Measurements top quark production associated with a W boson or a photon at CMS

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(on behalf of the CMS Collaboration)

Top associated production

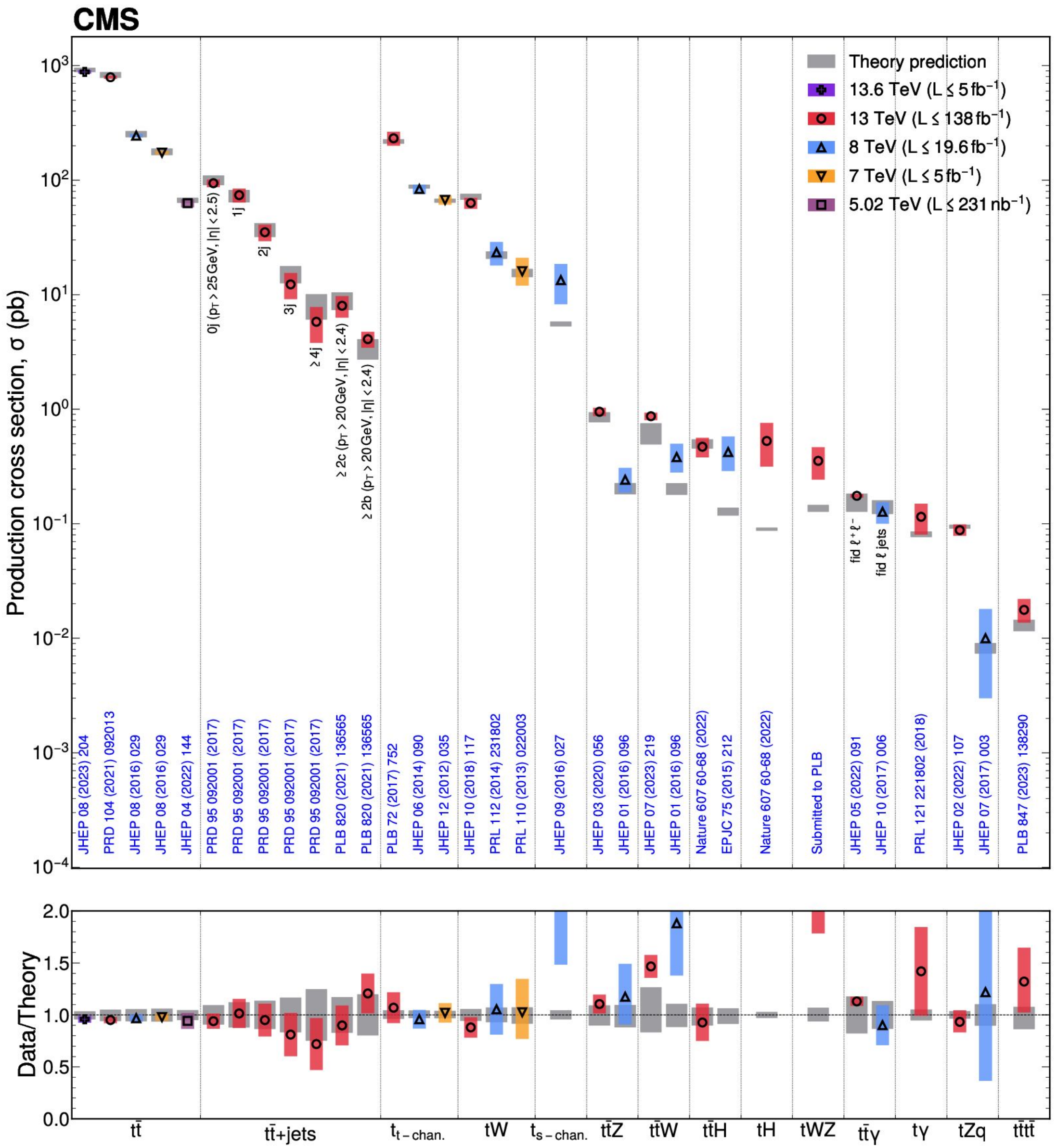
- **Cross sections < 1 pb**
- ~ 10^3 lower than $t\bar{t}$ production

- Reaching the **precision era** with full Run 2!
  - we can go differential

- Key to probe the EW couplings to the heaviest fermion

- Backgrounds to other SM processes with even smaller cross section

- Handle to search for BSM effects
  - $t\bar{t}Z$, t+Zq: CP violation [S. Sanchez talk]



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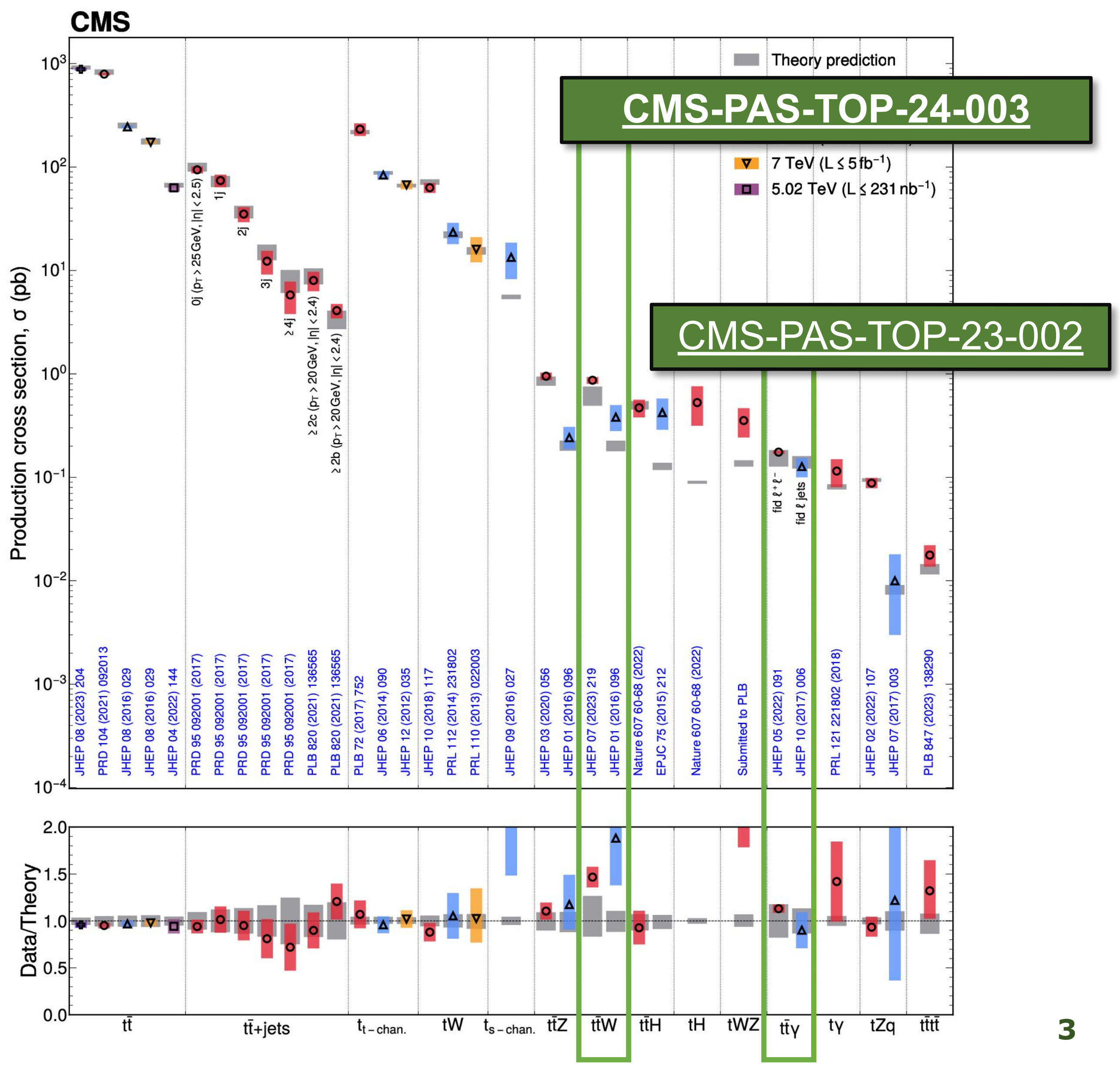
In this talk: will focus on the newest results by CMS both of them including differential measurements!

