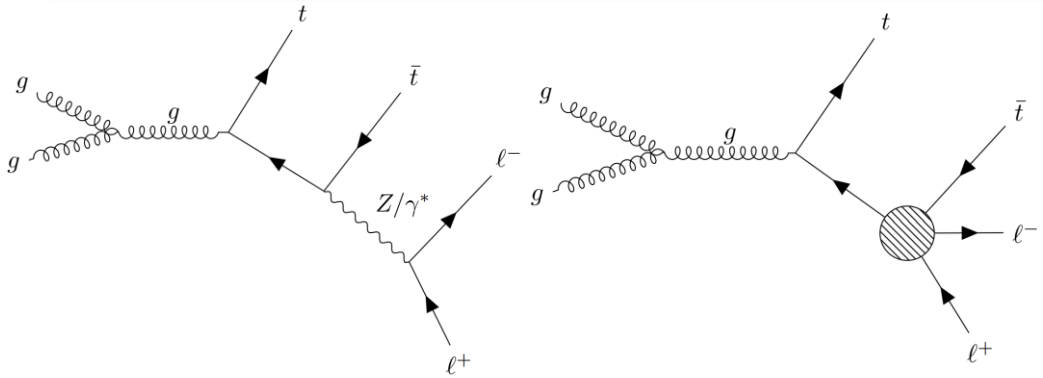






Measurement high-mass ttll production and LFU-inspired EFT interpretation

ATLAS-TOPQ-2023-02



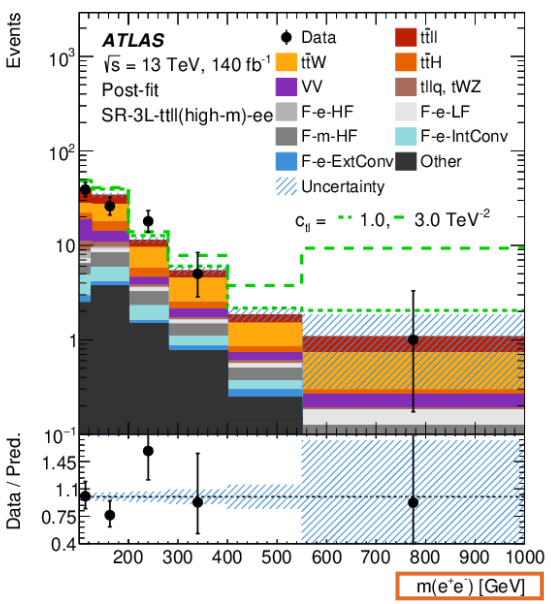
- New measurement of off-Shell $tt\bar{t}l^+l^-$ at high invariant mass (mll>101.2 GeV) that is sensitivity to the effective coupling.
- Search of LFU violation that could be present (flavour-relative WCs).
- Search for new physics via four-fermion top quark–lepton EFT operators (dimension-6).
- Signal region splitted by flavor and using 13 control regions.

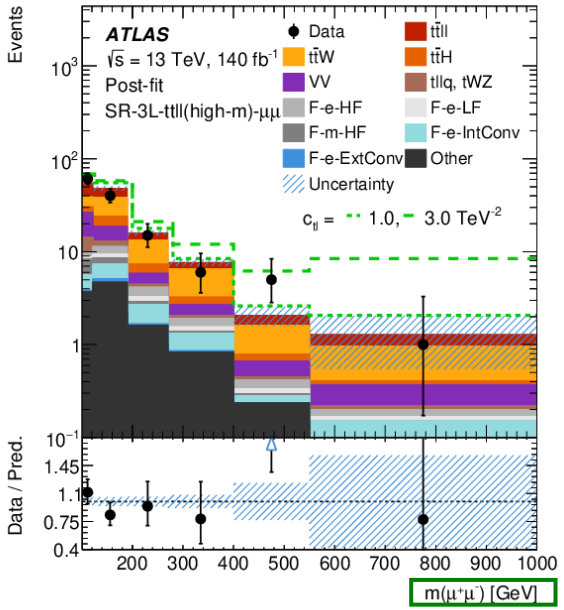
Three different fit strategies:

- Shared WC across all leptons (flavour-inclusive).
- Independent WCs for e and μ leptons (flavour-split).
- Test LFU with C_e – C_μ (flavour-relative).

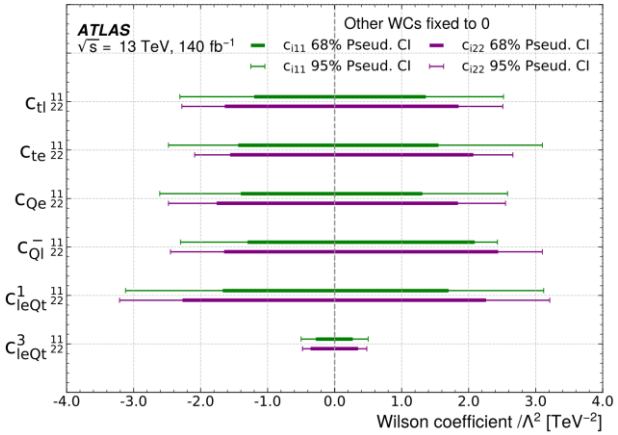
Result of SM signal ttll measurement with a significance of 2.9σ:

$$\mu\ell\ell = 1.0 \pm 0.4$$





- No significant deviations from the SM.
- Wilson coefficients consistent with zero.



Summary and conclusions

- Several new results of top production including EFT interpretations were presented. In general, obtaining good agreement with SM predictions.
- Measurements of top quark production processes are of great interest in studies of Standard Model physics as well as in searches for beyond Standard Model.
- Recent public results from both CMS and ATLAS provide competitive measurements.
- Obtaining competitive results and gaining a detailed understanding of the processes allows for the exploration of new physics and the imposition of constraints on EFT operators.

With the upcoming Run 3, many new results are expected!!

Universidad de Oviedo

ICTEA
Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias

CMS

ATLAS EXPERIMENT

Thank you for your attention!

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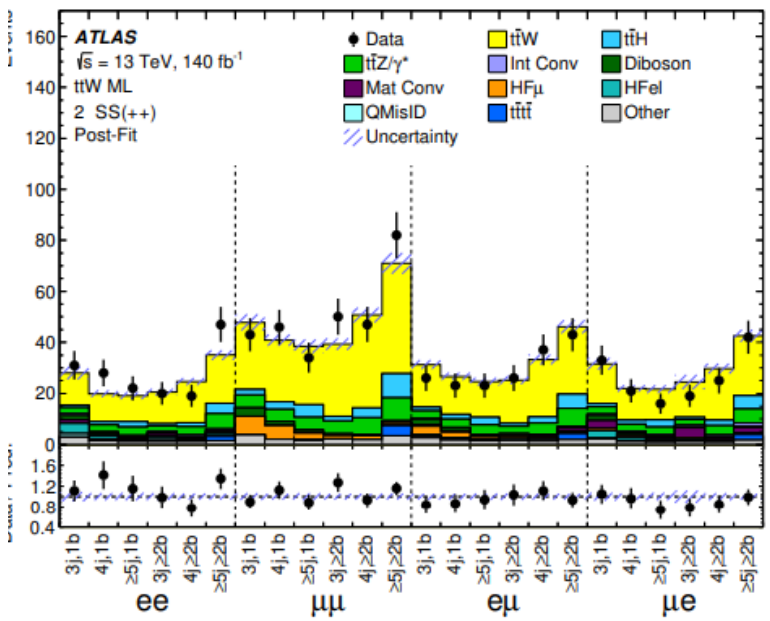
Backup

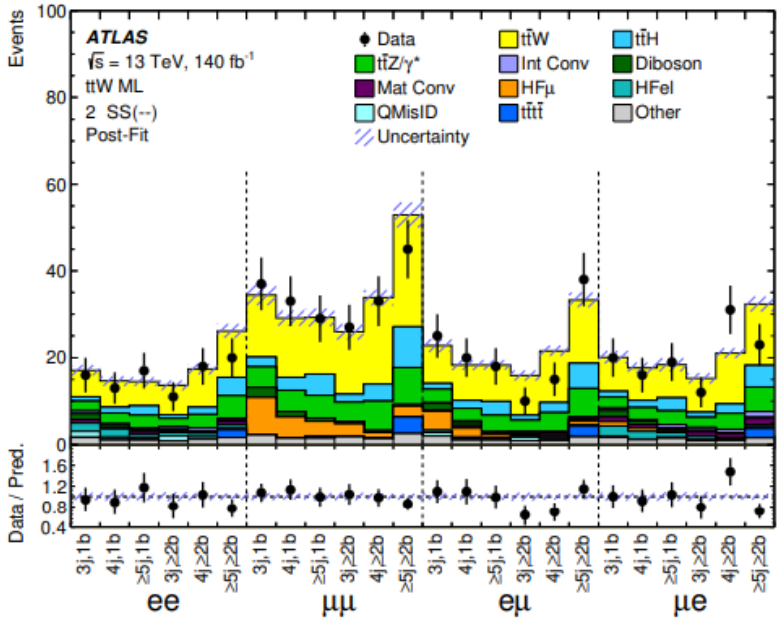
ttW differential and asymmetry measurement with full Run 2

JHEP05(2024)131

Signal region preselection	2ℓSS	3ℓ
Lepton definition	TT	LTT
Lepton p_T [GeV]	(20, 20)	(10, 20, 20)
$m^{SF}_{\ell^+\ell^-}$ [GeV]	—	> 12
$\lvert m^{SF}_{\ell^+\ell^-} - m_Z \rvert$ [GeV]	—	> 10
$\lvert m_{3\ell} - m_Z \rvert$ [GeV]	—	> 10
N_{jets}	≥ 2	
$N_{b\text{-jets}}$	$\geq 1\ b^{60\%}$ or $\geq 2\ b^{77\%}$	
	Inclusive cross-section measurement	
Lepton charge split	$(\ell^+\ell^+, \ell^-\ell^-)$	$(\ell^+\ell^-\ell^-, \ell^-\ell^+\ell^+)$
Lepton flavour split	($\mu\mu$, $e\mu$, μe, ee)	—
Jet multiplicity split	(3, 4, $\geq$5)	(2, $\geq$3)
b-jet multiplicity split	(1, $\geq$2)	
Total inclusive SRs	48	8
	Differential cross-section measurement	
Lepton charge split	$(\ell^+\ell^+, \ell^-\ell^-)$	$(\ell^+\ell^-\ell^-, \ell^-\ell^+\ell^+)$
Number of OS-SF pairs split	—	(0, 1, 2)
Total differential SRs	2	6

2 lepton same-sign categories:





ttW differential and asymmetry measurement with full Run 2

JHEP05(2024)131

Signal region preselection	2ℓSS	3ℓ
Lepton definition	TT	LTT
Lepton p_T [GeV]	(20, 20)	(10, 20, 20)
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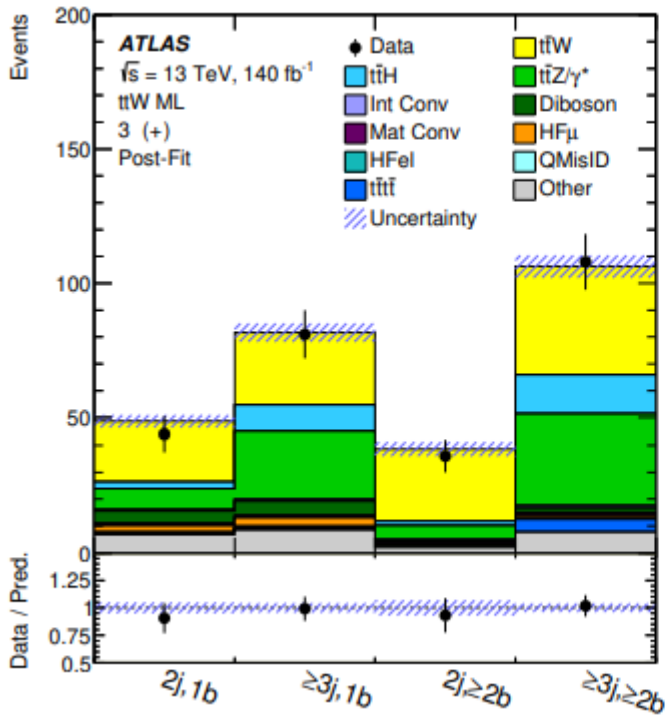
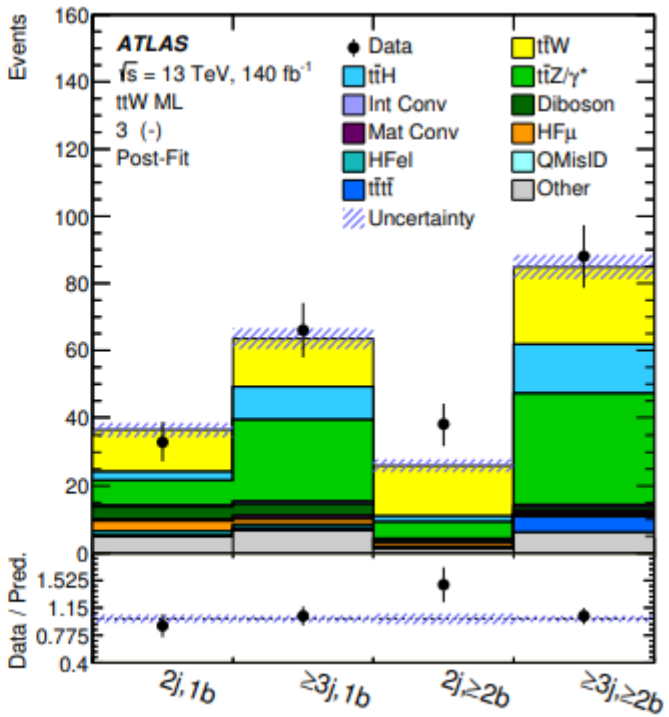
$\lvert m_{3\ell} - m_Z \rvert$ [GeV]	—	> 10
N_{jets}	≥ 2	
$N_{b\text{-jets}}$	$\geq 1\ b^{60\%}$ or $\geq 2\ b^{77\%}$	
	Inclusive cross-section measurement	
Lepton charge split	$(\ell^+\ell^+, \ell^-\ell^-)$	$(\ell^+\ell^-\ell^-, \ell^-\ell^+\ell^+)$
Lepton flavour split	($\mu\mu$, $e\mu$, μe, ee)	—
Jet multiplicity split	(3, 4, $\geq$5)	(2, $\geq$3)
b-jet multiplicity split	(1, $\geq$2)	
Total inclusive SRs	48	8
	Differential cross-section measurement	
Lepton charge split	$(\ell^+\ell^+, \ell^-\ell^-)$	$(\ell^+\ell^-\ell^-, \ell^-\ell^+\ell^+)$
Number of OS-SF pairs split	—	(0, 1, 2)
Total differential SRs	2	6

