Universidá d'Uviéu

Associated production of tX and tt+X, including their EFT interpretation in CMS

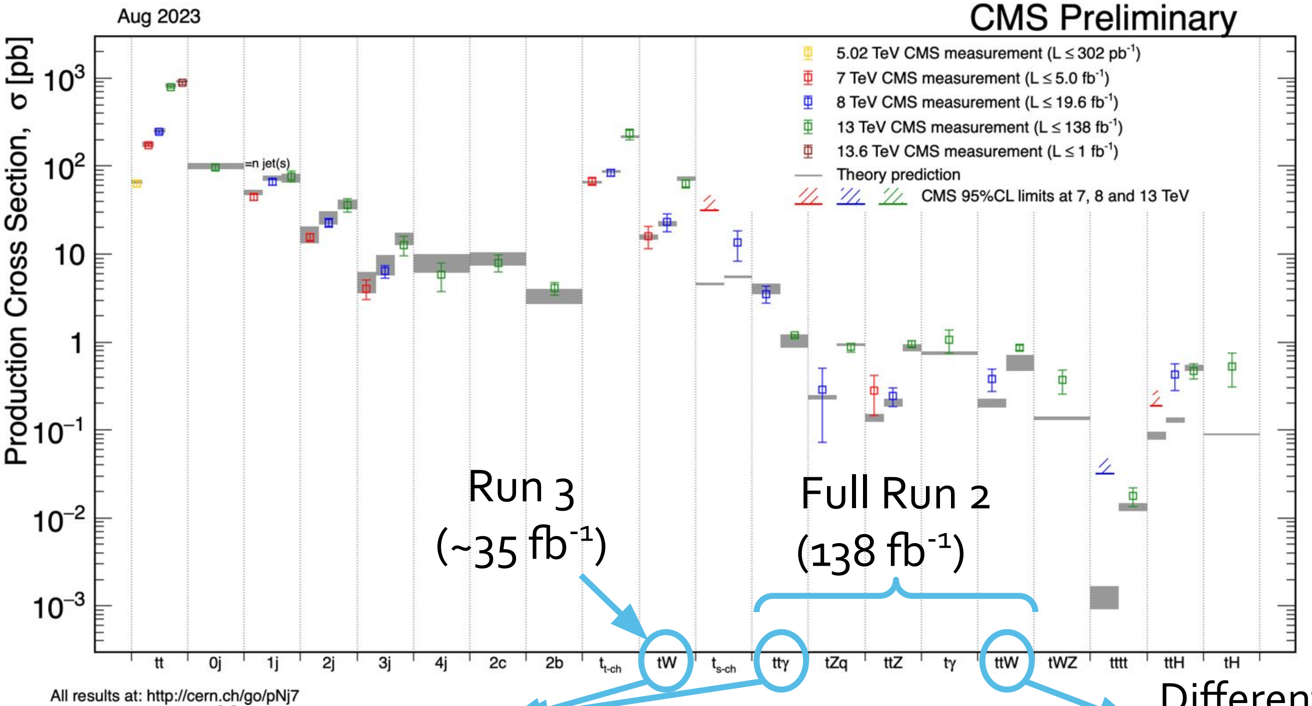
Jorge Ayllón Torresano on behalf of the CMS Collaboration

09/04/2025

SM@LHC 2025

EFTs interpretation covered in Maryam's talk about EFTs in the fermionic sector!

In this talk…



Run 3 (~35 fb^{-1})

Full Run 2 (138 fb^{-1})

Inclusive + differential cross sections

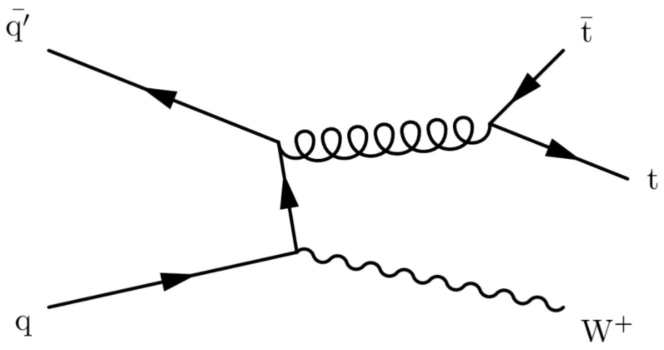
Differential cross section

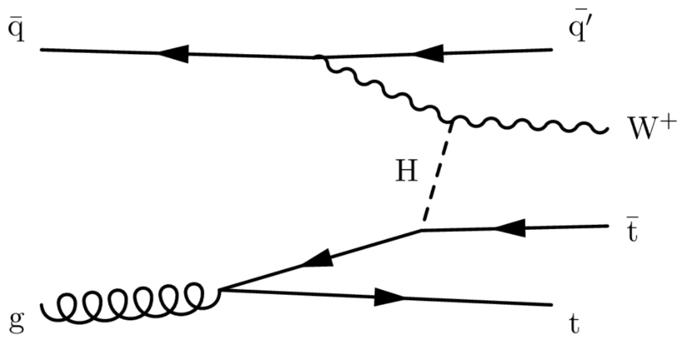
The top

The anti-top

The eXtra

ttX measurements





Differential ttW with full Run 2

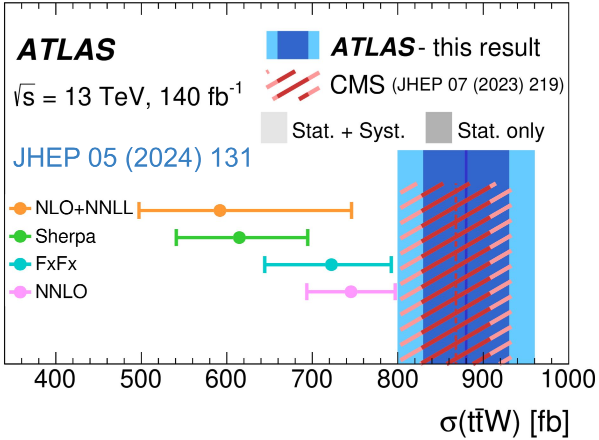
[CMS-PAS-TOP-24-003](#)

[Mind the gap! Top quark pairs with W bosons continue to defy the latest predictions](#)

ttW differential: motivation

This is the first differential measurement of ttW in CMS.

Tensions seen with SM even at NNLO in the previous inclusive measurements.



<u>For this measurement</u>: signal is modelled using aMC@NLO with multijet merging up to 1 jet. Compared to state-of-the-art predictions at particle level.

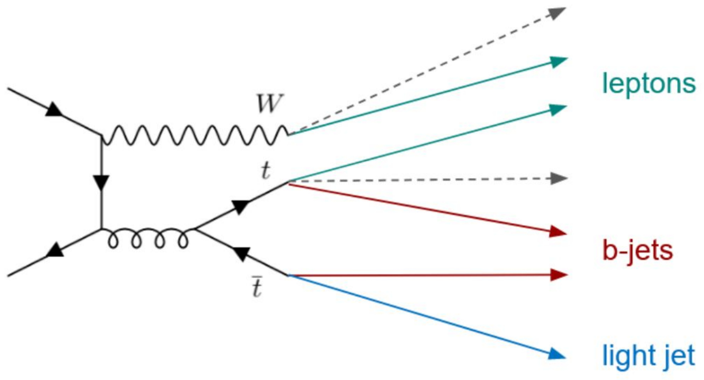
Presented in this talk:

- ➢ Differential cross section
- ➢ Leptonic charge asymmetry

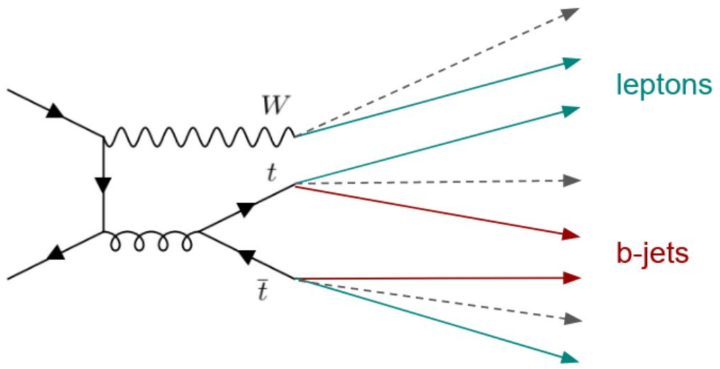
ttW differential: selection strategies

Two regions of measurement: two leptons with the same electric charge (2lss), and three leptons (3l) with two different approaches for 2lss.