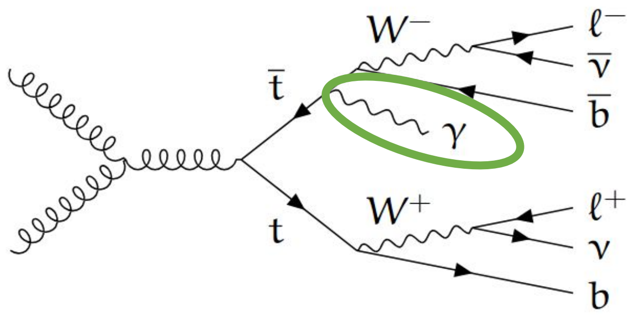


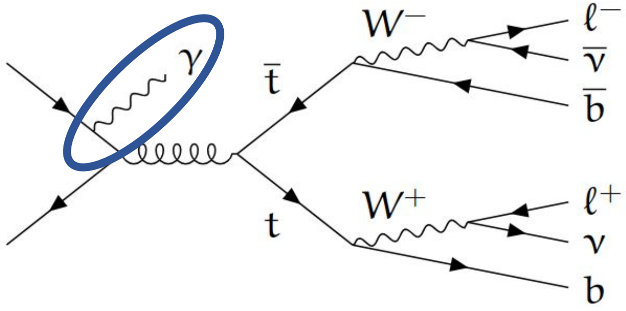
$t\bar{t}\gamma$

CMS-PAS-TOP-23-002

What can we learn?

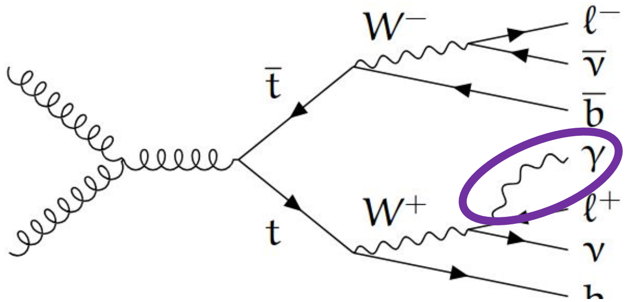
- Signature with a high pT isolated photon
- Allows to measure top-γ coupling at LO
- Charge asymmetry from diagram interference, stronger (60%) than on $t\bar{t}$ given $q\bar{q}$.
- Challenge: experimentally it's difficult to distinguish photon origin:
  - Production: from initial state or top quarks
  - Decay





In this analysis we use the full Run 2 dataset to provide:

- Inclusive and differential measurements of $t\bar{t}\gamma$
- Top charge asymmetry
- Ratio $t\bar{t}\gamma/t\bar{t}$



Analysis strategy

Selection: 2 opposite-sign leptons, 1 isolated photon with p_T> 20 GeV, ≥2 jets and ≥1 b tag

Main backgrounds:
- With **real photon:** Zγ+jets largest
- With **fake photons:** from hadronic source or matched to other particles at gen-level (pion decay)

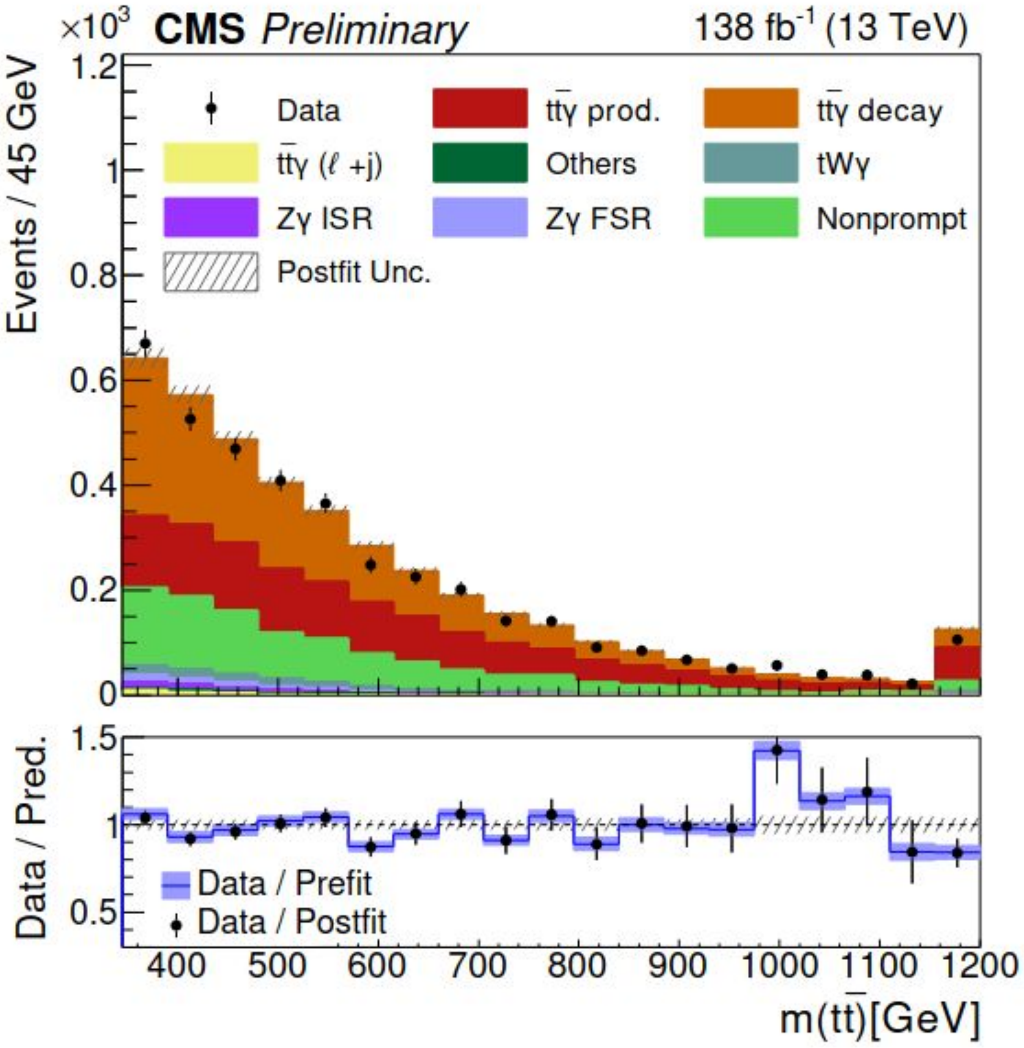
Dedicated control regions

Estimated from data

Dedicated MC to predict $t\bar{t}\gamma$ from:
- Decay:
  - with MADGRAPH5aMC@NLO at **LO in QCD • k factor**
  - with POWHEG, filtering for events with hard photons from the parton shower
- Production: at **NLO in QCD** with MADGRAPH5 aMC@NLO + top decay with Madspin.
  Photons p_T > 10 GeV and |η| < 5 are accepted. ΔR > 0.05.