3 leptons categories:

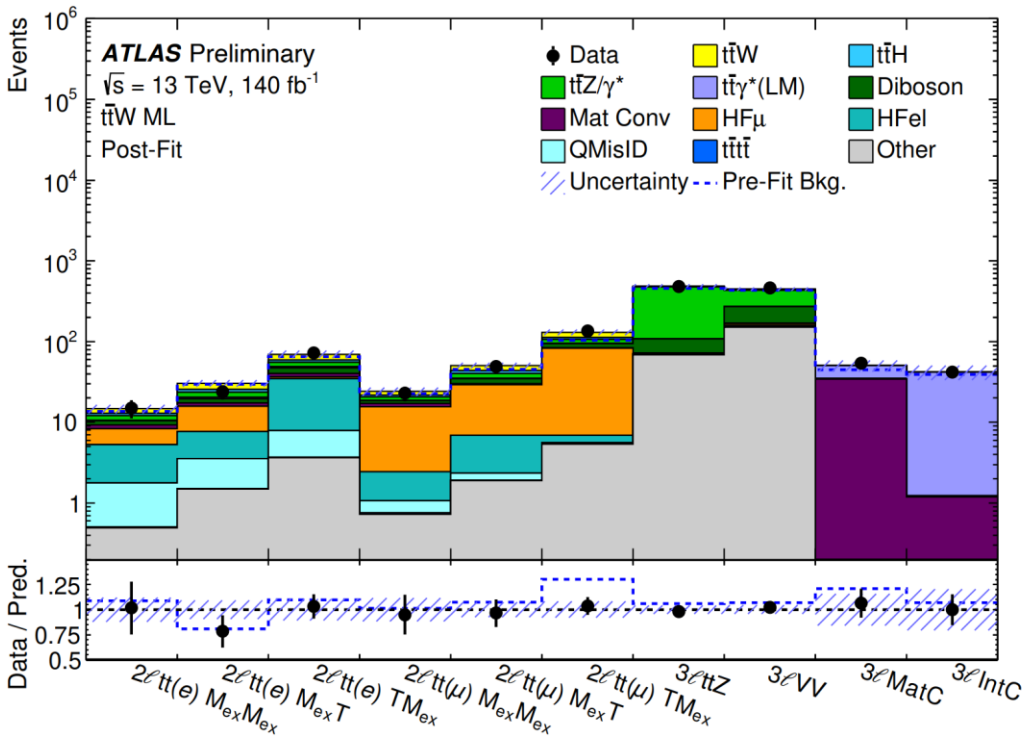




ttW differential and asymmetry measurement with full Run 2

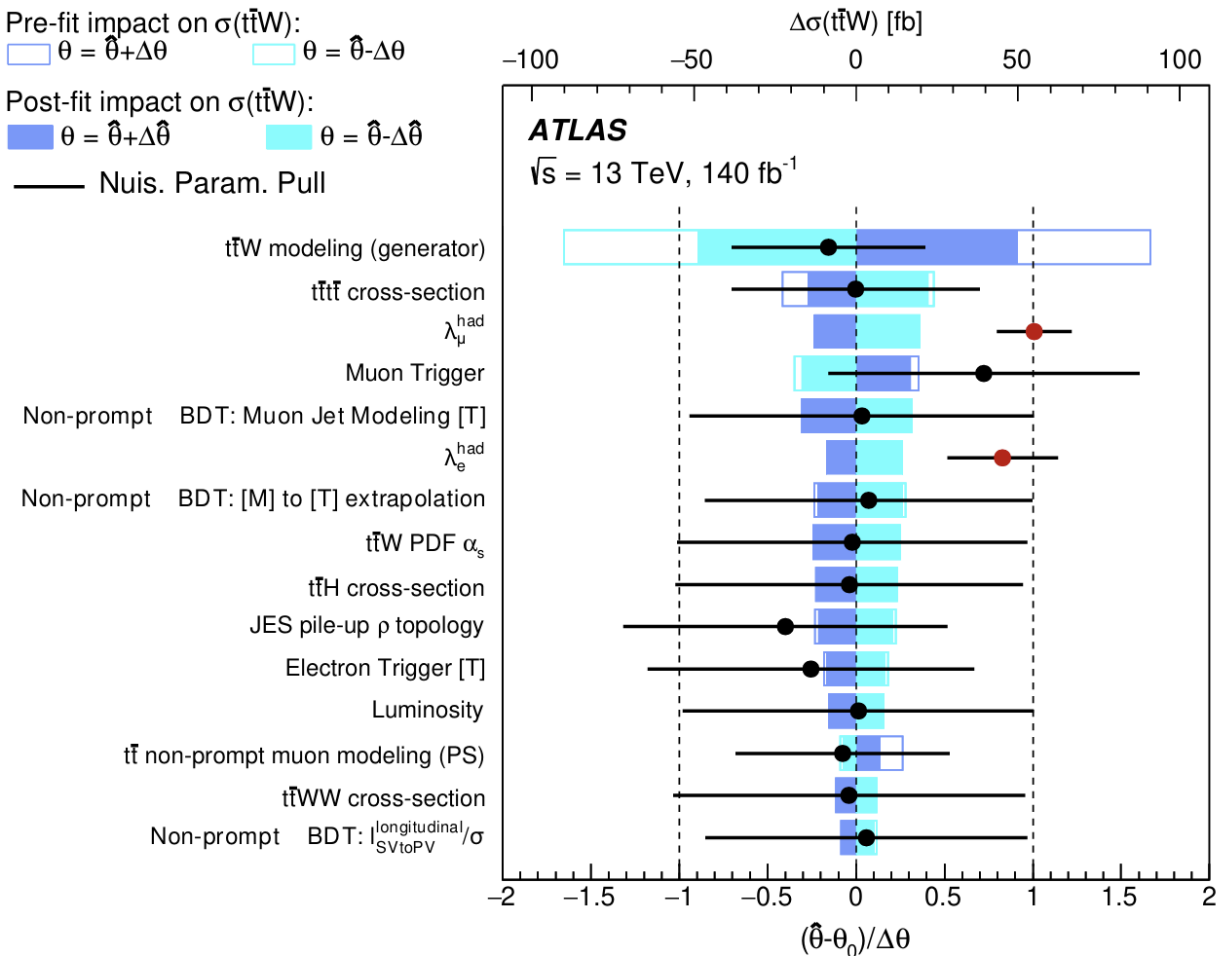
JHEP05(2024)131

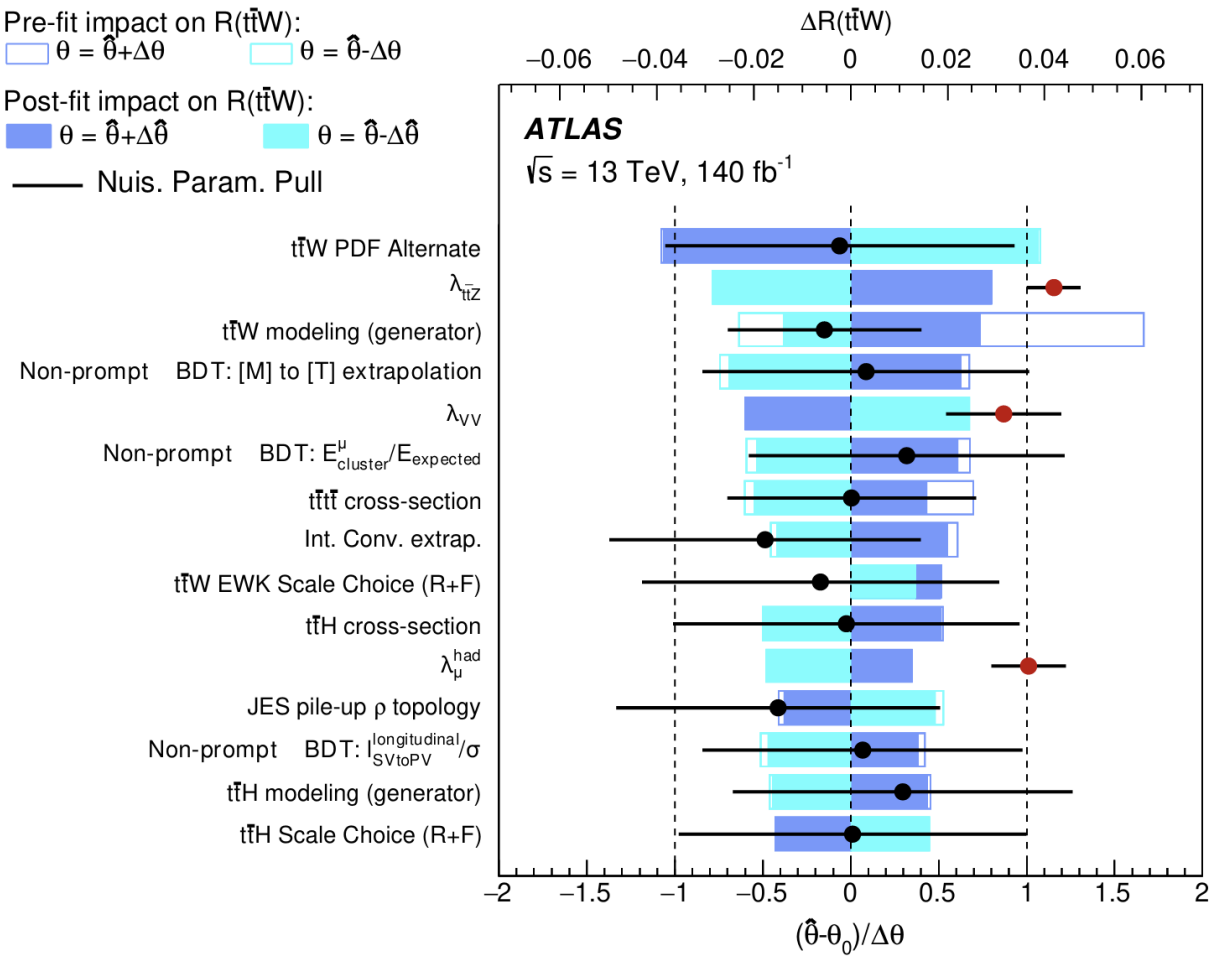
Control regions for:	Diboson	$t\bar{t}Z$	Conversions	HF non-prompt
Lepton requirement	3ℓ		$\mu\mu e^*$	2ℓSS
Lepton definition	(L, M, M)			$(T, M_{\text{ex}}) \mid (M_{\text{ex}}, T) \mid (M_{\text{ex}}, M_{\text{ex}})$
Lepton p_{T} [GeV]	(10, 20, 20)			(20, 20)
$m^{\text{SF}}_{\ell^+\ell^-}$ [GeV]	> 12		> 12	—
$\lvert m^{\text{SF}}_{\ell^+\ell^-} - m_Z \rvert$ [GeV]	< 10		> 10	—
$\lvert m_{3\ell} - m_Z \rvert$ [GeV]	> 10		< 10	—
$m_{\text{T}}(\ell_0, E^{\text{miss}}_{\text{T}})$ [GeV]	—			< 250 for TM_{ex} and $M_{\text{ex}}T$ pairs
N_{jets}	2 or 3	≥ 4	≥ 0	≥ 2
$N_{b\text{-jets}}$	1 $b^{60\%}$	≥ 1 $b^{60\%}$ or ≥ 2 $b^{77\%}$	0 $b^{77\%}$	1 $b^{77\%}$
Region split	—	—	internal / material	sub-leading $e/\mu \times (TM_{\text{ex}}, M_{\text{ex}}T, M_{\text{ex}}M_{\text{ex}})$
Region naming	3ℓVV	3ℓttZ	3ℓIntC / 3ℓMatC	$2\ell\text{tt(e)}_{TM_{\text{ex}}}$, $2\ell\text{tt(e)}_{M_{\text{ex}}T}$, $2\ell\text{tt(e)}_{M_{\text{ex}}M_{\text{ex}}}$ $2\ell\text{tt}(\mu)_{TM_{\text{ex}}}$, $2\ell\text{tt}(\mu)_{M_{\text{ex}}T}$, $2\ell\text{tt}(\mu)_{M_{\text{ex}}M_{\text{ex}}}$