2lss



3l



ttW differential: selection strategies

Two regions of measurement: two leptons with the same electric charge (2lss), and three leptons (3l) with two different approaches for 2lss.

MVA method

- ❖ Uses a looser selection on leptons
- ❖ Purity of signal (or S/B) achieved with an MVA

Used in the 2lss measurement

Counting method

- ❖ Uses a tighter selection on leptons
- ❖ Larger S/B
- ❖ Direct unfolding to observables

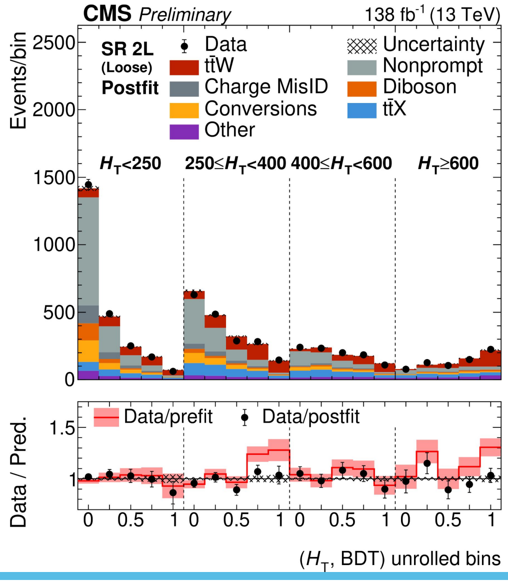
Used in the 3l measurements (and in 2lss as complementary)

➢ In both: various validation and control regions to study the backgrounds.

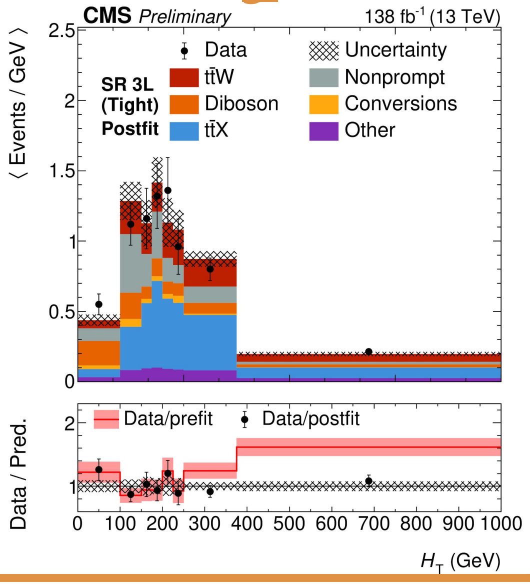
ttW differential: selection strategies

The differential measurement is split in two regions with two strategies:

2lss



3l

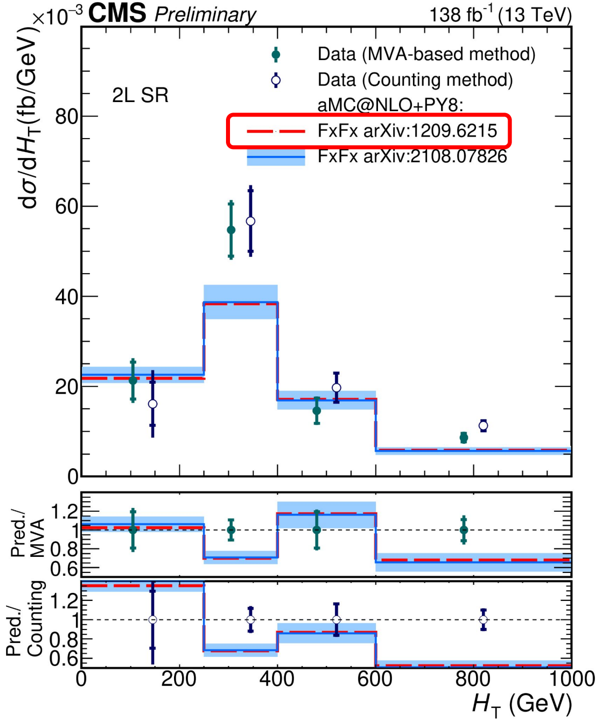


➢ To get the result, these variables are unfolded using maximum likelihood (ML) fits.

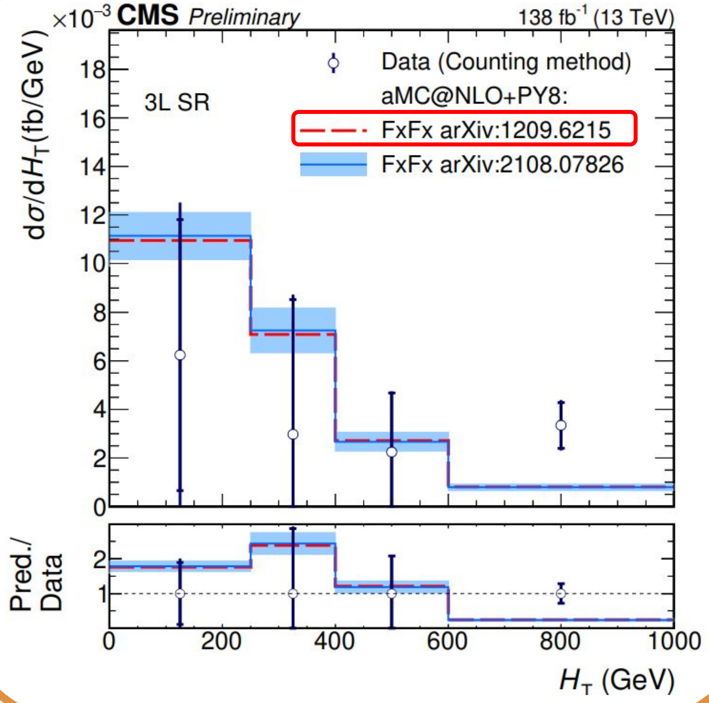
Nominal simulation

ttW differential: differential results

2lss



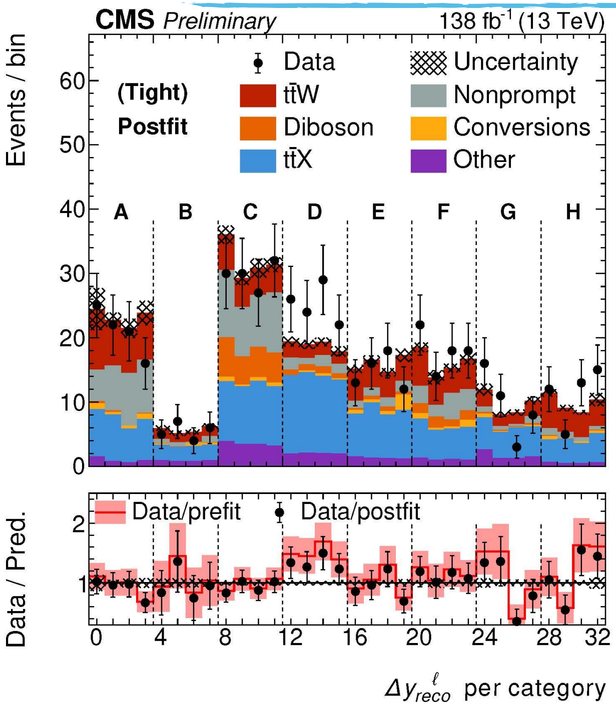
3l



Results compatible within uncertainties and in slight tension with SM predictions.