Reconstruction of the $t\bar{t}$ system:
- Using kinematic fit

Good postfit agreement



Inclusive measurement

Signal extraction performing **maximum likelihood fit to $\Delta R(\ell, \gamma)$:**

- good discrimination between production and decay

- **Result for $t\bar{t}\gamma$ (production + decay):**

$$\mu_{t\bar{t}\gamma} = 1.09 \pm 0.06$$
$$\sigma_{t\bar{t}\gamma} = 134 \pm 7(\mathrm{syst}) \pm 3(\mathrm{stat})\ \mathrm{fb}$$

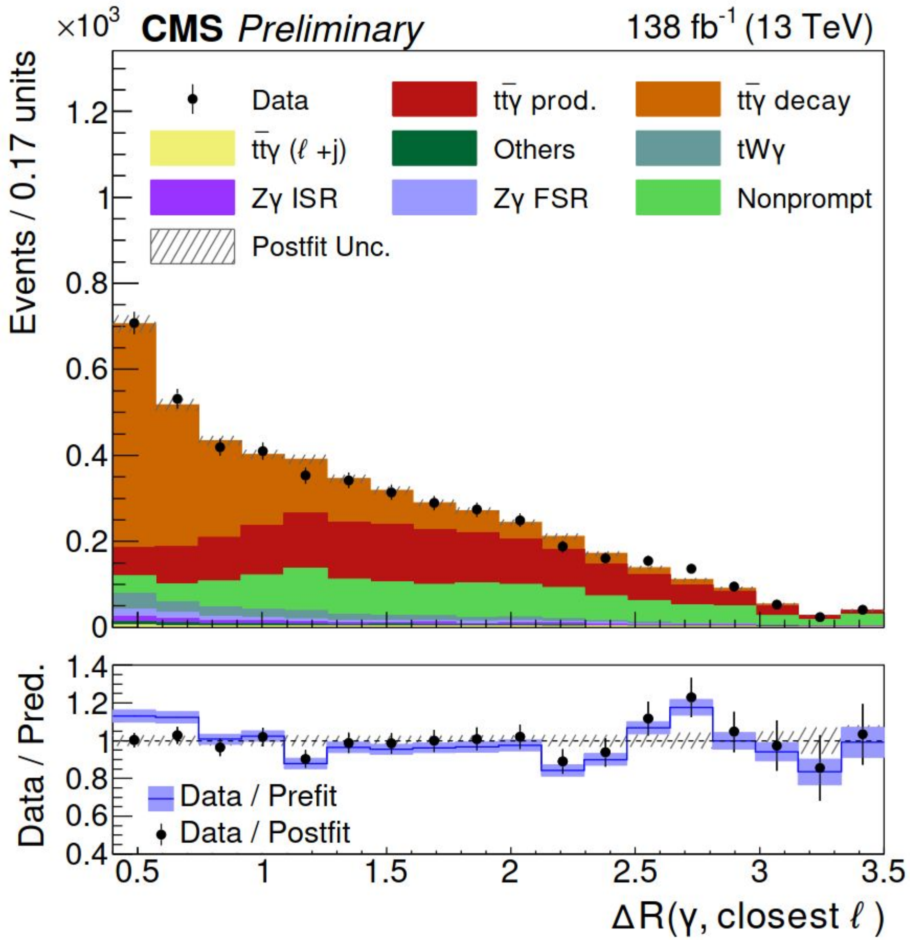
- **Result for $t\bar{t}\gamma$ (production):** fit with $t\bar{t}\gamma$ decay considered as background:

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

Both in good agreement with SM!

Main uncertainties: normalisation of the nonprompt background, γ identification, normalization of $t\bar{t}\gamma$ decay simulation

Reaching precisions of current best theoretical predictions

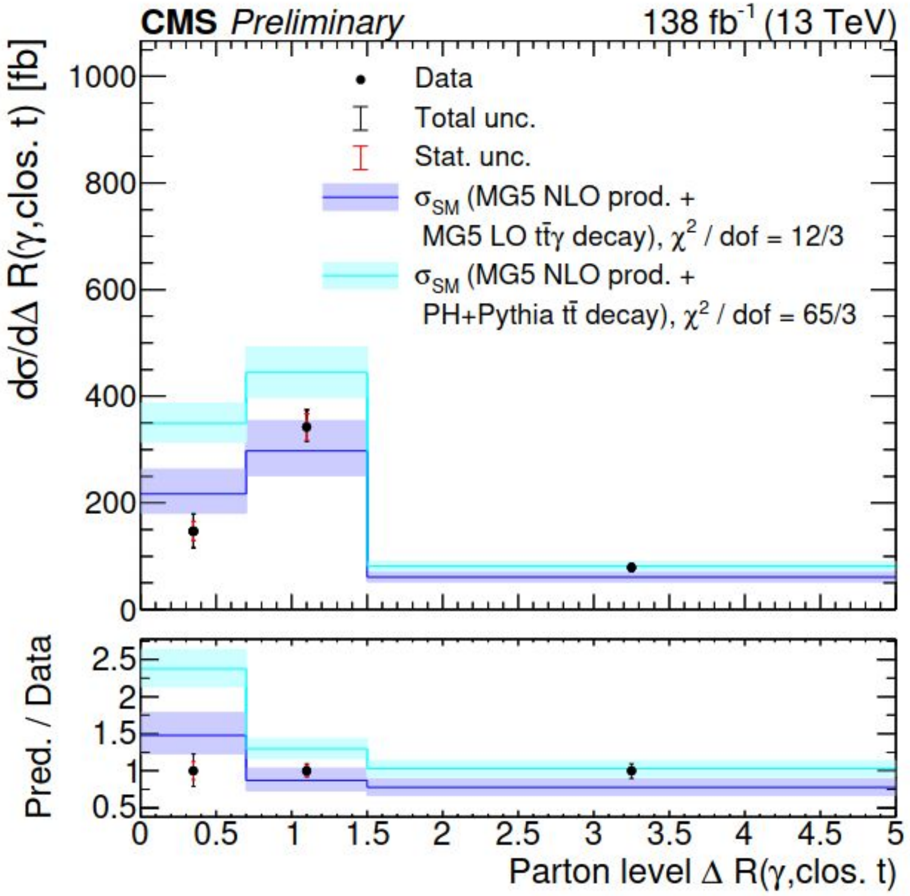


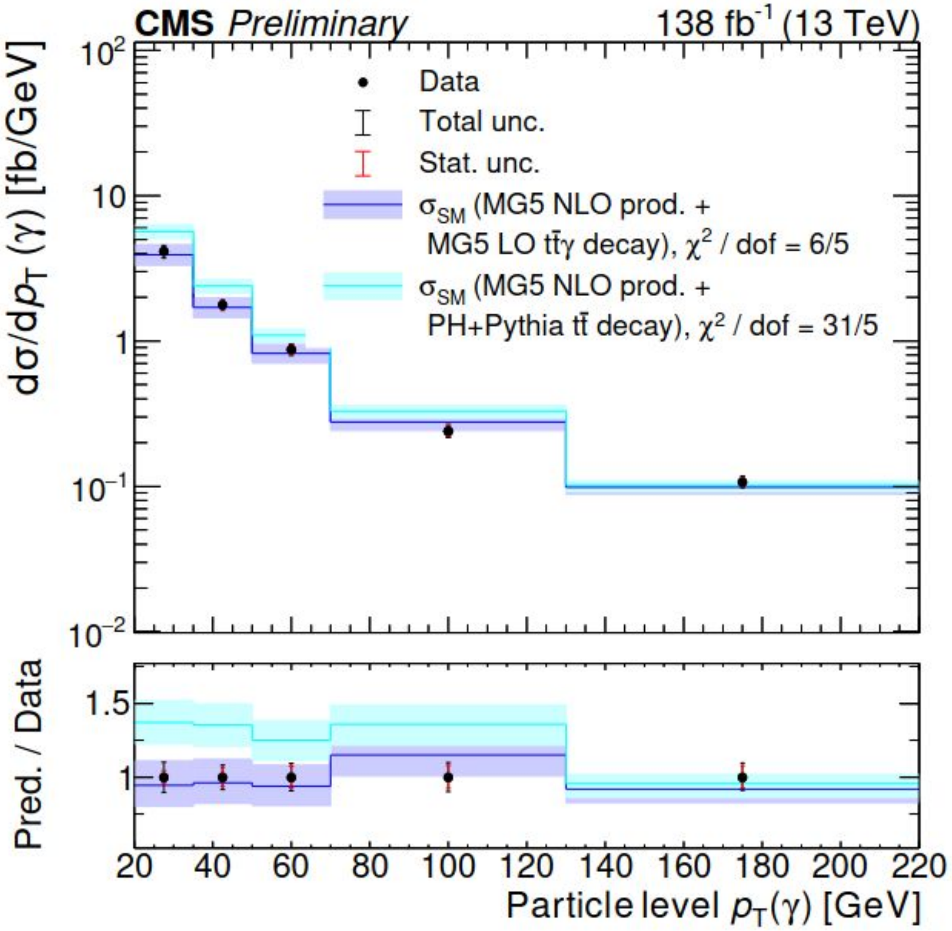
Differential measurement

Likelihood-based unfolding technique

- Lepton and photon variables are measured at particle level in a fiducial phase space.
- Top and $t\bar{t}$ variables are measured at the parton level in an enlarged phase space