ttW differential and asymmetry measurement with full Run 2

JHEP05(2024)131

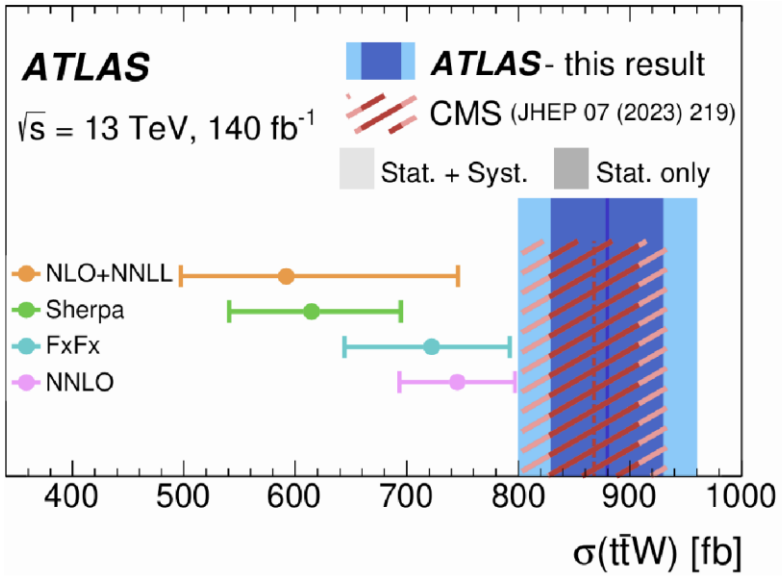


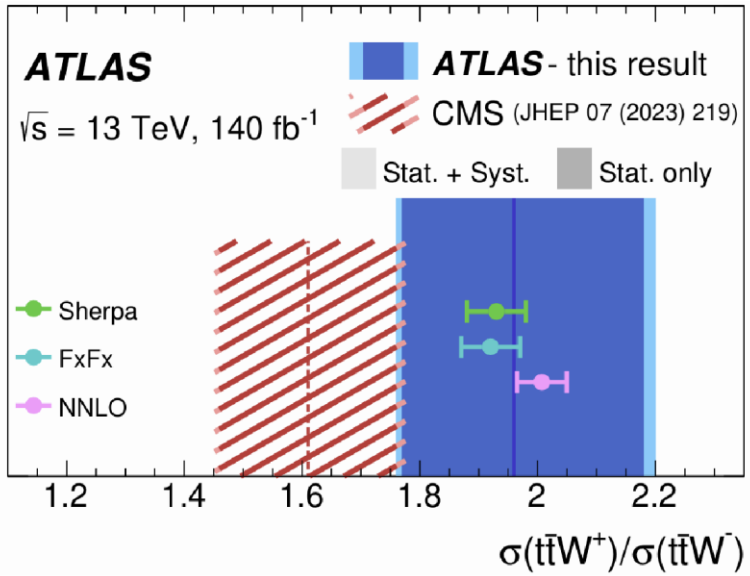


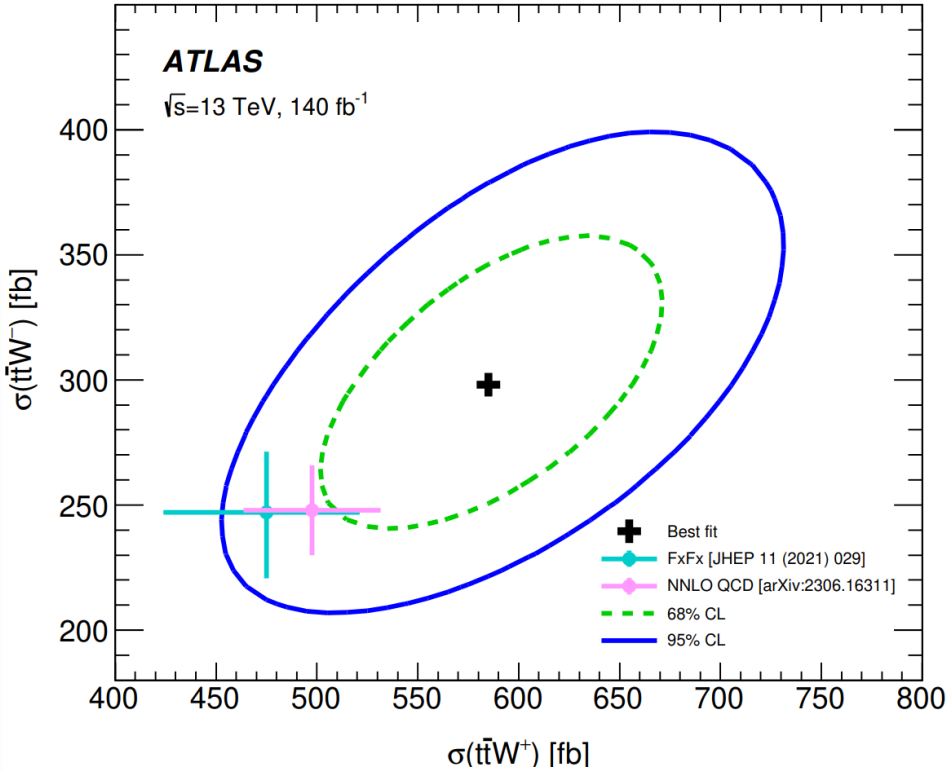
ttW differential and asymmetry measurement with full Run 2

JHEP05(2024)131

$$A_C^{rel} = \frac{\sigma(t\bar{t}W^+) - \sigma(t\bar{t}W^-)}{\sigma(t\bar{t}W^+) + \sigma(t\bar{t}W^-)}$$







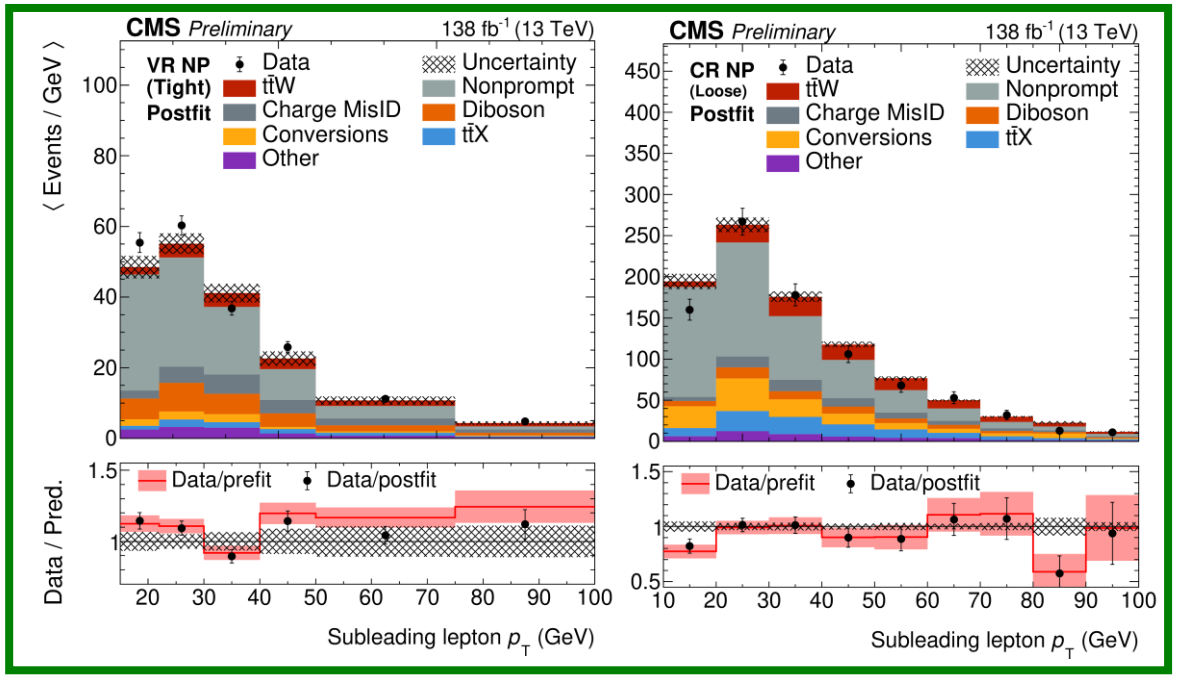
ttW differential and asymmetry with full Run 2

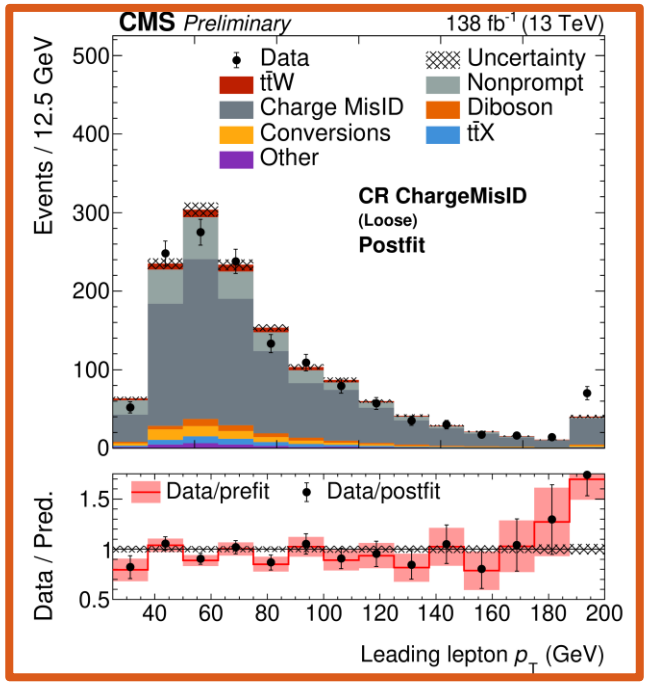
CMS-PAS-TOP-24-003

Backgrounds estimated with MC simulations excluding nonprompt contributions and charge misidentification that are estimated with data-driven methods.

Nonpromt estimation: Using a fake factor method. Get the fake rate and extrapolate to the signal region.

Charge misidentification: Selecting events in the SR selection but with OS of DY + SS events in the Z peak.