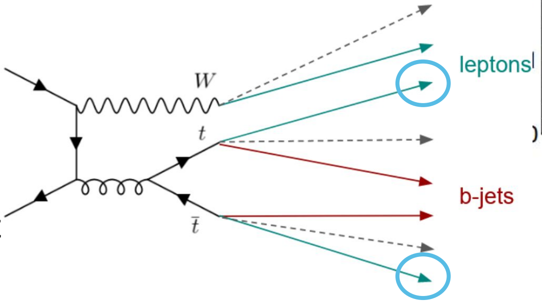
3l channel

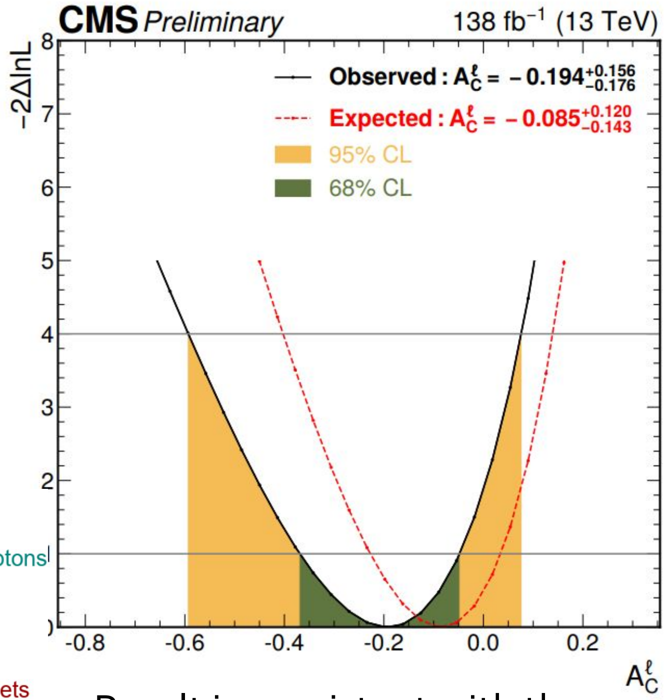
ttW differential: lepton charge asymmetry



ML fit to the distribution with the signal normalization also as a parameter

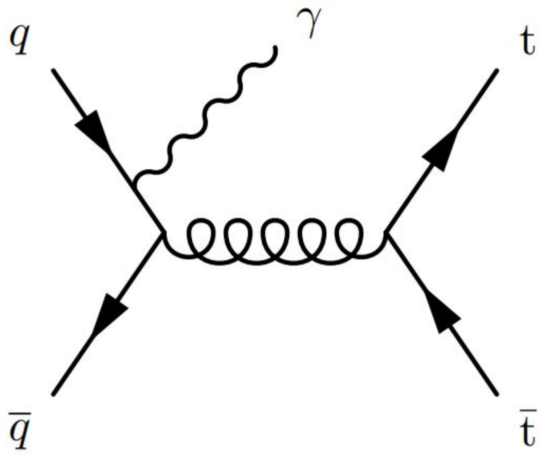
$$A_c^{\ell} = \frac{N(\Delta y_{\ell} > 0) - N(\Delta y_{\ell} < 0)}{N(\Delta y_{\ell} > 0) + N(\Delta y_{\ell} < 0)}.$$





➢ OS leptons with a DNN used to select the second lepton from the top

Result is consistent with the SM expectation.



Inclusive and differential ttγ with full Run 2

[CMS-PAS-TOP-23-002]

[Shiny top quarks: what happens when top quarks emit light?]

ttγ: motivation

Several features to study from the process:

- ➢ Direct access to the tγ coupling (serves as a precision test of the SM)
- ➢ Sensitive to new physics (EFTs)
- ➢ Measurement of some top properties

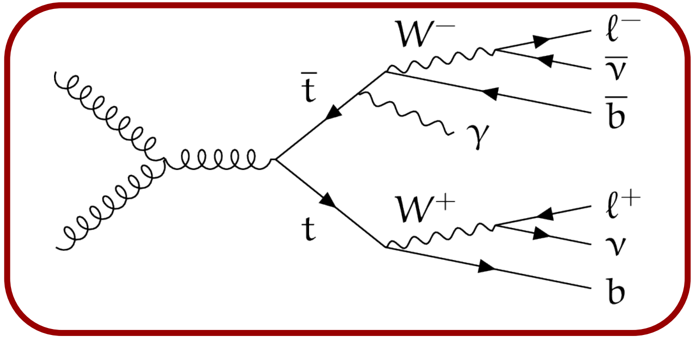
Presented in the talk:

- ❖ Inclusive cross section with full Run 2
- ❖ Differential cross section
- ❖ Top quark charge asymmetry
- ❖ Ratio of xsec between ttγ and tt (in backup, details in the PAS)

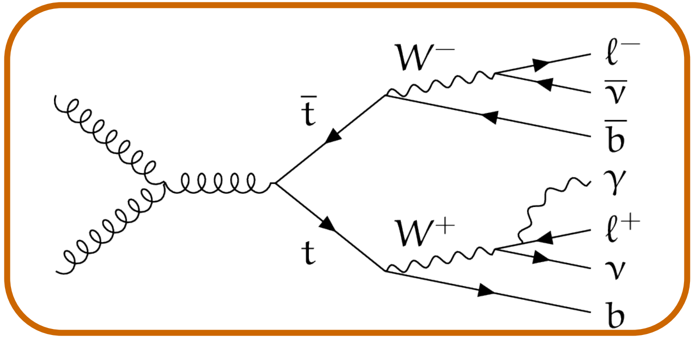
$t\bar{t}\gamma$: signal region definition

Two sources of $t\bar{t}\gamma$

- ➢ Production: γ generated from the top or ISR
- ➢ Decay: γ generated in the final states



Both sources simulated separately at NLO (production) and LO (decay) using aMC@NLO.



tWγ overlap with $t\bar{t}\gamma$ removed with DR1 (diagram removal) method.

tty inclusive: results

Fiducial cross section measured implementing a ML fit:

Production + decay:

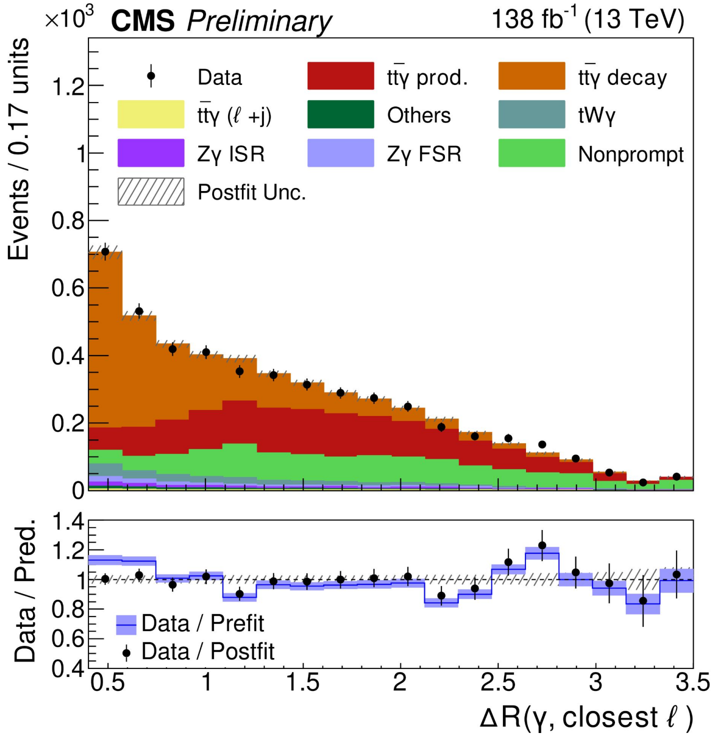
$$\sigma_{t\bar{t}\gamma} = 134 \pm 7\ (syst) \pm 3\ (stat)\ fb$$

In agreement with prediction: $\sigma^{sim}_{t\bar{t}\gamma} = 123 \pm 16\ fb$

Only production:

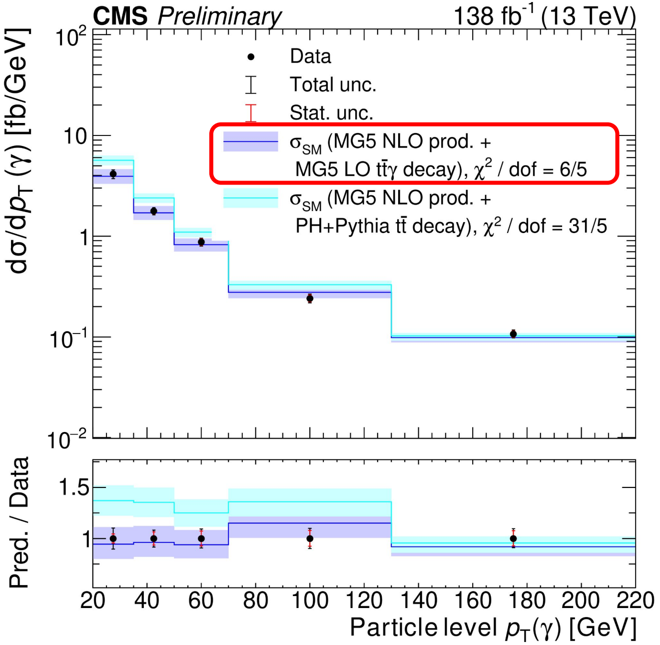
$$\sigma^{prod}_{t\bar{t}\gamma} = 54 \pm 4\ (syst) \pm 2\ (stat)\ fb$$

In agreement with prediction: $\sigma^{prod,sim}_{t\bar{t}\gamma} = 55 \pm 5\ fb$

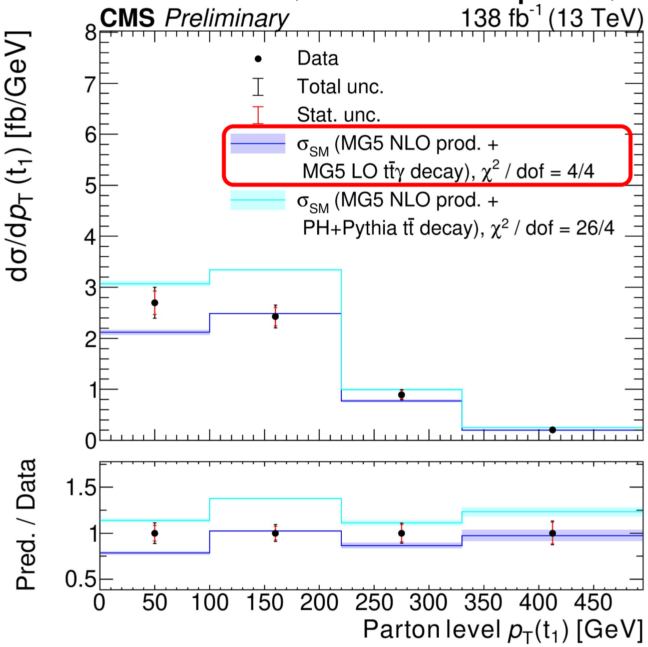


ttγ differential: results

Particle level (fiducial)



Parton level (extended space)



General good agreement with the SM in the nominal simulation.

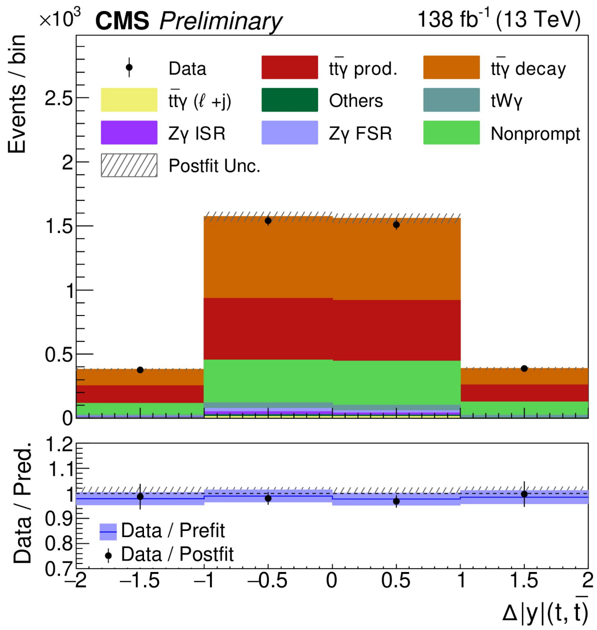
ttγ differential: top quark charge assymmetry

Same procedure as ttW but with the top quark (parton level).

ML fit

$$A_C = \frac{\sigma(\Delta|y| > 0) - \sigma(\Delta|y| < 0)}{\sigma(\Delta|y| > 0) + \sigma(\Delta|y| < 0)},$$

Ac = -0.012 ± 0.042

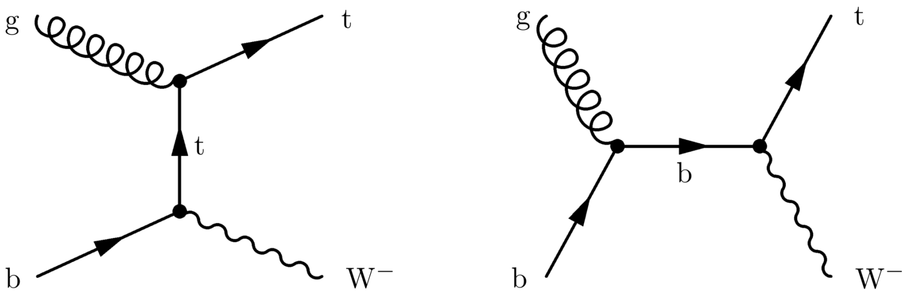


➢ In agreement with the SM expectation: $Ac^{SM} = 0.005 \pm 0.002$

The top

The eXtra

tX measurements



Inclusive and differential tW with Run 3 (2022)

[JHEP 01 (2025) 107](#)

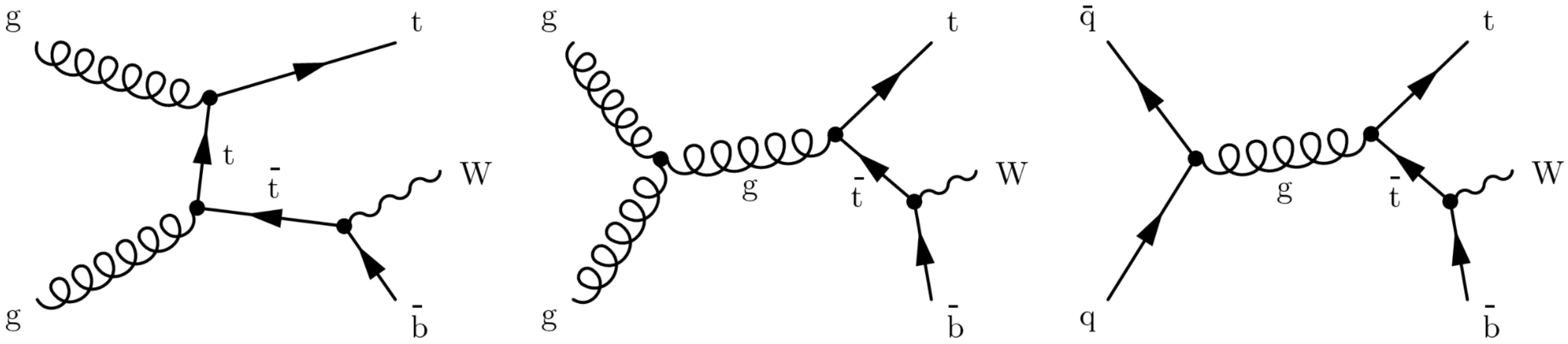
tW measurement: introduction

First measurement in Run 3 of a single top process.

Similar sensitivity to the full Run 2 result (*JHEP 07 (2023) 046*).

Main challenge is to separate the signal from dominant and irreducible $t\bar{t}$ background.

Diagram removal and subtraction procedures to avoid double counting.