Selections	Lepton	Photon	Jet	B jet
p_T (GeV)	15	20	30	30
$\|\eta\|$	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	-	-





Charge asymmetry

Top charge asymmetry
Making use of the reconstructed information on the $t\bar{t}$ system:

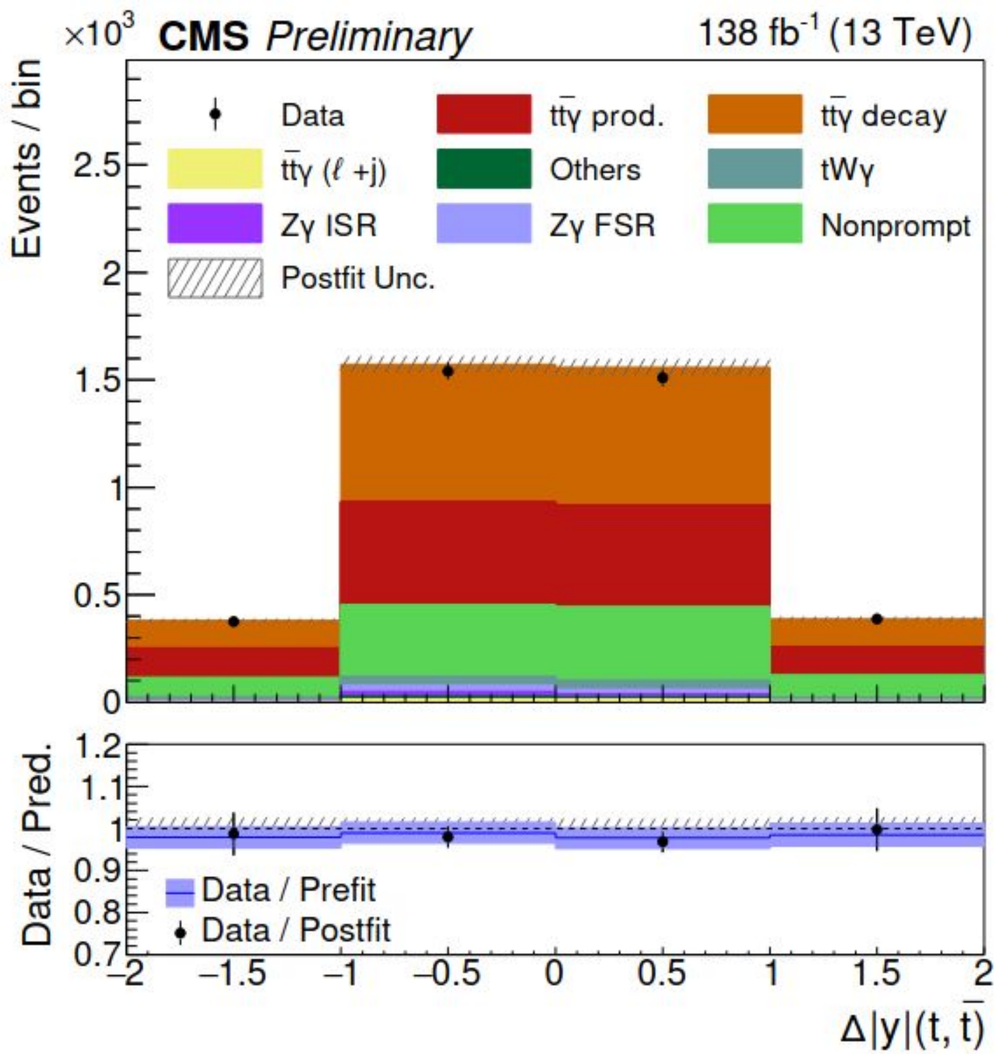
$$A_C = \frac{\sigma(\Delta|y| > 0) - \sigma(\Delta|y| < 0)}{\sigma(\Delta|y| > 0) + \sigma(\Delta|y| < 0)}$$

Fit to the difference in absolute rapidity between the top quark and antiquark in the signal region.

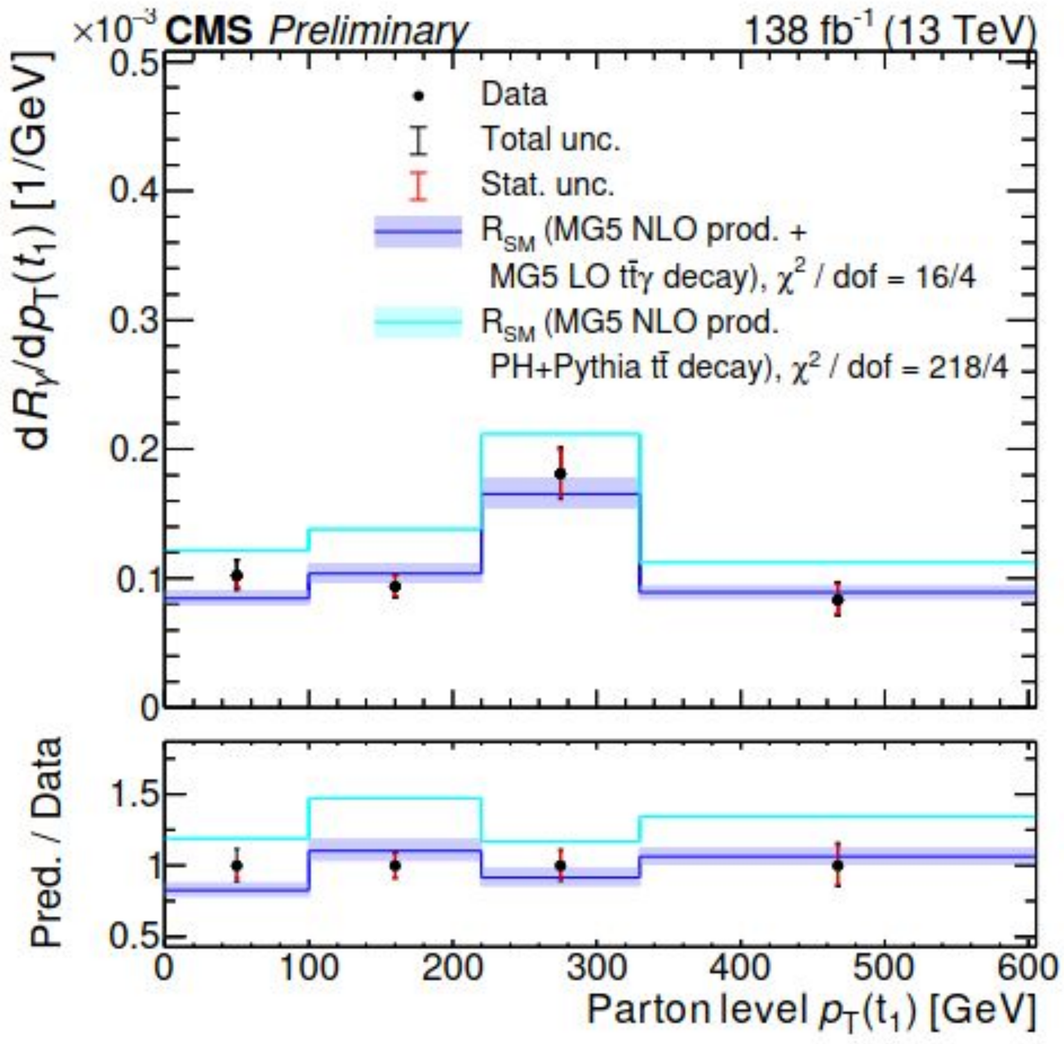
- **Ac** and **μ($t\bar{t}\gamma$)** simultaneously extracted