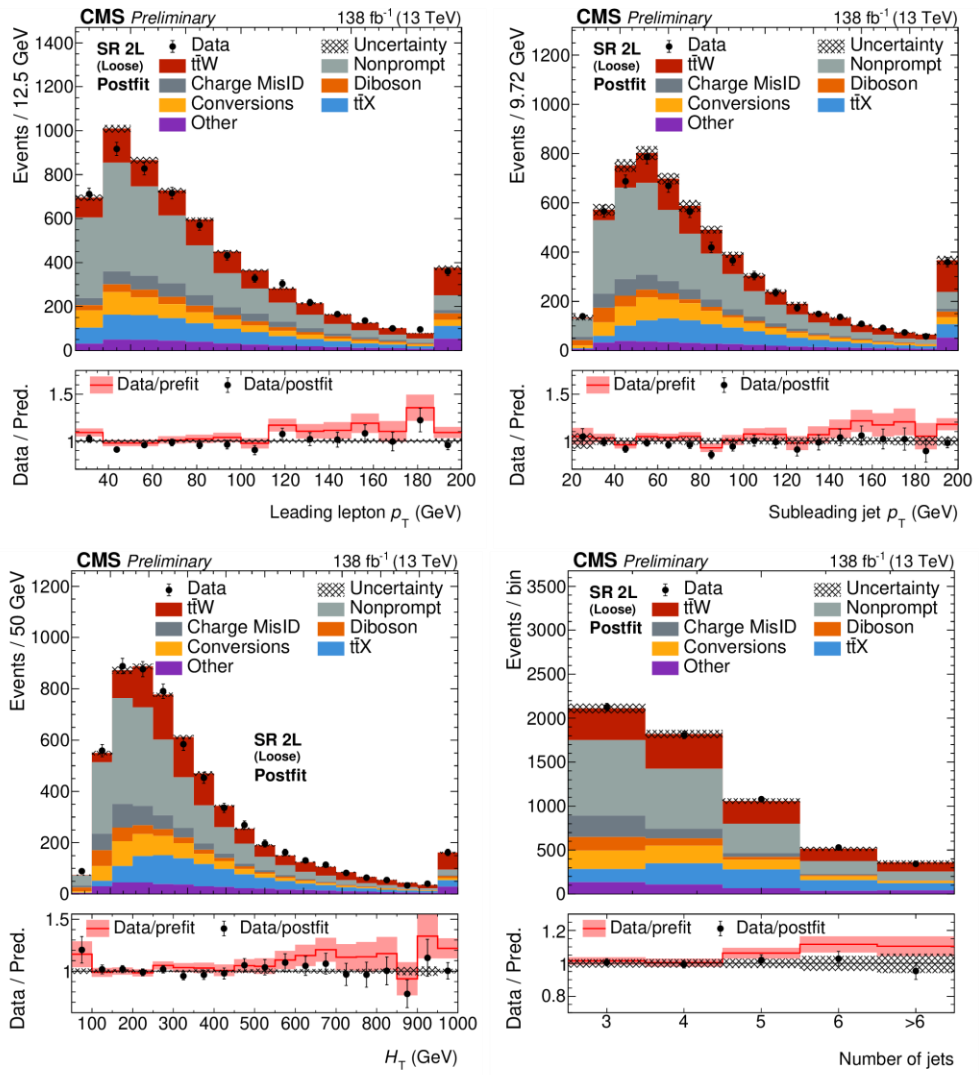


ttW differential and asymmetry with full Run 2

CMS-PAS-TOP-24-003

<u>2 lepton same-sign region:</u>

- Exactly 2 same-sign leptons.
- p_T> 25 GeV and p_T >15 GeV for the leading lepton and the subleading lepton respectively.
- Veto to the invariant mass of the lepton pair in the Z peak (+- 15 GeV).
- At least 3 jets (2 b-tagged).

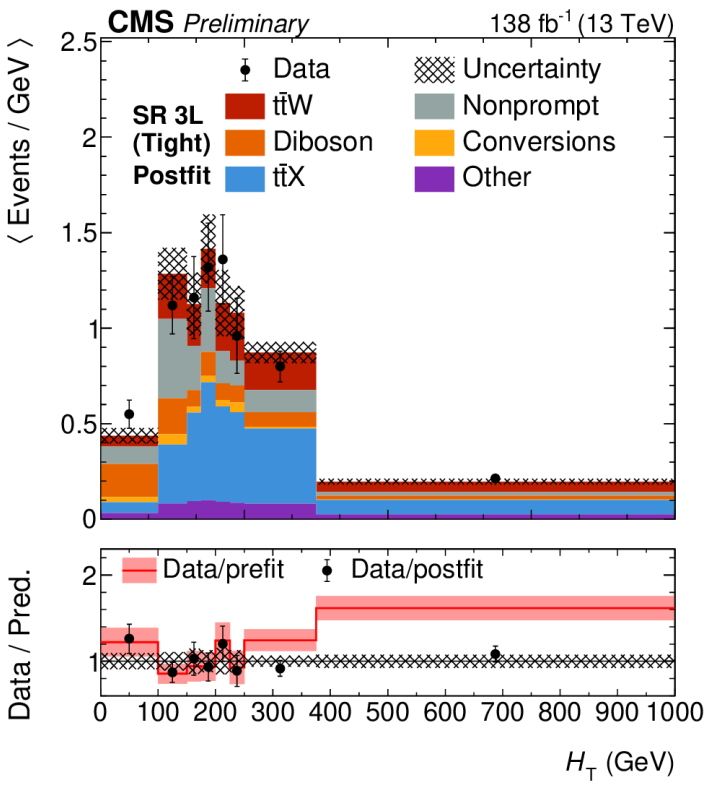


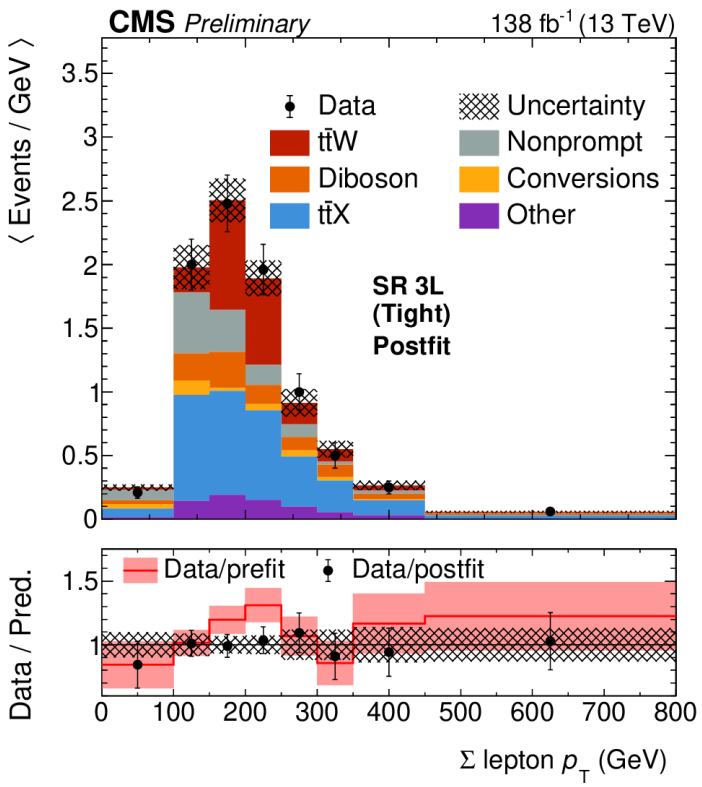
ttW differential and asymmetry with full Run 2

CMS-PAS-TOP-24-003

<u>3 lepton region:</u>

- Exactly 3 leptons.
- p_T> 25 GeV, p_T >15 GeV and p_T >15 GeV for the leading lepton and the subleadings leptons.
- Veto to the invariant mass of the OSSF lepton pair in the Z peak (+- 15 GeV).
- At least 3 jets (2 b-tagged).



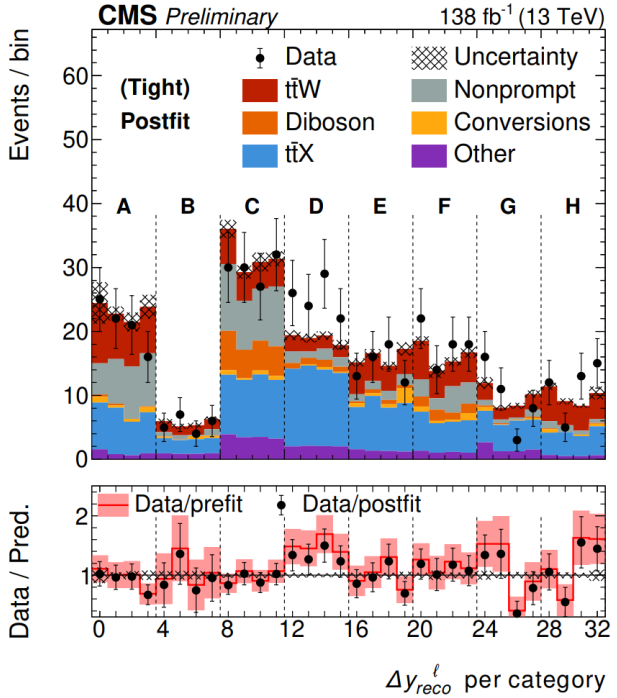


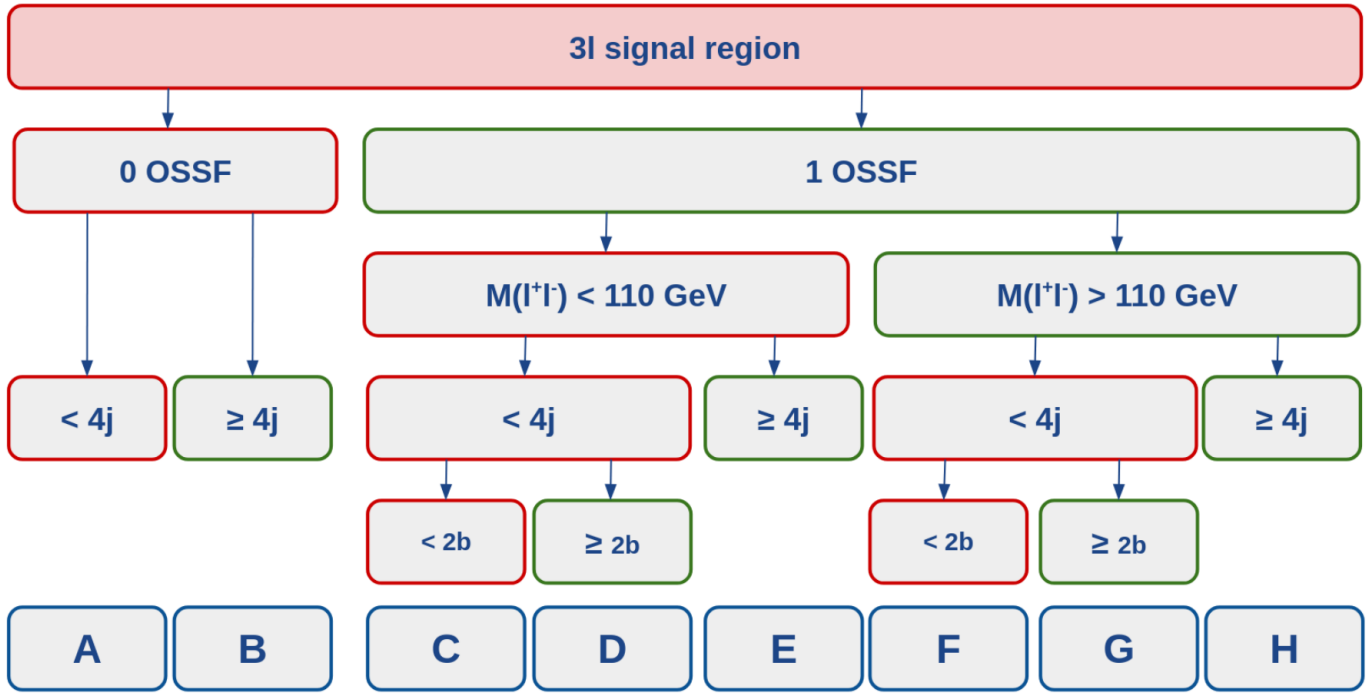
ttW differential and asymmetry with full Run 2

CMS-PAS-TOP-24-003

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

Δy_ℓ denotes $|y_\ell| - |y_{\bar{\ell}}|$





ttW differential and asymmetry with full Run 2

CMS-PAS-TOP-24-003

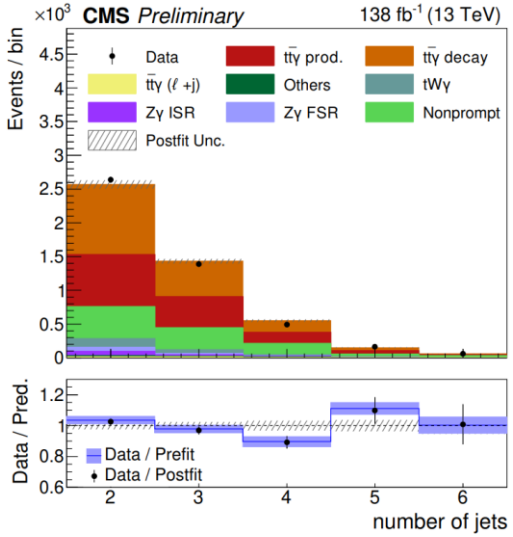
Variable	Description
Angles between objects	
$\lvert\Delta\eta(\ell_1,\ell_2)\rvert$	absolute difference in pseudorapidity between the two leading leptons
$\Delta R(\ell_1,\ell_2)$	separation in (η,ϕ) space between the two leading leptons
$\Delta R(\ell_1,\text{jet})$	separation in (η,ϕ) space between the leading lepton and its closest jet
Jet-related variables	
H_T	scalar sum of jet p_T
leading jet $\lvert\eta\rvert$	$\lvert\eta\rvert$ of the jet with highest p_T
leading jet p_T	p_T of the jet with highest p_T
subleading jet $\lvert\eta\rvert$	$\lvert\eta\rvert$ of the jet with next-to-highest p_T
subleading jet p_T	p_T of the jet with next-to-highest p_T
Lepton-related variables	
leading lepton p_T	p_T of the lepton with highest p_T
subleading lepton p_T	p_T of the lepton with next-to-highest p_T
lepton maximum $\lvert\eta\rvert$	maximum $\lvert\eta\rvert$ among the leptons
$\sum$ lepton p_T	sum of the lepton p_T's
$m(\ell_1,\ell_2)$	invariant mass of the system of the two leading leptons
Object multiplicity	
Jet multiplicity	number of jets