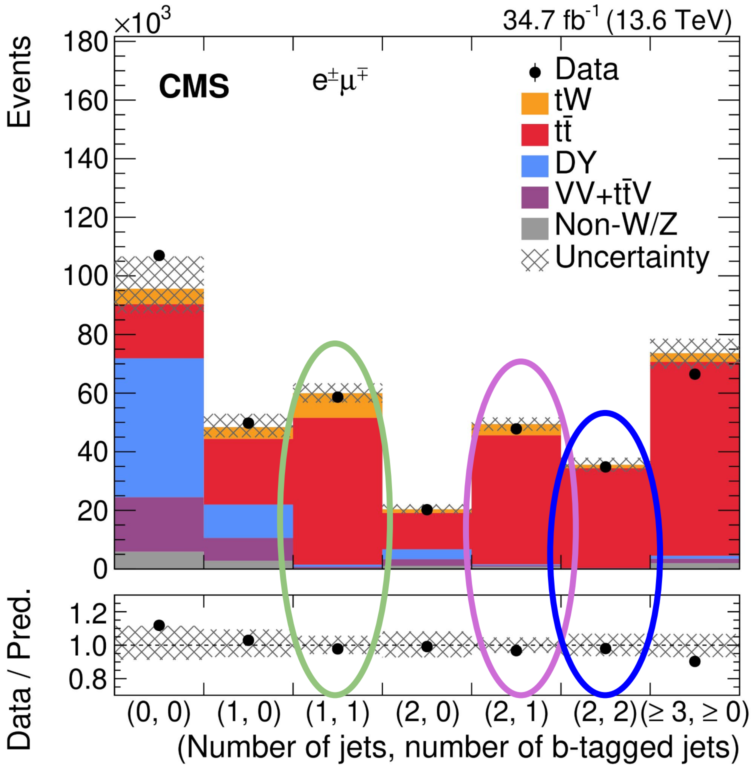
tW inclusive: strategy

Selected these 3 regions in OS eμ to get the cross section:

- ➢ 1j1b
- ➢ 2j1b
- ➢ 2j2b

Also, two multiclassifiers to separate signal from background in:

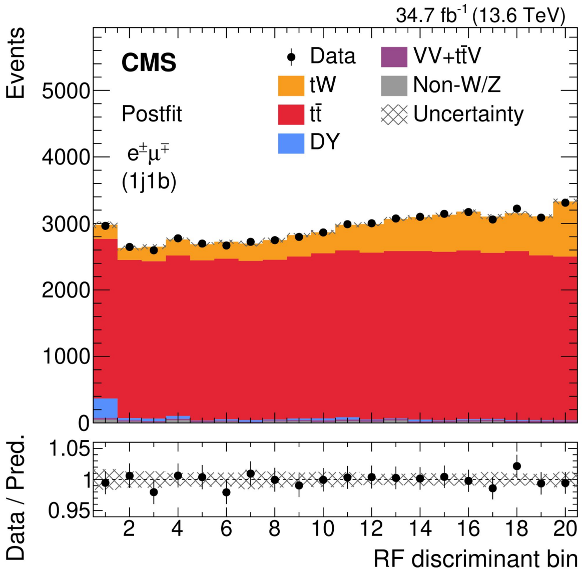
- ➢ 1j1b: Random Forest to discriminate DY vs tt vs tW
- ➢ 2j1b: Random Forest including tt semilep. vs tt vs tW

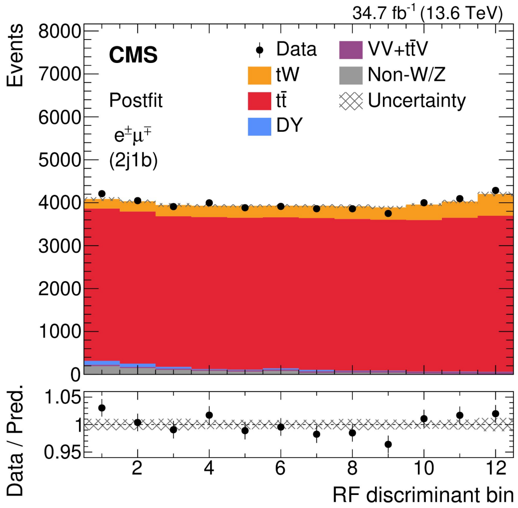


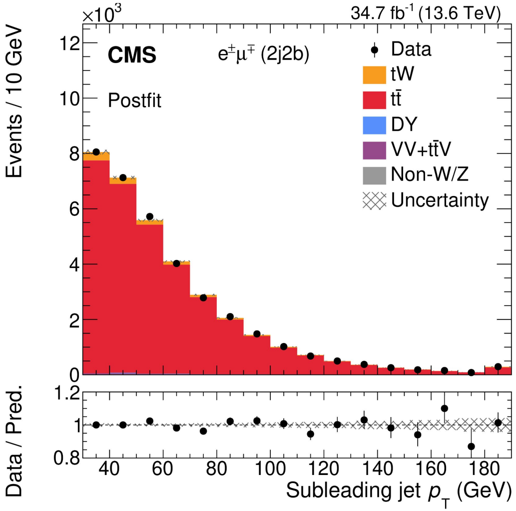
tW inclusive: results

The inclusive cross section is measured performing a ML fit in:

- ➢ Random Forest in 1j1b
- ➢ Random Forest in 2j1b
- ➢ Subleading lepton pt in 2j2b







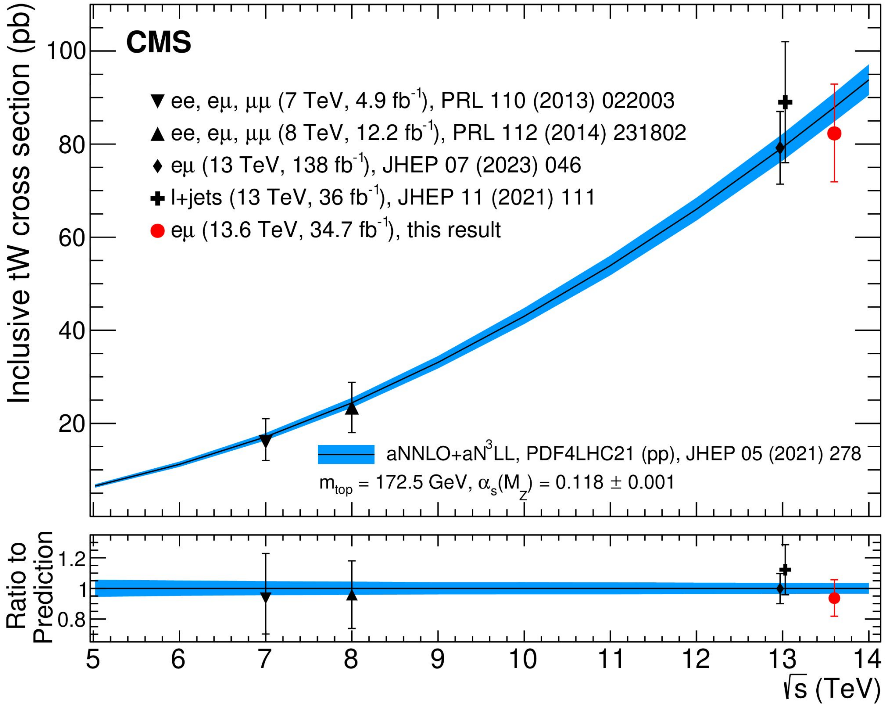
tW inclusive: results

The measured cross section is:

$$\sigma_{tW}^{obs} = 82.3 \pm 2.1\ (stat)\ ^{+9.9}_{-9.7}\ (syst) \pm 3.3\ (lumi)\ pb$$