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

- In agreement with SM prediction at NLO: −0.5 ± 0.2 %
- Statistically limited



$R(t\bar{t}\gamma/t\bar{t})$



Ratio between $t\bar{t}\gamma$ and $t\bar{t}$ measured for first time

- Using an extra $t\bar{t}$ dedicated region with 0 photons
- R and **$\mu(t\bar{t})$** are fitted simultaneously:

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

- Inclusive and differential measurement

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

$t\bar{t}W$

CMS-PAS-TOP-24-003

What can we learn?

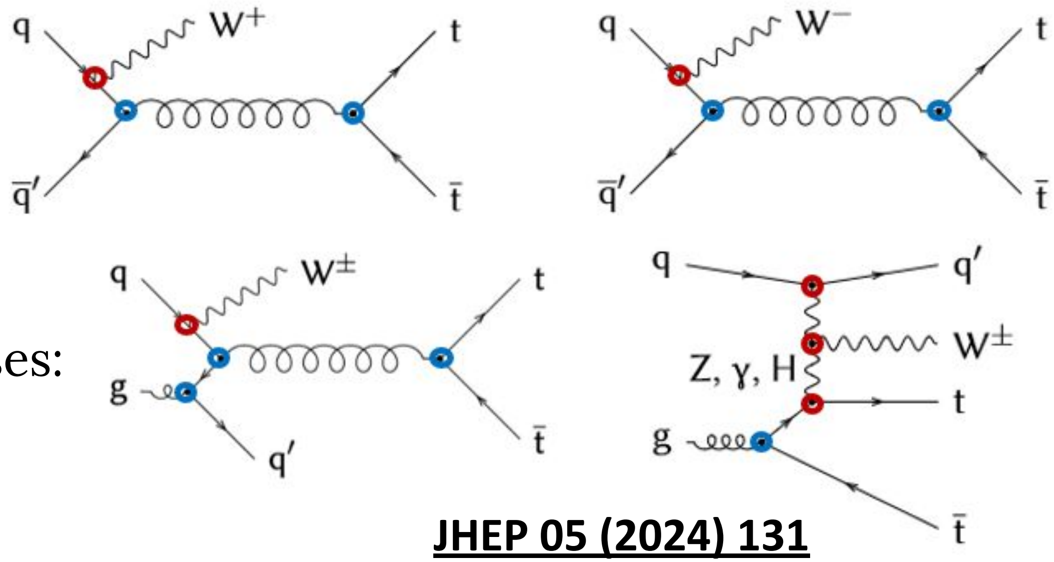
EWK coupling
QCD coupling

Cross section measured both by CMS and ATLAS reported to be **above the theory prediction**
- challenging modelling
- latest NLO+NNLL still show some tension

Important background for many SM low cross section processes: $t\bar{t}H$, $t\bar{t}t\bar{t}$...

qq' initiated state: good handle to measure the **rapidity asymmetry** in top quark production

In this analysis we use the full Run 2 dataset to provide:
- First $t\bar{t}W$ differential measurements by CMS
  - 2lss and 3l final states
- First leptonic charge asymmetry of $t\bar{t}$ by CMS
  - Final states with 3l



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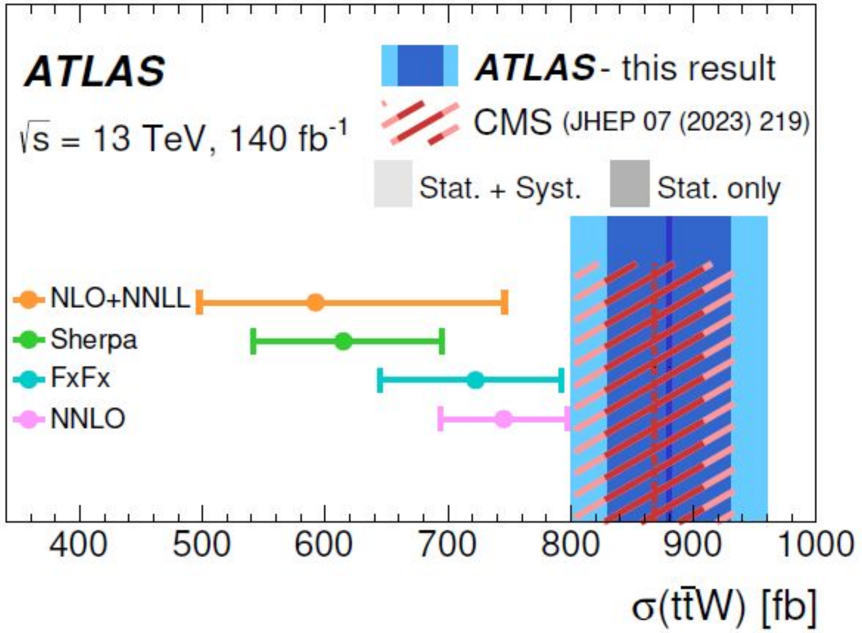
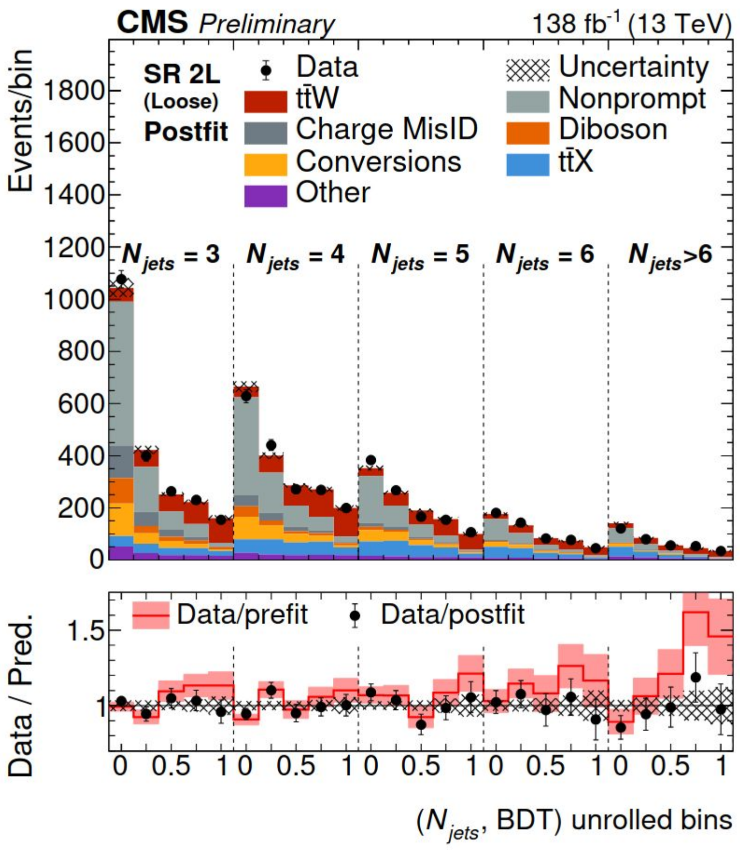