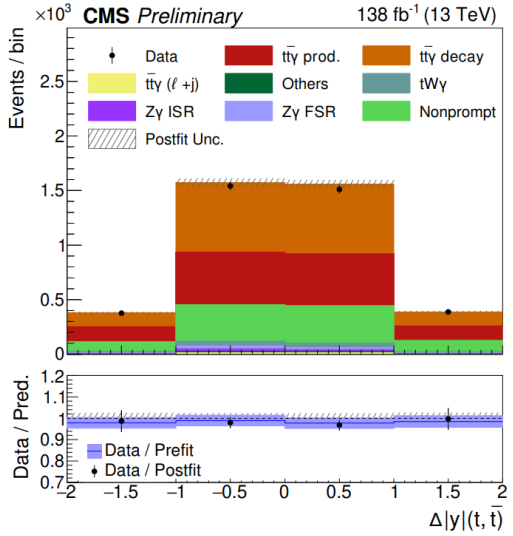
$t\bar{t}\gamma$ inclusive and differential measurement with full Run 2

CMS-PAS-TOP-23-002

<u>Event selection (signal region):</u>

- Exactly 2 opposite-sign leptons.
- Exactly one photon.
- p_T> 25 GeV and p_T >15 GeV for the leading lepton and the subleading lepton respectively.
- Veto in the invariant mass of the lepton pair in the Z peak (+- 15 GeV).
- Veto in the invariant mass of the lepton pair and photon in the Z peak (+- 15 GeV).
- At least 2 jets (1 b-tagged).
- Reconstruction of the top quark.





$t\bar{t}\gamma$ inclusive and differential measurement with full Run 2

CMS-PAS-TOP-23-002

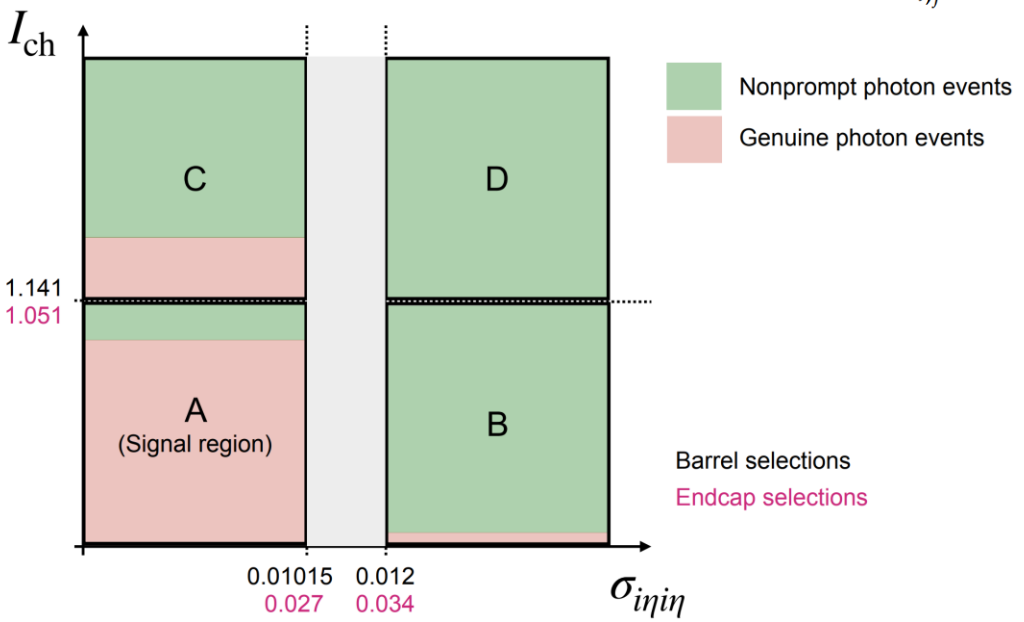
Photons contributions:

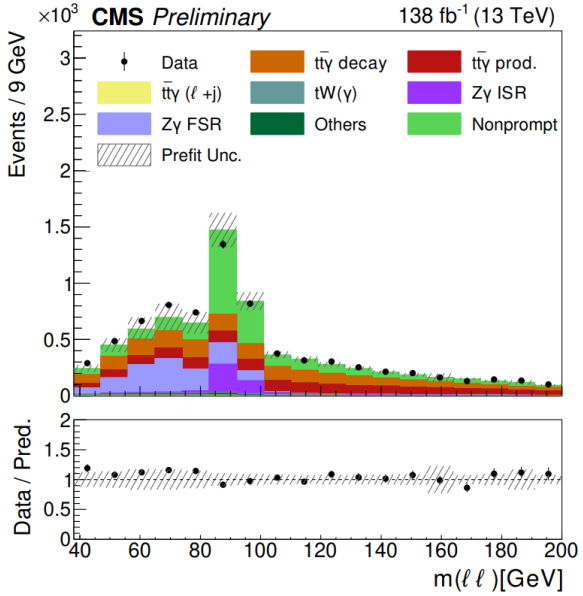
- Genuine photons: Estimated with MC samples.
- Nonprompt photons: Estimated with data-driven methods.

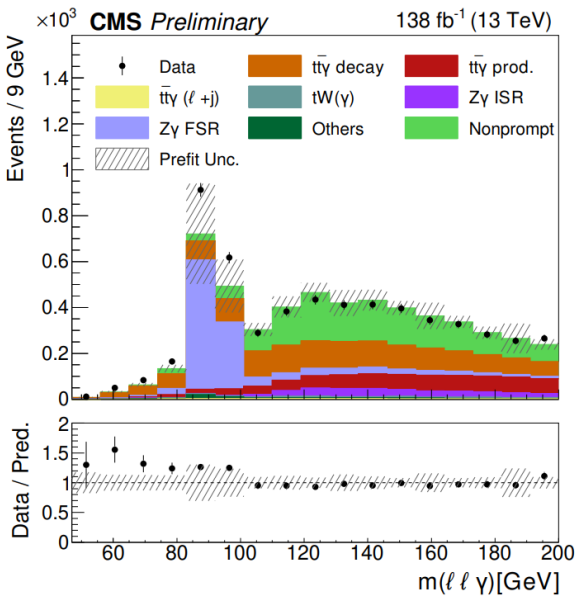
Nonprompt Photons estimation:

- Using ABCD method to compute the contribution using sideband regions as a function of: PF charged isolation and width of electromagnetic shower.

$$\text{nonprompt } \gamma \text{ contribution} = \sum_{i,j}(\text{Data}_B^{ij} \times \text{FR}^{ij} \times k_{\text{MC}}^{ij}) - \sum_{i,j}(\text{genuine MC}_B^{ij} \times \text{FR}^{ij} \times k_{\text{MC}}^{ij})$$





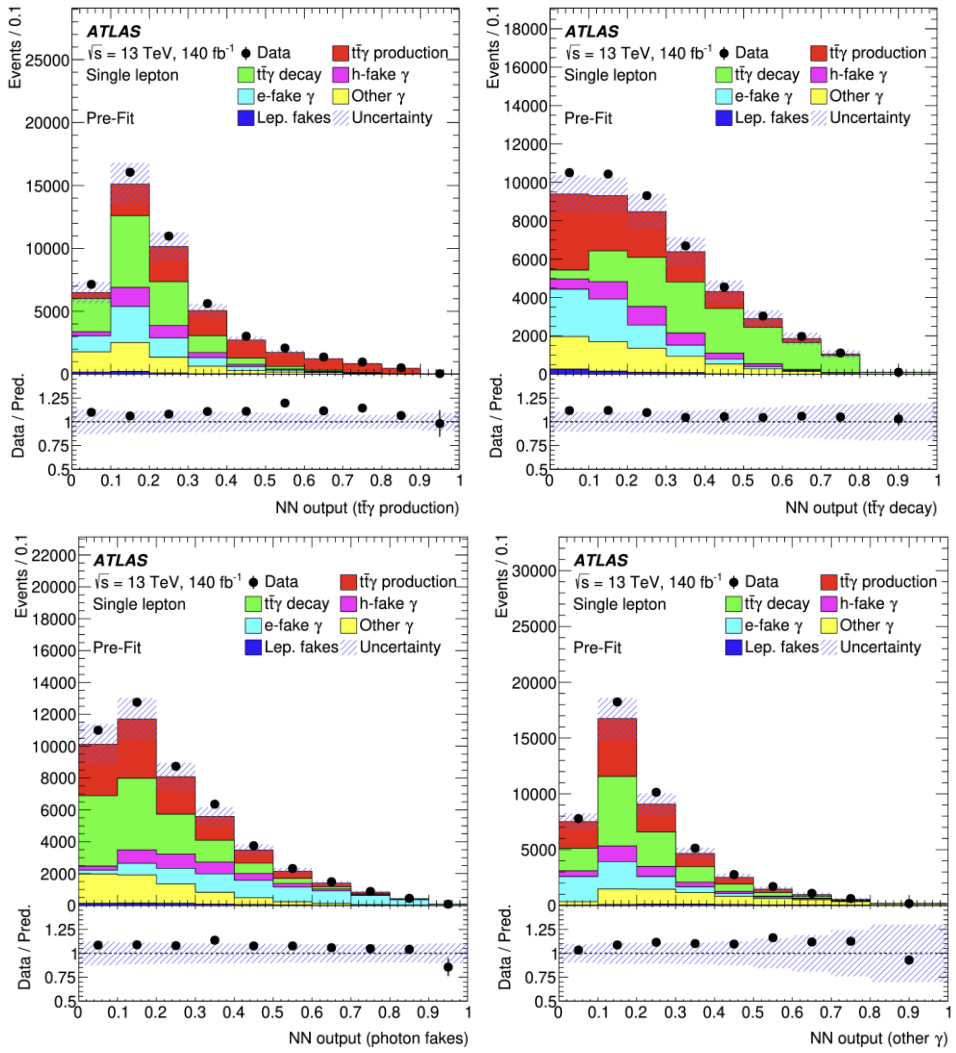


$t\bar{t}\gamma$ differential and asymmetry measurement with full Run 2

JHEP10(2024)191

<u>Single-lepton channel selection:</u>

- One photon.
- One isolated light lepton.
- Pt requirement of 25 GeV for 2015 data, 27 GeV for 2016 data and 28 GeV for 2017 and 2018 data.
- Invariant mass of the lepton pair to avoid the Z boson mass window (+- 5 GeV).
- At least 4 jets (at least 1 b-tagged).