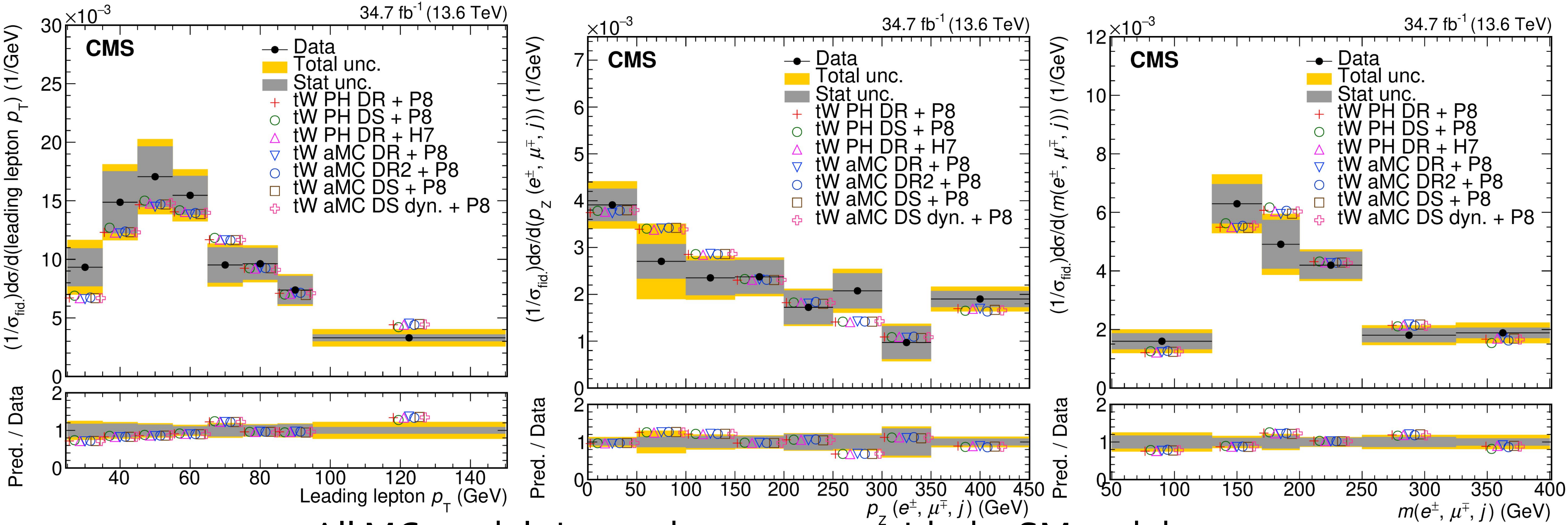
in good agreement with the SM expectation:

$$\sigma_{tW}^{SM} = 87.9\ ^{+2.0}_{-1.9}\ (scale) \pm 2.4\ (PDF\ +\ \alpha_s)\ pb$$



tW differential: results

To measure the differential cross section only the 1j1b region is used.



All MC models in good agreement with the SM and data.

Summary

- Several new low cross section measurements with full Run 2 (specially differential)
- In general, good agreement with the SM in the presented measurements
- ttW keeps having tensions with the predictions → more study in Run 3
- Many of these analyses have EFT interpretations that you can see in Maryam's talk.
- First single top measurement with Run 3 with very good performance.

- Many more analyses on their way with Run 3 data!!

Thank you!

jorge.aylon.torresano@cern.ch

Backup

Why measuring the top quark?

- ★ Very useful to test the standard model (SM) very precisely:
  - ○ Proton components, CKM matrix, cross sections…
- ★ Present in BSM processes.
  - ○ Dark matter, EFTs, exotic processes…
- ★ Also present as background in lots of SM processes:
  - ○ Diboson, associated Higgs production…

- ★ Full Run 2 (138 fb^{-1}) allows to observe the low cross section processes.
- ★ Beginning of Run 3 (35 fb^{-1}) also allows to get results at a new energy regime.

ttW differential: selection strategies

The differential measurement is split in two regions with two strategies:

2lss

- Exactly 2 SS leptons
- pT > (25, 15) GeV
- mll > 30 GeV
- Veto to mll in the Z peak (+- 15 GeV)
- MET > 30 GeV
- At least 3 jets (2 b-tagged)

3l

- Exactly 3 leptons
- One pair with opposite sign (OS)
- pT > (25, 15, 15) GeV
- mll > 30 GeV
- Veto to OSSF mll in the Z peak
- At least 2 jets (1 b-tagged)

ttW differential: backgrounds

Several backgrounds to deal with:

Estimation

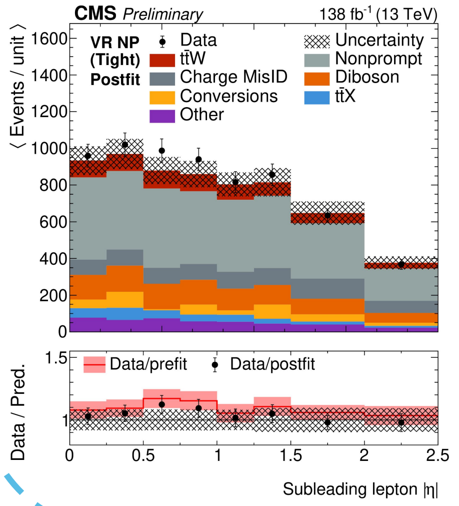
- Non-prompt leptons → Data Driven
- Charge miss Id leptons → Data Driven
- Conversions (ttγ, tγ and Zγ) → MC samples
- Irreducible backgrounds (ttX, WZ, ZZ) → MC samples

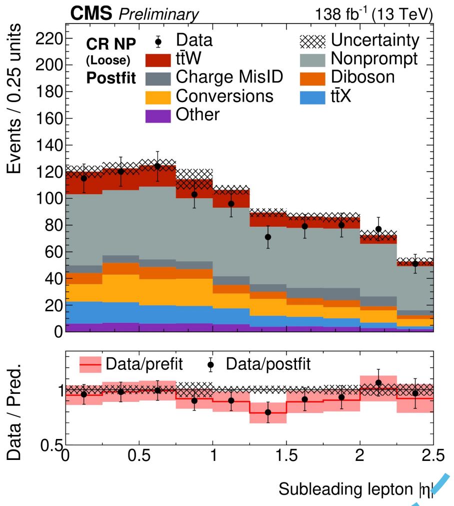
ttW differential: data-driven estimations

Non-prompt estimation

Using a fake factor method:

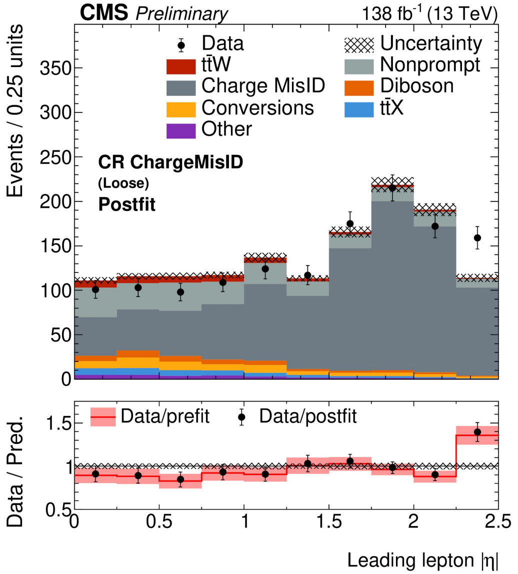
- ➢ Get the fake rate in a sideband
- ➢ Extrapolate to the signal region