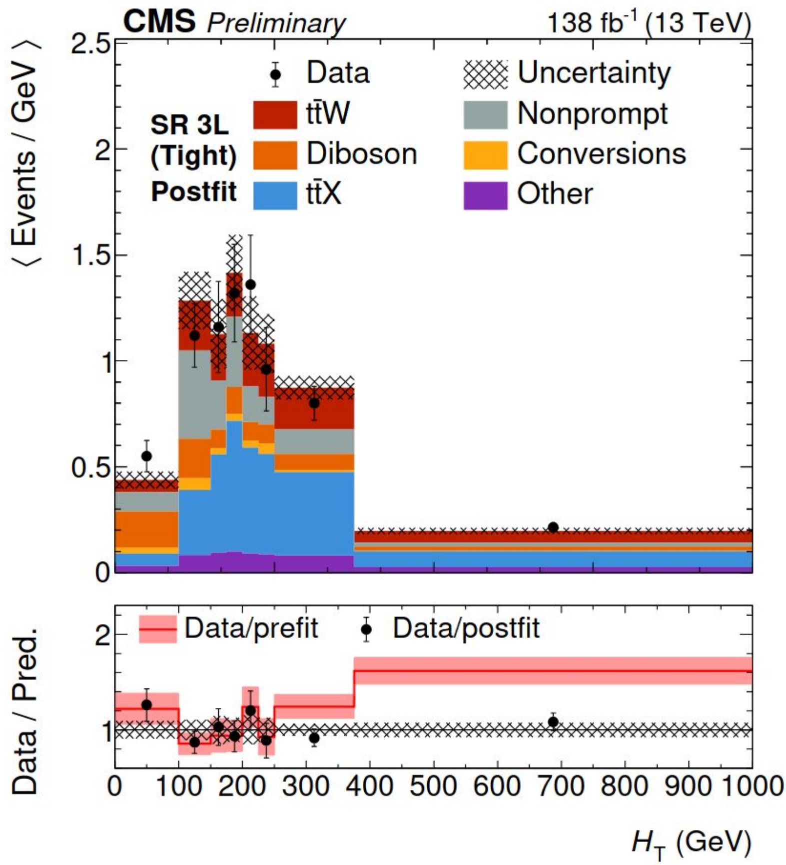
Analysis strategy

Selection: 2lss (3l), Veto events on the Z peak, nJet ≥ 3 (2), nb-tag ≥ 2

One of the dominant **backgrounds** arise from **Non-prompt leptons**, two different strategies for 2lss final state:

- **MVA-based**: more inclusive signal sample + MVA to discriminate signal from background.
- **Counting-based**: Tighter lepton selection, to get a purer signal sample.



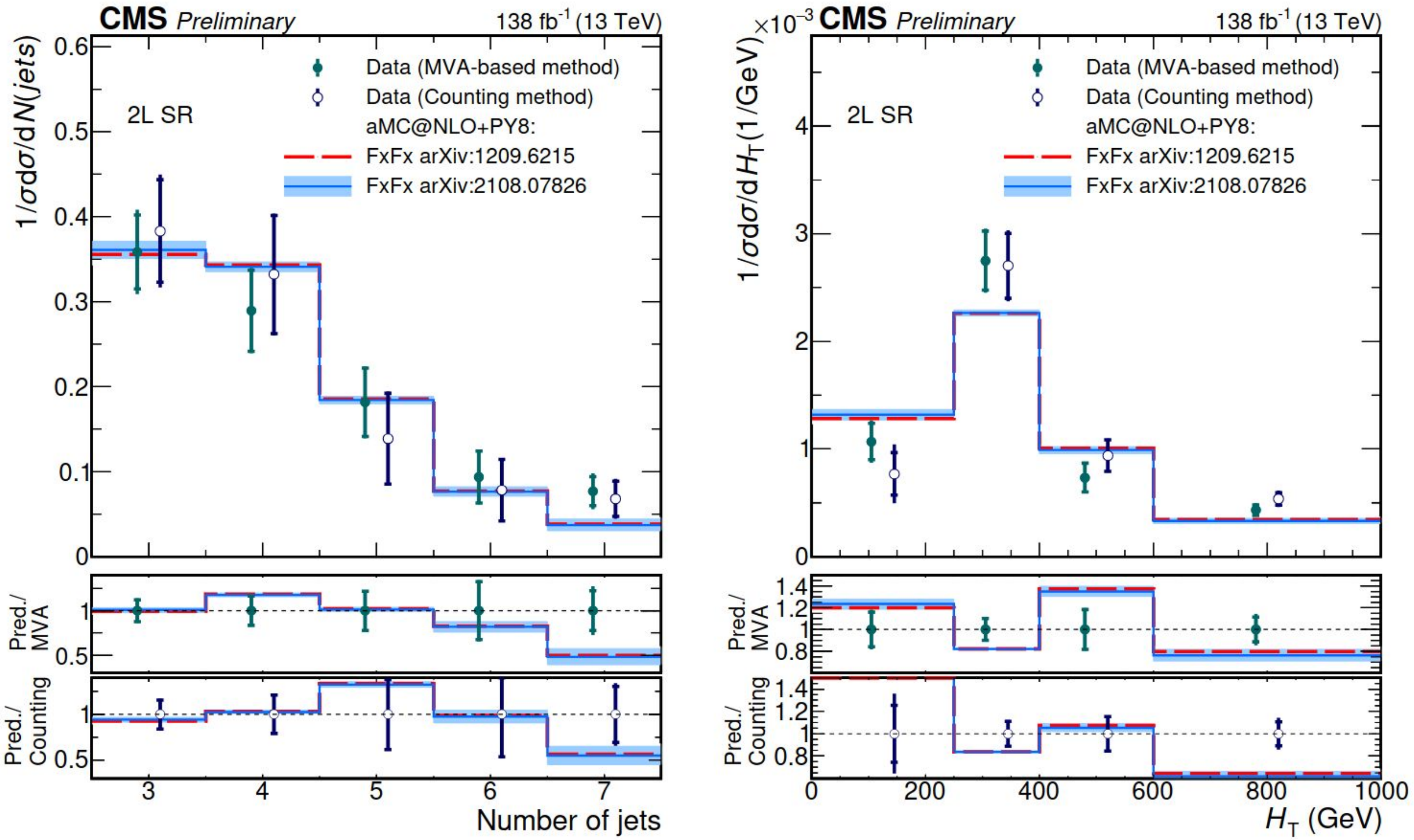


We perform a **likelihood-based unfolding**:

- 2lss: 2D binning on BDT or dilepton charge and variable of interest
- 3l: binning on variable of interest given smaller number of events
- Control regions used to constrain MC-estimated backgrounds ($t\bar{t}Z$ and dibosons)

Differential measurement

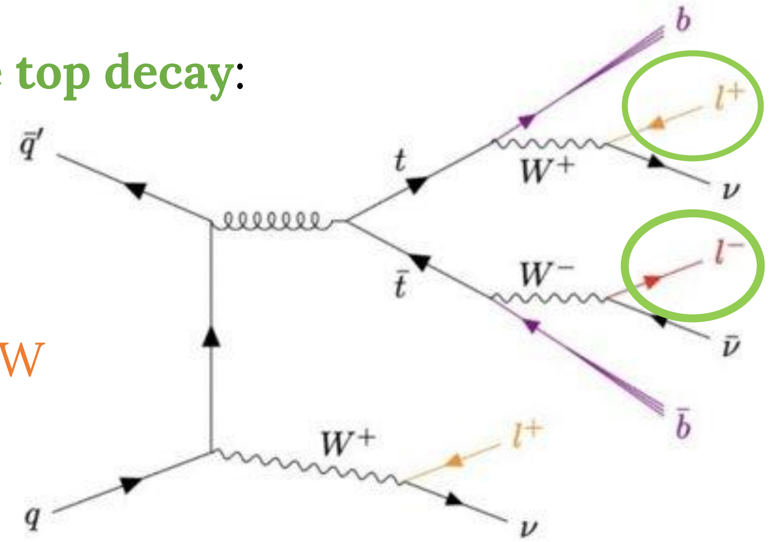
- Overall good agreement between MVA and counting methods
- Normalized differential cross sections are consistent with SM within uncertainties
- Absolute cross sections show some tension in agreement with previous observations
- Limited sensitivity for 3l (see backup)
- Compare results to improved FxFx merging model
  - exclude "EWK" jets from merging procedure