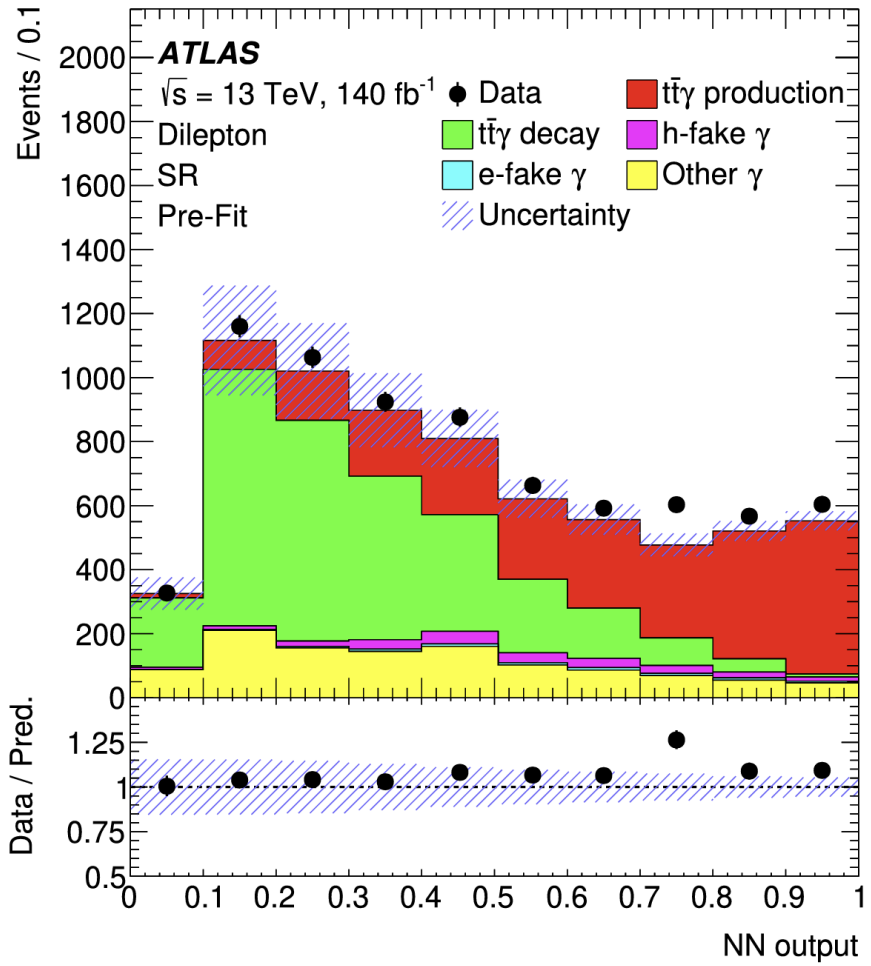


ttγ differential and asymmetry measurement with full Run 2

JHEP10(2024)191

<u>Two leptons channel selection:</u>

- One photon.
- Two light leptón of opposite sign.
- Pt requirement of 25 GeV for 2015 data, 27 GeV for 2016 data and 28 GeV for 2017 and 2018 data.
- OSSF lepton pairs require to have an invariant mass that avoid the Z boson mass window (+- 5 GeV).
- Invariant mass of the lepton pair higher than 15 GeV (supress contribution from low-mass DY or heavy flavor resonances).
- At least 2 jets (at least 1 b-tagged).
- MET higher than 30 30 GeV (reject Zγ processes)



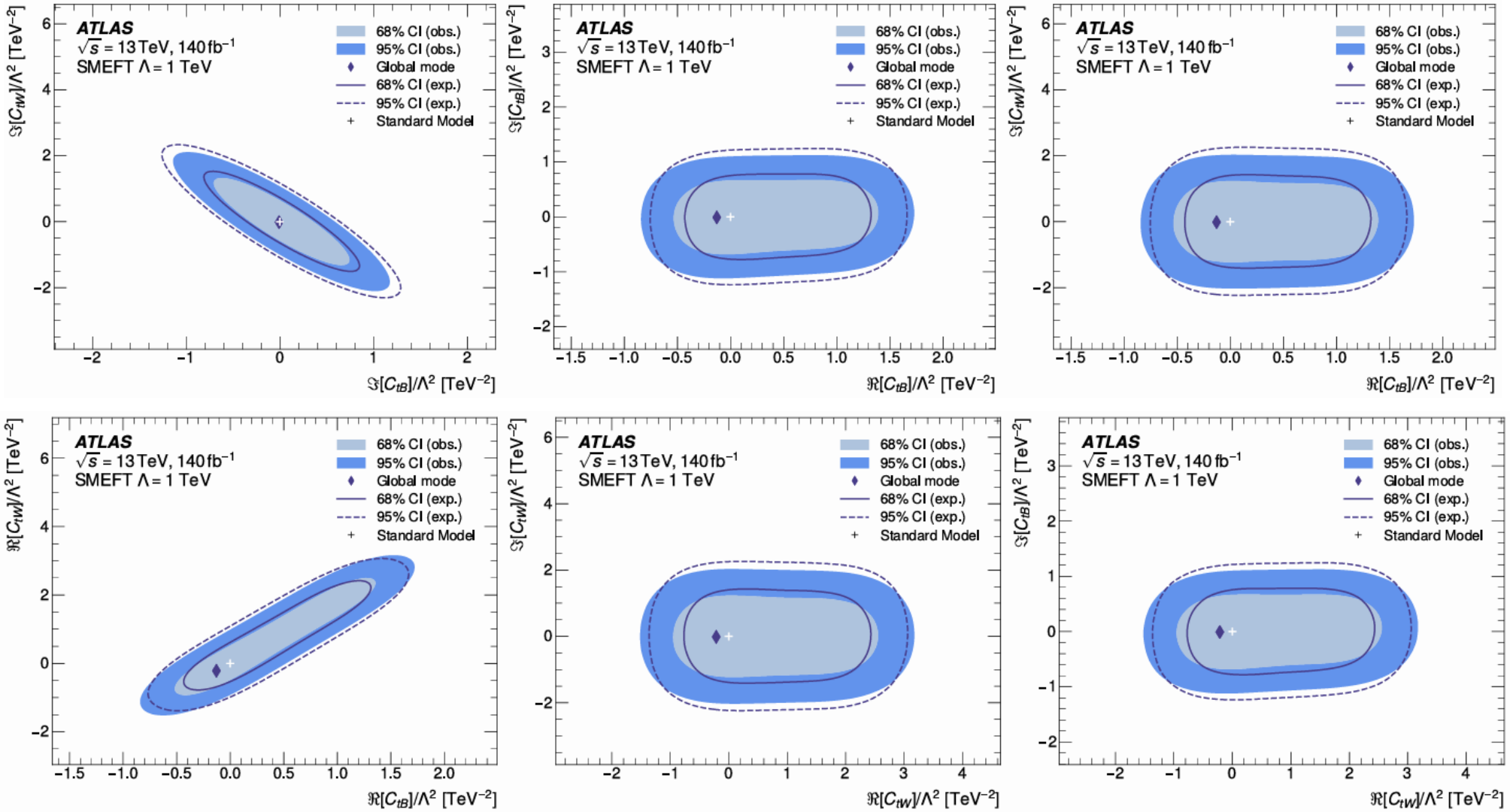
ttγ differential and asymmetry measurement with full Run 2

JHEP10(2024)191

Category	$t\bar{t}\gamma$ decay classifier	fake γ classifier	other prompt γ 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 γ	< 0.15	> 0.2	< 0.5	50%
CR Other γ		remaining events		26%

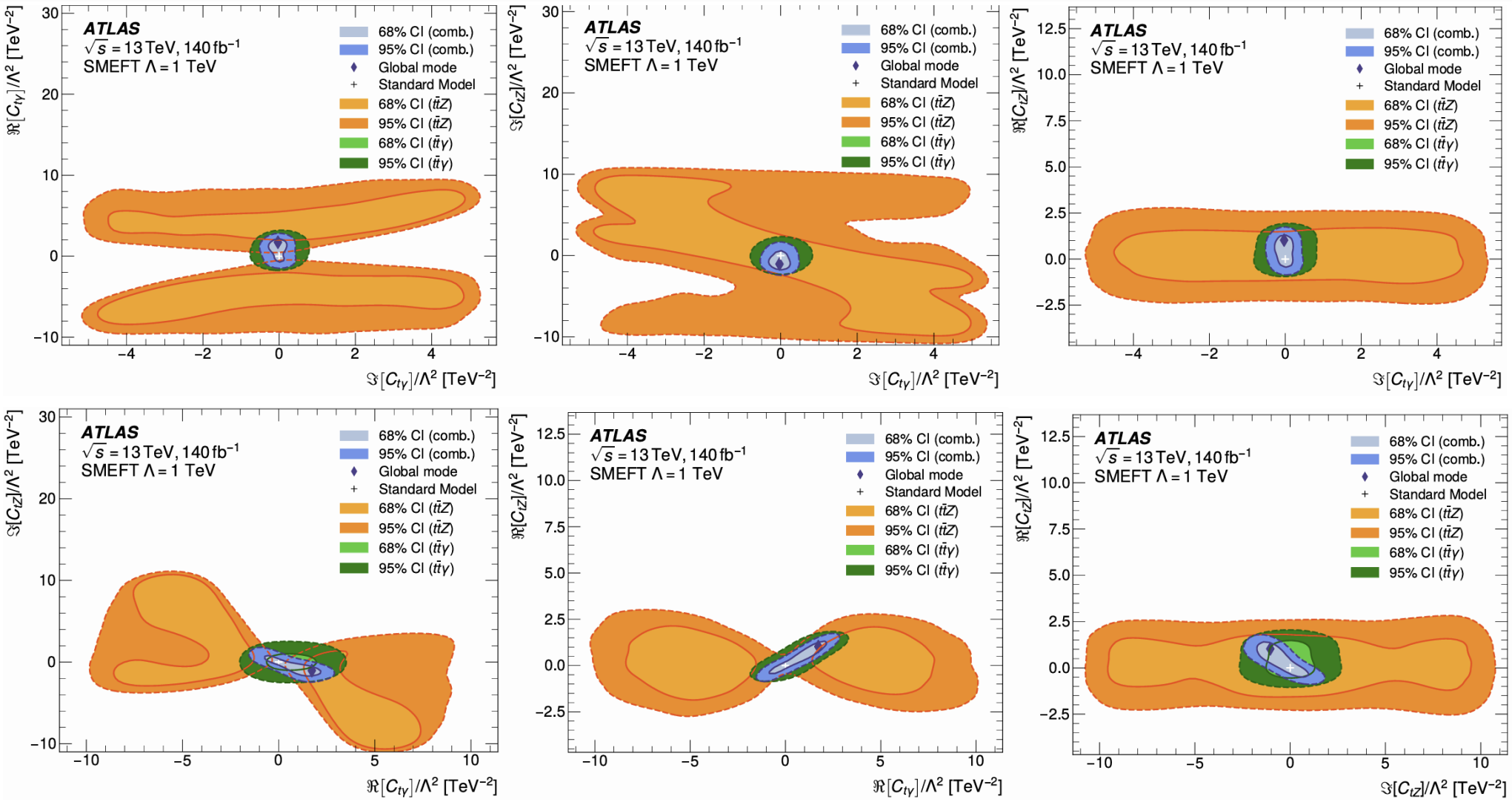
ttγ differential and asymmetry measurement with full Run 2

JHEP10(2024)191



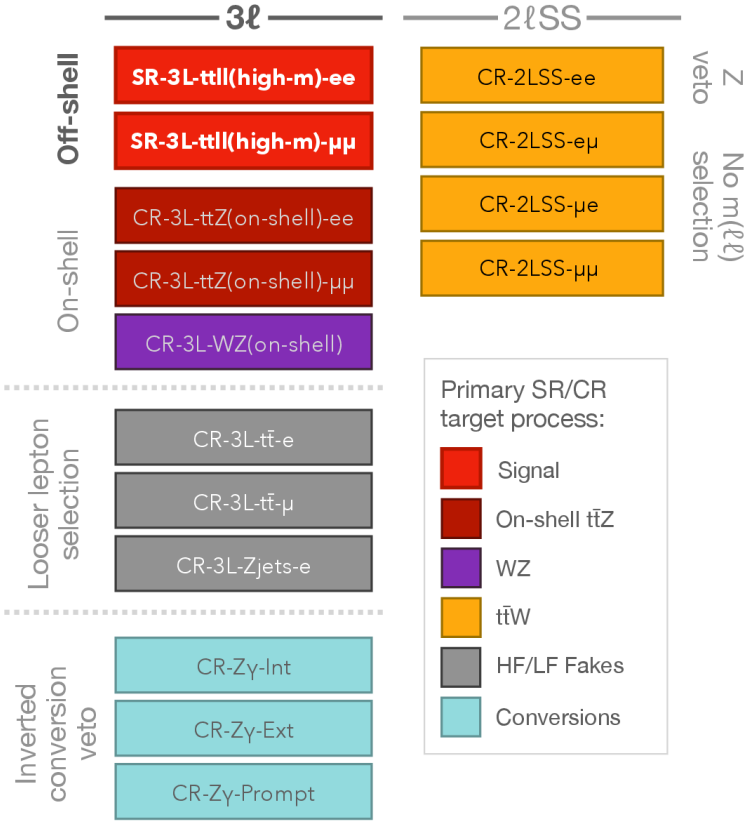
ttγ differential and asymmetry measurement with full Run 2

JHEP10(2024)191



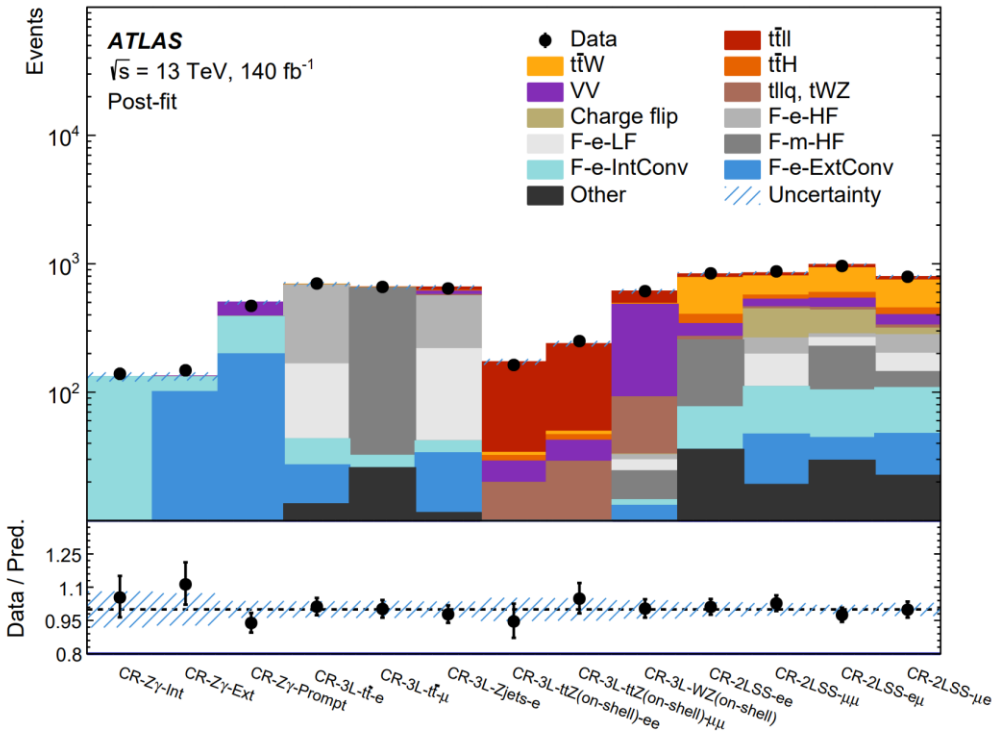
Measurement high-mass ttll production and LFU-inspired EFT interpretation

ATLAS-TOPQ-2023-02



Event selection ofthe signal region:

- Three leptons with at least 1 OSSF pair.
- At least 3 jets (with at least 1 b-tagged jet).