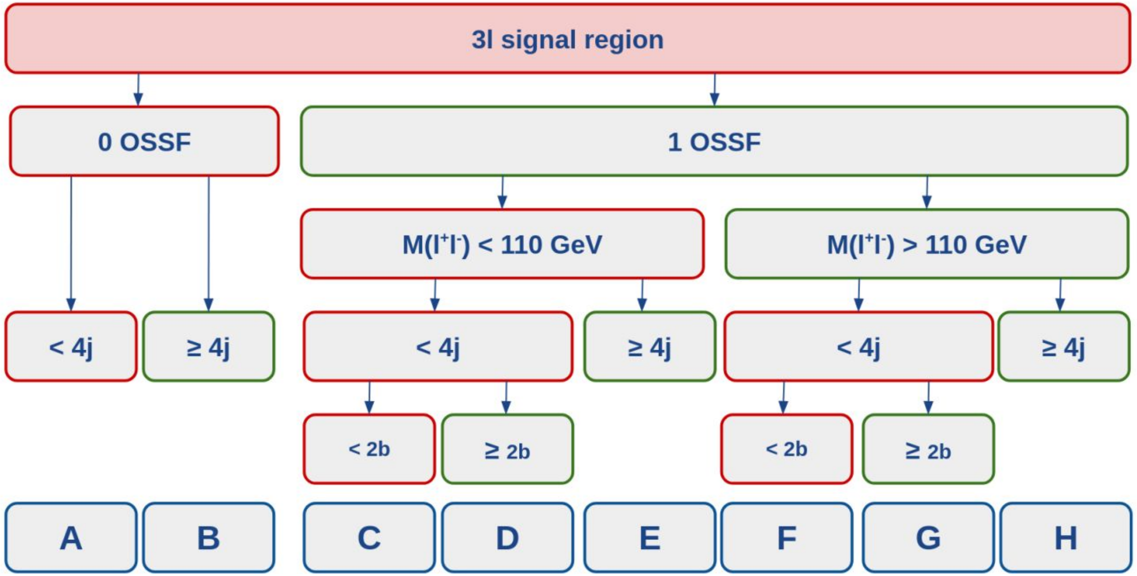
Charge miss Id. estimation

Selecting events with the SR selection but OS of DY + SS events in the Z peak



ttW differential: lepton charge asymmetry

Categorization:



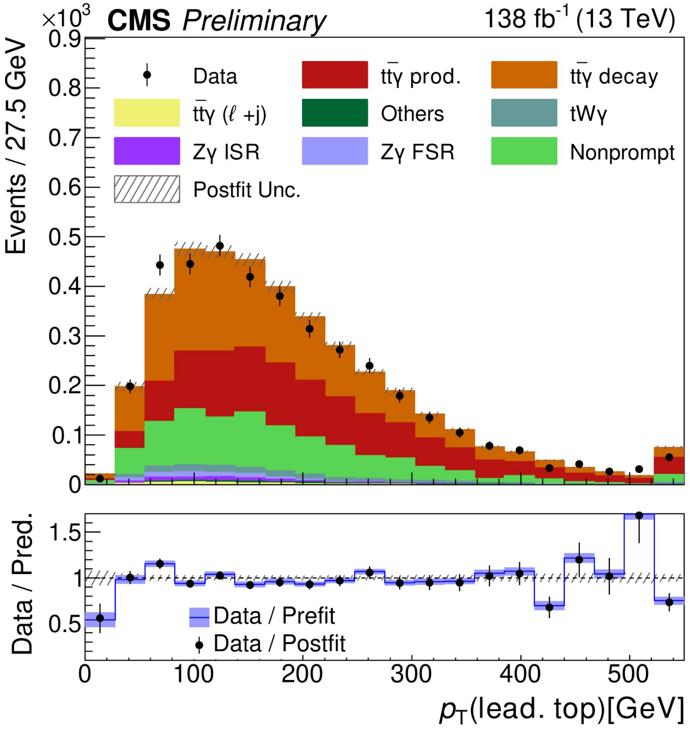
ttγ: signal region definition

Two sources of ttγ

- Production: γ generated in ISR
- Decay: γ generated in FSR

Event selection:

- At least 2 OS leptons
- Exactly 1 photon
- Lepton pT > (25, 15) GeV
- mll > 40 GeV
- Veto to mll and mllγ in the Z peak (+- 15 GeV)
- At least 2 jets (1 b-tagged)
- Reconstruction of the top quark

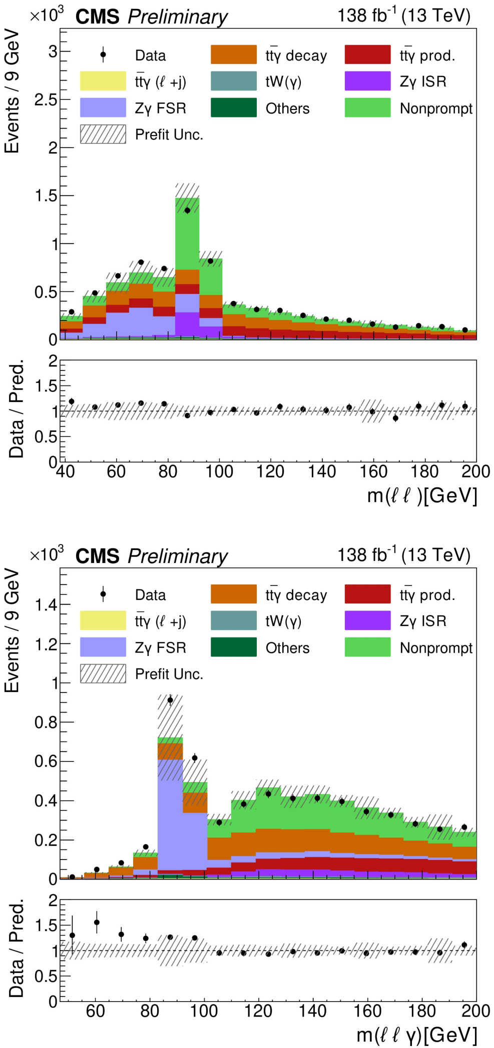


ttγ: backgrounds

Processes split in genuine photons and non-prompt photons.

Genuine photons: estimated with MC samples → main background is Zγ

Non-prompt photons: estimated with a data-driven method

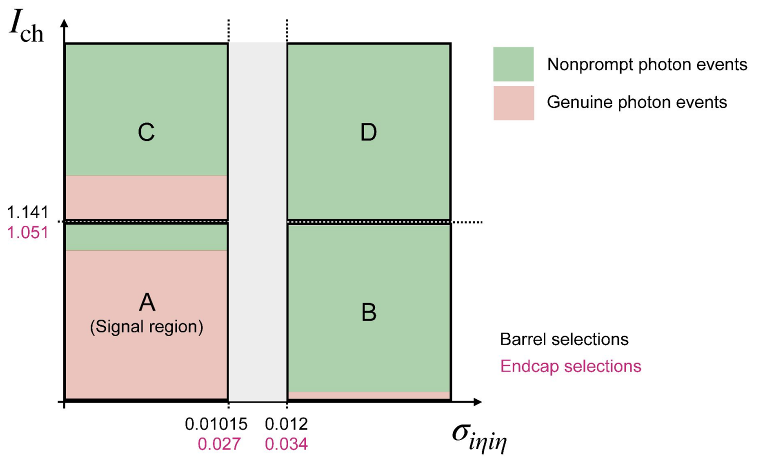


ttγ: non-prompt estimation

Using ABCD method to compute the contribution

Sideband regions defined as a function of:

- ➢ PF charged isolation
- ➢ Width of the electromagnetic shower



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

ttγ inclusive: fiducial selection

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	-	-

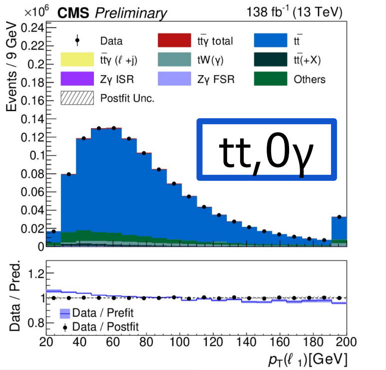
$t\bar{t}\gamma$ differential: systematic uncertainties

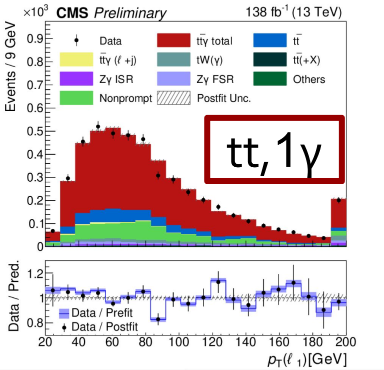
	Source	Corr. (period)	Corr. (process)
Experimental	Integrated luminosity	$\sim$	✓
	Pileup reweighting	✓	✓
	Electron reconstruction and identification	✓	✓
	Muon reconstruction and identification	✓	✓
	Photon reconstruction and identification	$\sim$	✓
	Nonprompt photon estimation	$\times$	—
	Trigger efficiencies	$\times$	✓
	L1 prefiring	✓	✓
	JES	$\sim$	✓
	JER	$\times$	✓
	b tagging	$\sim$	✓
Theoretical	μ_R scale	✓	$\sim$
	μ_F scale	✓	$\sim$
	PDF	✓	✓
	PS scales: ISR	✓	$\times$
	PS scales: FSR	✓	$\times$
	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	✓	—