Charge asymmetry

In the 3l final state one can define the following using the **leptons from the top decay**:

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



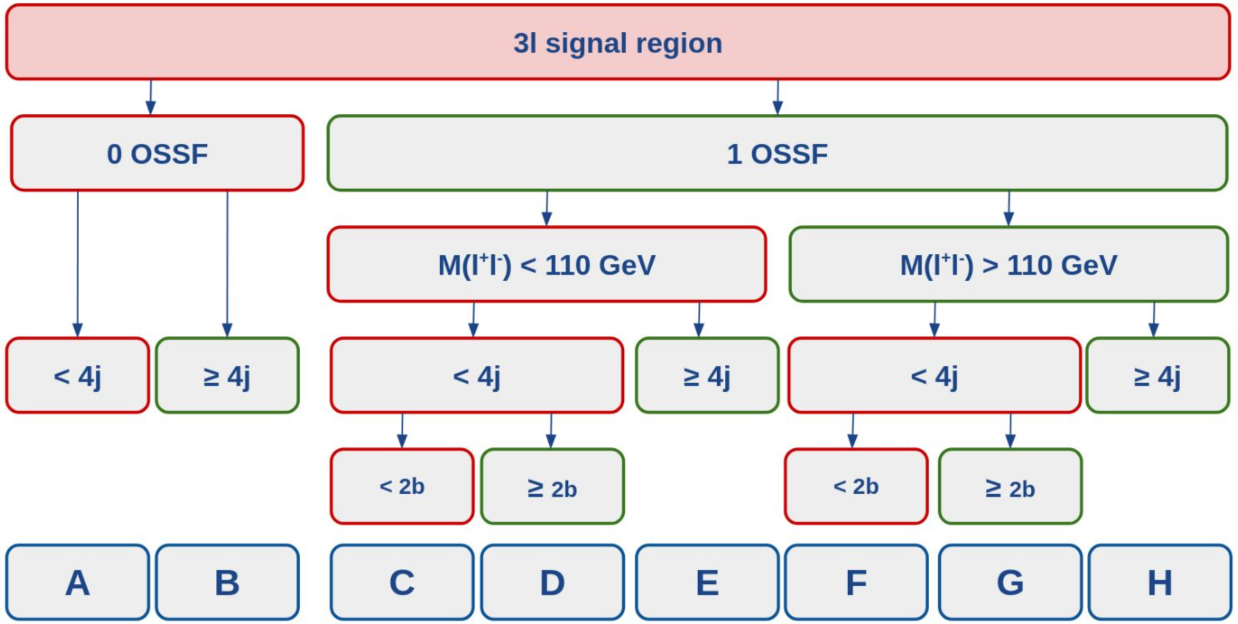
For the same sign pair leptons need to distinguish lepton form top vs from W

- Dedicated NN using kinematic info of the leptons and jets

Events Classification:

- 8 categories
- **different $t\bar{t}W$ purity**
- separate events with positive or negative Δy_ℓ
- Further binning on 4 bins of Δy_ℓ

at reconstruction level

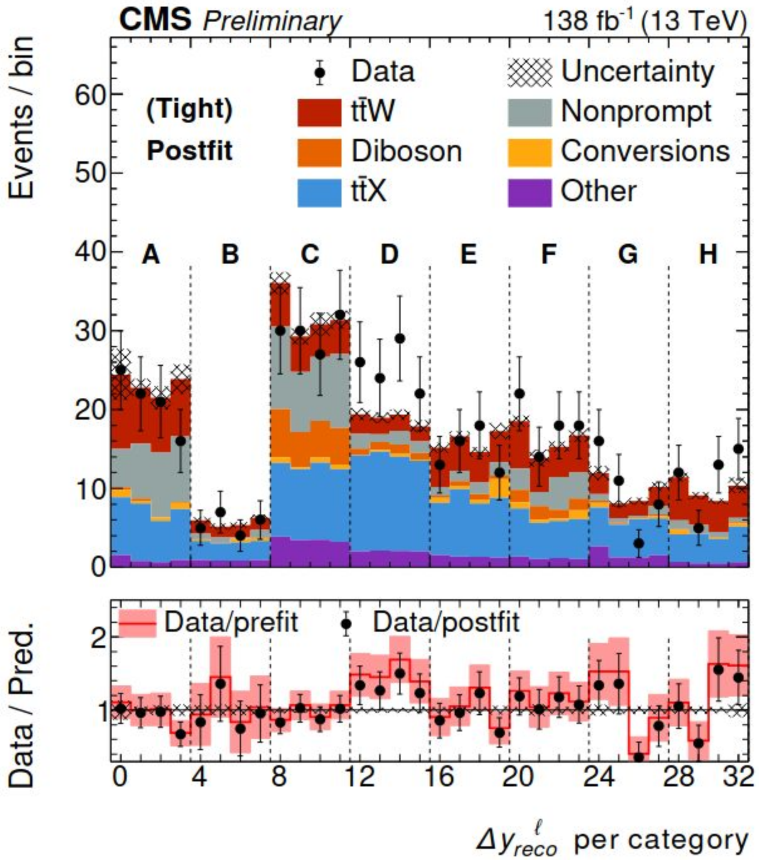


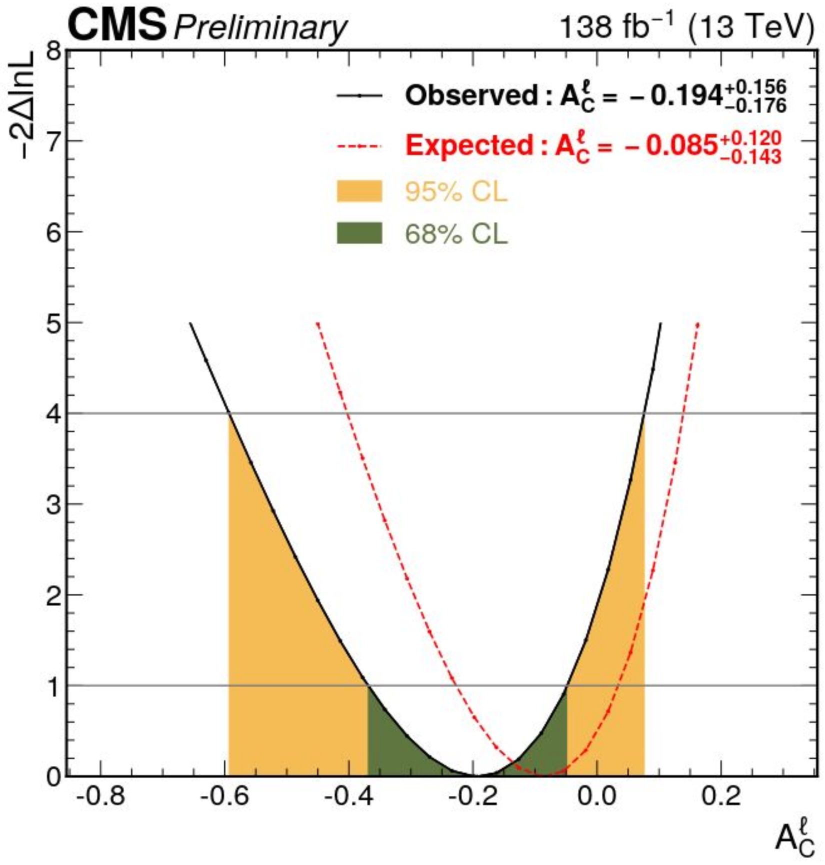
Charge asymmetry II

The fit to this distribution allows to extract the signal strength and the Ac simultaneously:

$$A_c^{\ell} = -0.19^{+0.05}_{-0.06}\,(\text{syst})\,{}^{+0.14}_{-0.16}\,(\text{stat})$$