Measurement high-mass ttll production and LFU-inspired EFT interpretation

ATLAS-TOPQ-2023-02

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

	$\mathcal{O}(\Lambda^{-4})[\text{TeV}^{-2}]$				
	Best fit	68% Asymp. CI	68% Pseud. CI	95% Asymp. CI	95% Pseud. CI
c_{tl}	−0.44	[−1.10, 1.24]	[−1.17, 1.31]	[−1.65, 1.80]	[−1.71, 1.86]
c_{te}	−0.45	[−1.05, 1.18]	[−1.21, 1.41]	[−1.57, 1.79]	[−1.64, 1.96]
c_{Qe}	−0.54	[−1.23, 1.19]	[−1.32, 1.32]	[−1.82, 1.83]	[−1.87, 1.88]
c_{Ql}^-	0.69	[−0.98, 1.41]	[−1.15, 1.74]	[−1.57, 2.03]	[−1.66, 2.33]
c_{leQt}^1	−0.61	[−1.51, 1.50]	[−1.55, 1.54]	[−2.27, 2.27]	[−2.32, 2.33]
c_{leQt}^3	−0.12	[−0.26, 0.26]	[−0.27, 0.27]	[−0.37, 0.37]	[−0.38, 0.38]

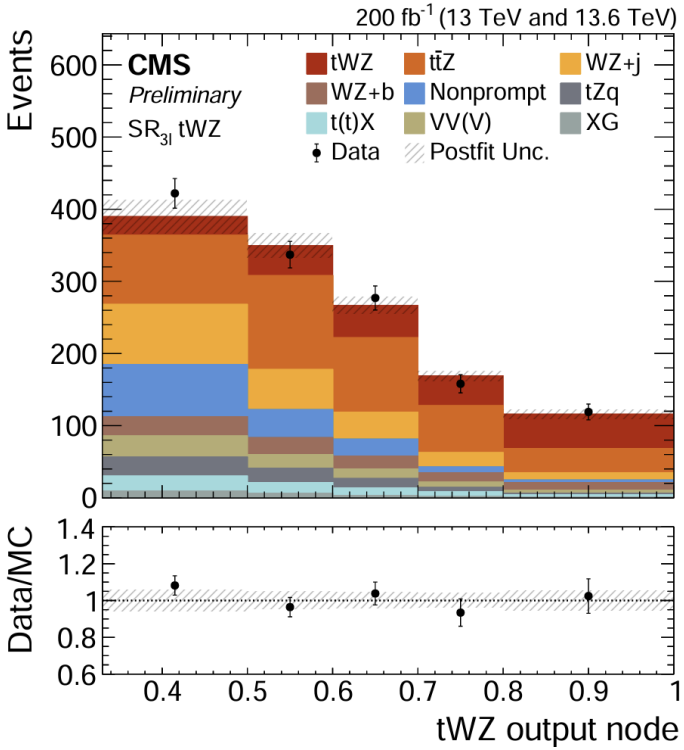
	$\mathcal{O}(\Lambda^{-2})[\text{TeV}^{-2}]$		
	Best fit value	68% Asymp. CI	95% Asymp. CI
c_{tl}	−1.21	[−8.23, 4.22]	[−11.83, 8.62]
c_{te}	−1.42	[−4.45, 1.09]	[−7.94, 3.10]
c_{Qe}	−11.65	[−25.75, 0.98]	[−40.97, 11.53]
c_{Ql}^-	−0.16	[−2.66, 1.91]	[−5.58, 3.67]

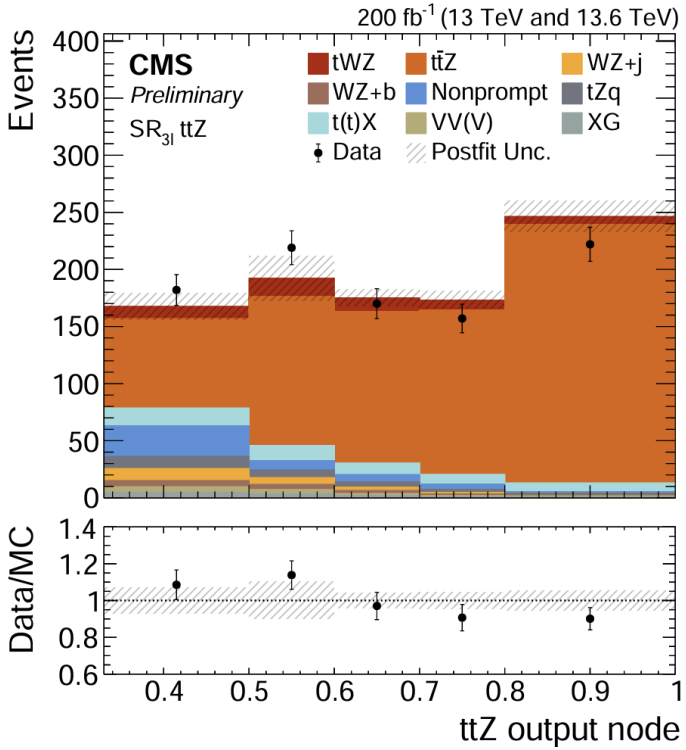
Observation of tWZ production at the CMS experiment (Run 2 + Run 3)

CMS-PAS-TOP-24-009

<u>3 lepton region:</u>

- Exactly 3 leptons.
- p_T> 25 GeV, p_T >15 GeV and p_T >15 GeV for the leading lepton and the subleadings leptons.
- The invariant mass of the OSSF lepton pair within the Z mass window (+- 15 GeV).
- Contain 2 jets (1 b-tagged).



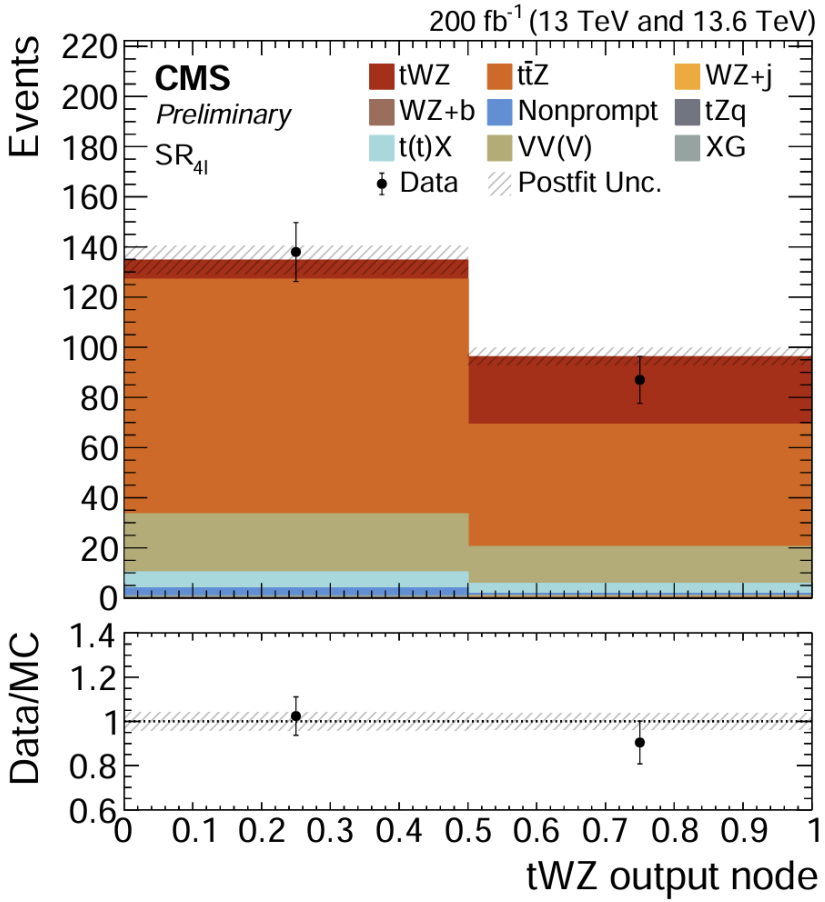


Observation of tWZ production at the CMS experiment (Run 2 + Run 3)

CMS-PAS-TOP-24-009

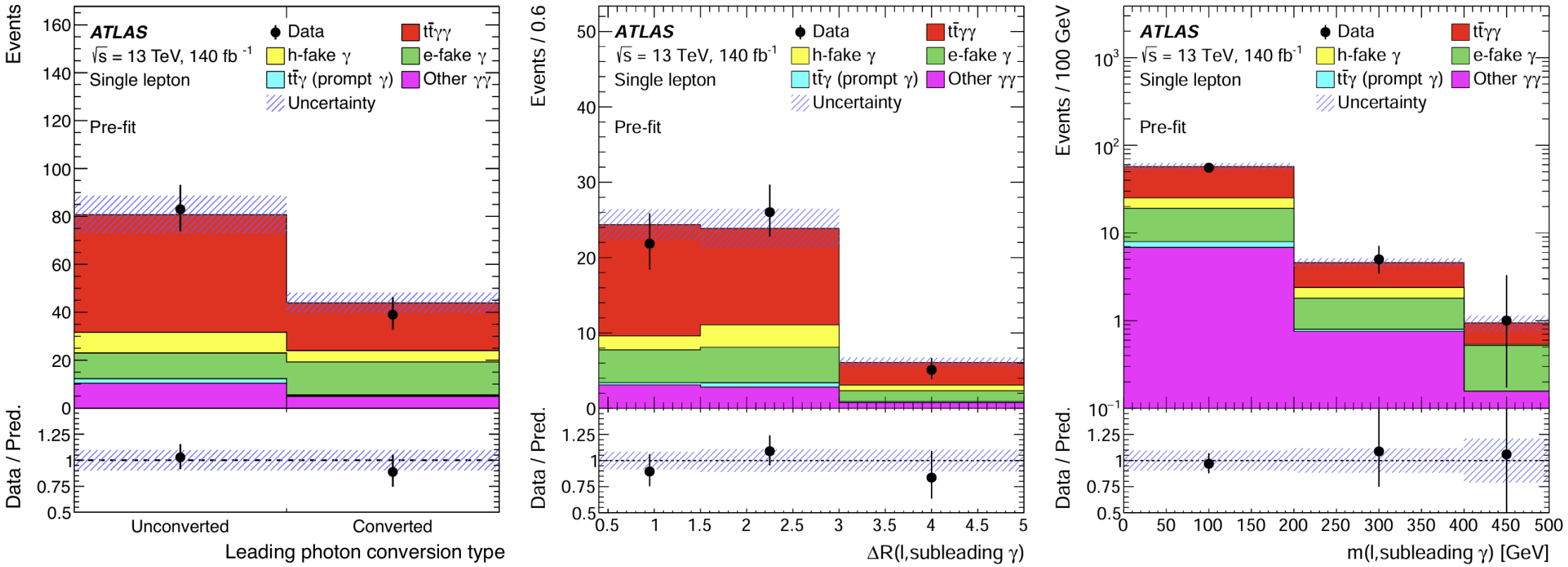
<u>4 lepton region:</u>

- Exactly 4 leptons.
- p_T> 25 GeV, p_T >15 GeV and p_T >15 GeV for the leading lepton and the subleadings leptons.
- The invariant mass of the OSSF lepton pair within the Z mass window (+- 15 GeV).
- 1 b-tagged.