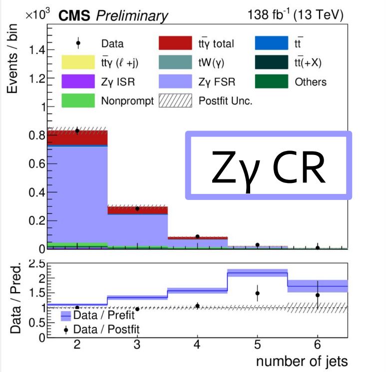
Main syst.

ttγ differential: ttγ and tt ratio

A tt enriched region is defined (no γ)







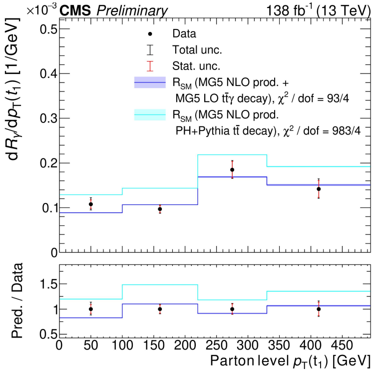
$$R = \frac{\sigma_{t\bar{t},1\gamma}}{\sigma_{t\bar{t},0\gamma} + \sigma_{t\bar{t},1\gamma}},$$

ML fit

<u>Inclusive</u>

R = 0.0125 ± 0.0005 (syst) ± 0.0002 (stat)

<u>Differential</u>



Overview of the EFTs interpretation

ttX measurements can be interpreted in the SM-EFT framework for (mainly) electroweak coefficients.

ttγ → previous result (*JHEP 05 (2022) 091*) with Run 2 studied electroweak dipole moments characterized by the tZ(γ) interaction vertex.

Recent results:

- ➢ Studying ttZ and tZq and odd coefficients from tZ coupling, CMS-PAS-TOP-24-012 obtained new limits in full Run 2 + 2022.
- ➢ Also CMS-PAS-TOP-23-009 studied coefficients from ttZ + WZ + ZZ in full Run 2 getting limits for 10 flavour related coefficients.

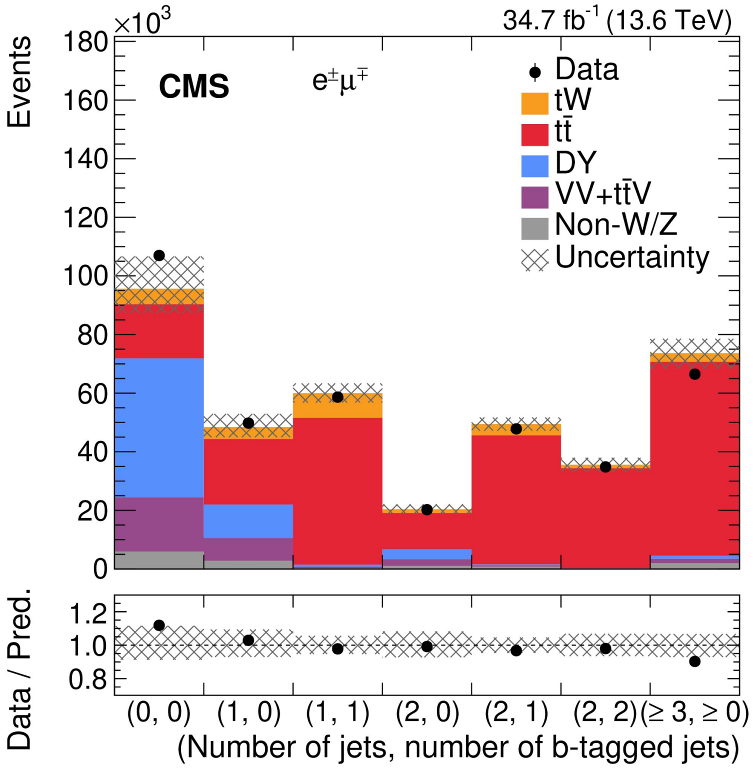
More details about these in Maryam's talk about EFTs in the fermionic sector!

tW measurement: strategy

Event selection:

- ➢ At least two leptons
- ➢ Lepton pT > 25 GeV
- ➢ mll > 20 GeV
- ➢ Only eμ events with OS

Separation in various regions as a function of the number of jets and b-tagged jets.



tW: particle level and fiducial regions

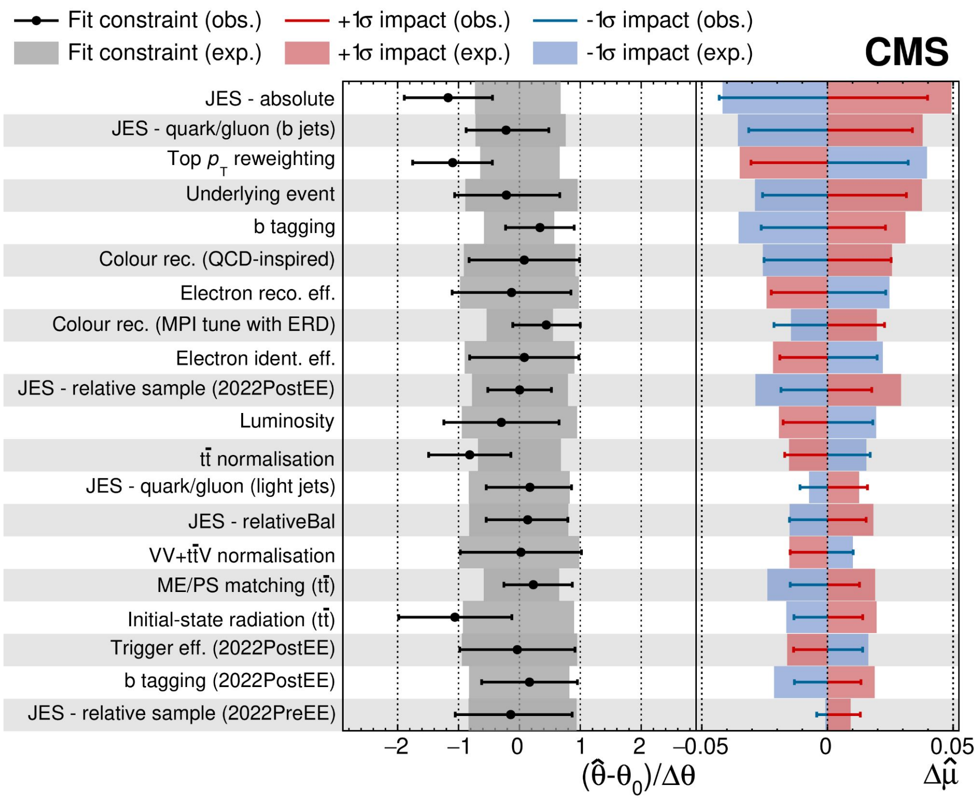
Particle level selection

Object	p_{T} (GeV)	$\lvert\eta\rvert$
Muons	>20	<2.4
Electrons	>20	<2.4, excluding [1.444–1.566]
Jets	>30	<2.4
Loose jets	[20, 30]	<2.4

Fiducial selection

Observable	Requirement
Number of leptons	≥ 2
Leading lepton p_{T}	>25 GeV
Invariant mass of all dilepton pairs	>20 GeV
Number of jets	1
Number of loose jets	0
Number of b jets	1

tW inclusive: uncertainties impact



tW differential: strategy

To measure the differential cross section only the 1j1b region is used

Event selection (fiducial) + veto to events with low energy (20-30 GeV)

Main keys from the analysis:

★ The signal extraction is performed by background subtraction

★ Fiducial space to full space with TUnfold

★ Several schemes to remove the interference between tW and tt are tested