Observation of ttγγ production

https://arxiv.org/abs/2506.05018



Observation of ttγγ production

https://arxiv.org/abs/2506.05018

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
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.4	1.1
Pile-up	1.6	1.4
MC statistical uncertainties	2.5	2.8
Total systematic uncertainty	15.0	10.0

ttγ inclusive and differential measurement with full Run 2

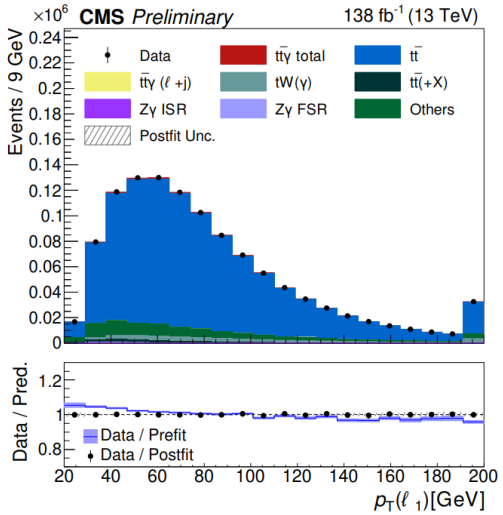
CMS-PAS-TOP-23-002

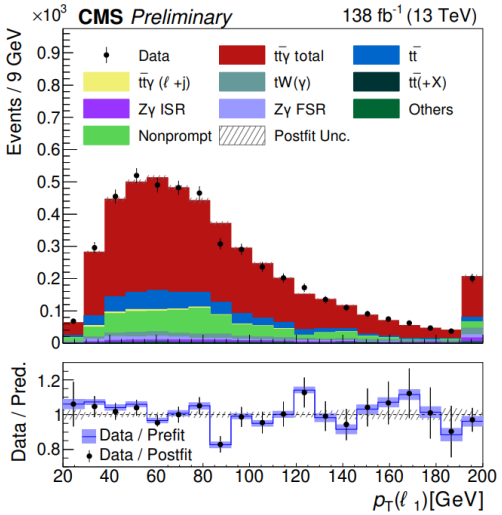
Selections	Lepton	Photon	Jet	B jet
p_T (GeV)	15	20	30	30
$\lvert\eta\rvert$	2.5	2.5	2.4	2.4
Multiplicity	≥ 2	1	≥ 2	≥ 1
Other requirements	$m(\ell\ell) > 30$	$\Delta R(\gamma, \ell) > 0.4$	$\Delta R(\gamma/\ell, \text{jet}) > 0.4$	-
Origin	prompt	not from hadrons	-	-

Definition of object and event selection used to define the fiducial phase space.

ttγ/tt ratio:

$$R = \frac{\sigma_{t\bar{t},1\gamma}}{\sigma_{t\bar{t},0\gamma} + \sigma_{t\bar{t},1\gamma}}$$





+(Zg + jets) CR

	Source	Corr. (period)	Corr. (process)
Experimental	Integrated luminosity	~	✓
	Pileup reweighting	✓	✓
	Electron reconstruction and identification	✓	✓
	Muon reconstruction and identification	✓	✓
	Photon reconstruction and identification	~	✓
	Nonprompt photon estimation	×	—
	Trigger efficiencies	×	✓
	L1 prefiring	✓	✓
	JES	~	✓
	JER	×	✓
	b tagging	~	✓
Theoretical	μ_R scale	✓	~
	μ_F scale	✓	~
	PDF	✓	✓
	PS scales: ISR	✓	×
	PS scales: FSR	✓	×
	ME-PS matching (h_{damp})	✓	—
	NNLO QCD reweighting	✓	—
	$t\bar{t}$ cross section	✓	—
	$tW\gamma$ cross section	✓	—
	$Z\gamma$+jets cross section	✓	—
	$t\bar{t}\gamma$ production/decay fraction	✓	—
	$Z\gamma$+jets cross section depending on jet multiplicity	✓	—

Search for CP violation in events with top quarks and Z bosons

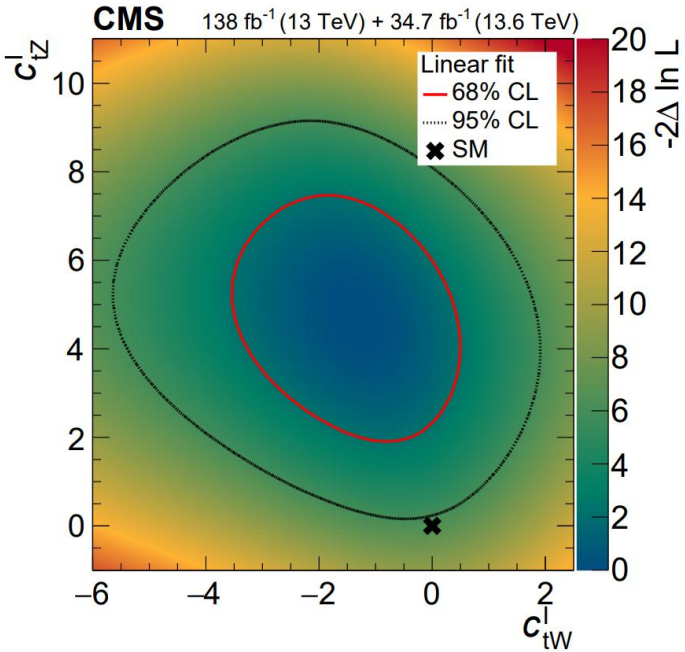
https://arxiv.org/abs/2505.21206

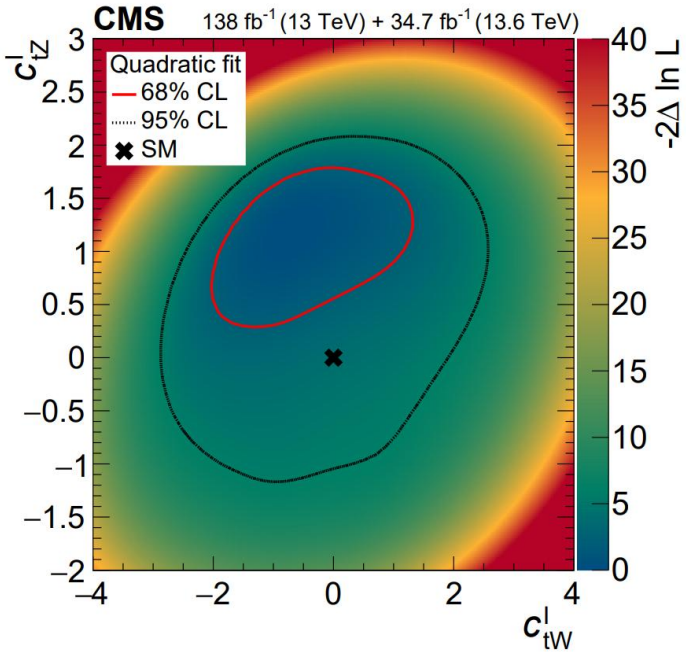
Input variables

x	$\vec{p}_{\ell^{Z+}}$	$\vec{p}_{\ell^{Z-}}$	$\vec{p}_{\ell^{W}}$	$\vec{p}_{j_i}$	$Q_{\ell^{W}}$	$\vec{p}_{T}^{miss}$	bscore_i	era
$CP(x)$	$-\vec{p}_{\ell^{Z-}}$	$-\vec{p}_{\ell^{Z+}}$	$-\vec{p}_{\ell^{W}}$	$-\vec{p}_{j_i}$	$-Q_{\ell^{W}}$	$-\vec{p}_{T}^{miss}$	bscore_i	era

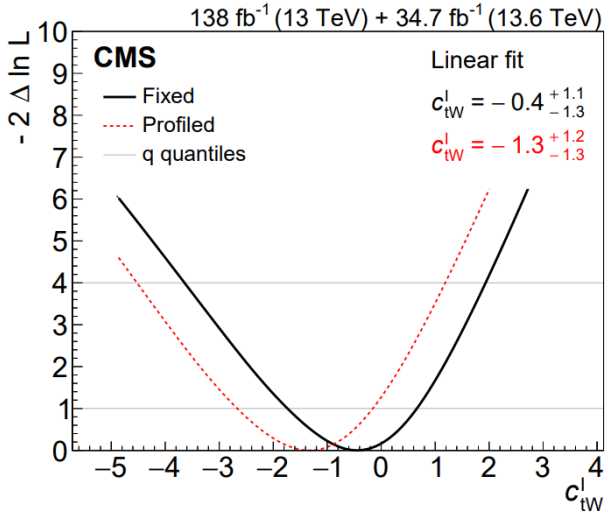
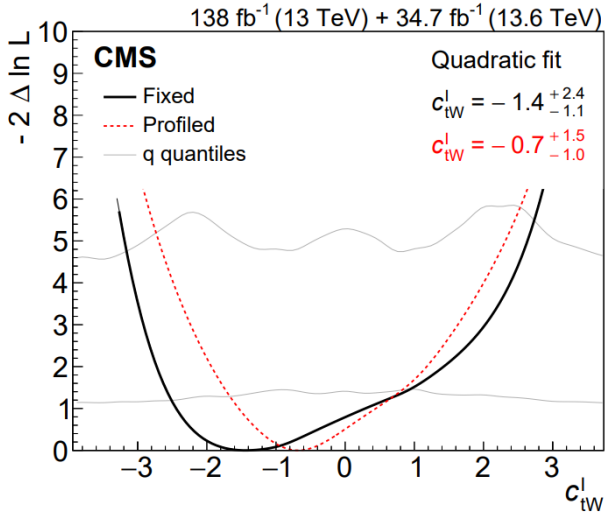
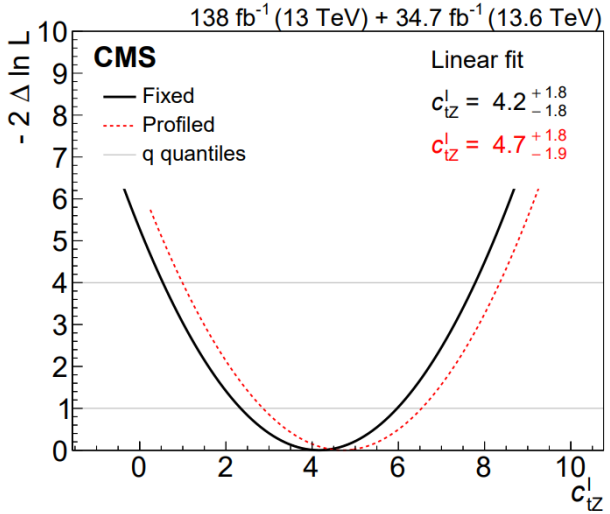
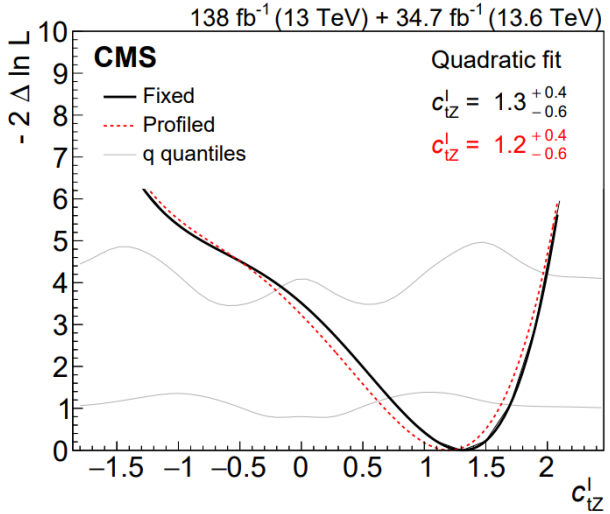
<u>Event selection:</u>

- 3 leptons
- At least 2 jets (at least 1 b-tagged jet).





Search for CP violation in events with top quarks and Z bosons

https://arxiv.org/abs/2505.21206

$$q(c^{\mathrm{I}}_{\mathrm{tW}}, c^{\mathrm{I}}_{\mathrm{tZ}}) = -2\ln\left(\frac{\mathcal{L}\left(\mathrm{data}\,|\,c^{\mathrm{I}}_{\mathrm{tW}}, c^{\mathrm{I}}_{\mathrm{tZ}}, \hat{\hat{\boldsymbol{\theta}}}(c^{\mathrm{I}}_{\mathrm{tW}}\ c^{\mathrm{I}}_{\mathrm{tZ}})\right)}{\mathcal{L}\left(\mathrm{data}\,|\,\widehat{c^{\mathrm{I}}_{\mathrm{tW}}}, \widehat{c^{\mathrm{I}}_{\mathrm{tZ}}}, \hat{\boldsymbol{\theta}}\right)}\right)$$