This is agreement with NLO in SM simulation:





Summary

- Run 2 data allows to measure top-associated production processes with low cross section
    - Not only more data, but improved analysis techniques
    - Allowing for differential measurements

- **$t\bar{t}\gamma$ and $t\bar{t}W$ comprehension (at the inclusive and differential level) is very important for** :
    - Improving the modelling of processes that are important backgrounds on other SM measurements
    - Probe the electroweak coupling
    - Search for BSM effects
    - Measure the top quark charge asymmetry

- Run 3 dataset has already double the Run 2 luminosity

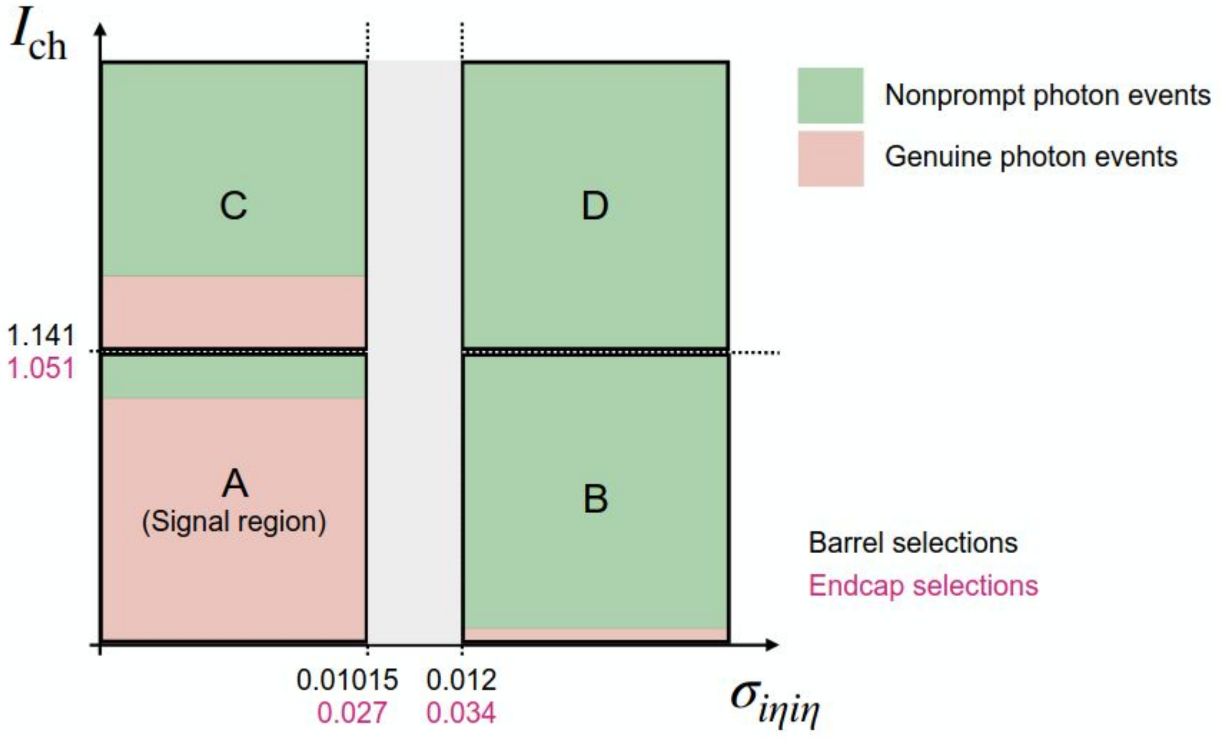
    - **Many top-quark associated events to be measured!**

Back-up

Nonprompt estimation

D, C: measurement region
B: application region

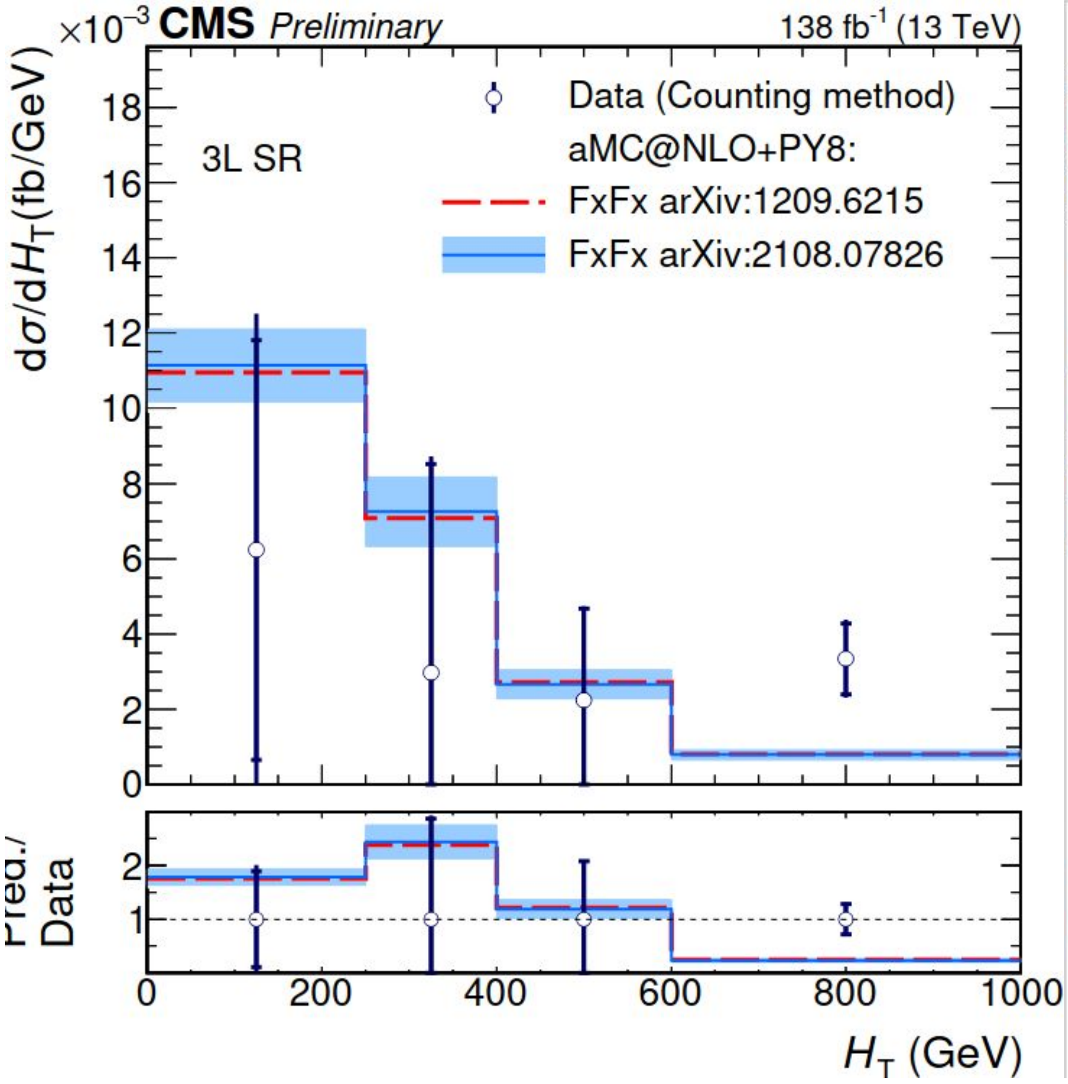
$$\text{nonprompt } \gamma \text{ contribution} = \sum_{i,j}(\text{Data}_B^{ij} \times \text{FR}^{ij} \times k_{\text{MC}}^{ij}) - \sum_{i,j}(\text{genuine MC}_B^{ij} \times \text{FR}^{ij} \times k_{\text{MC}}^{ij}) \quad (1)$$

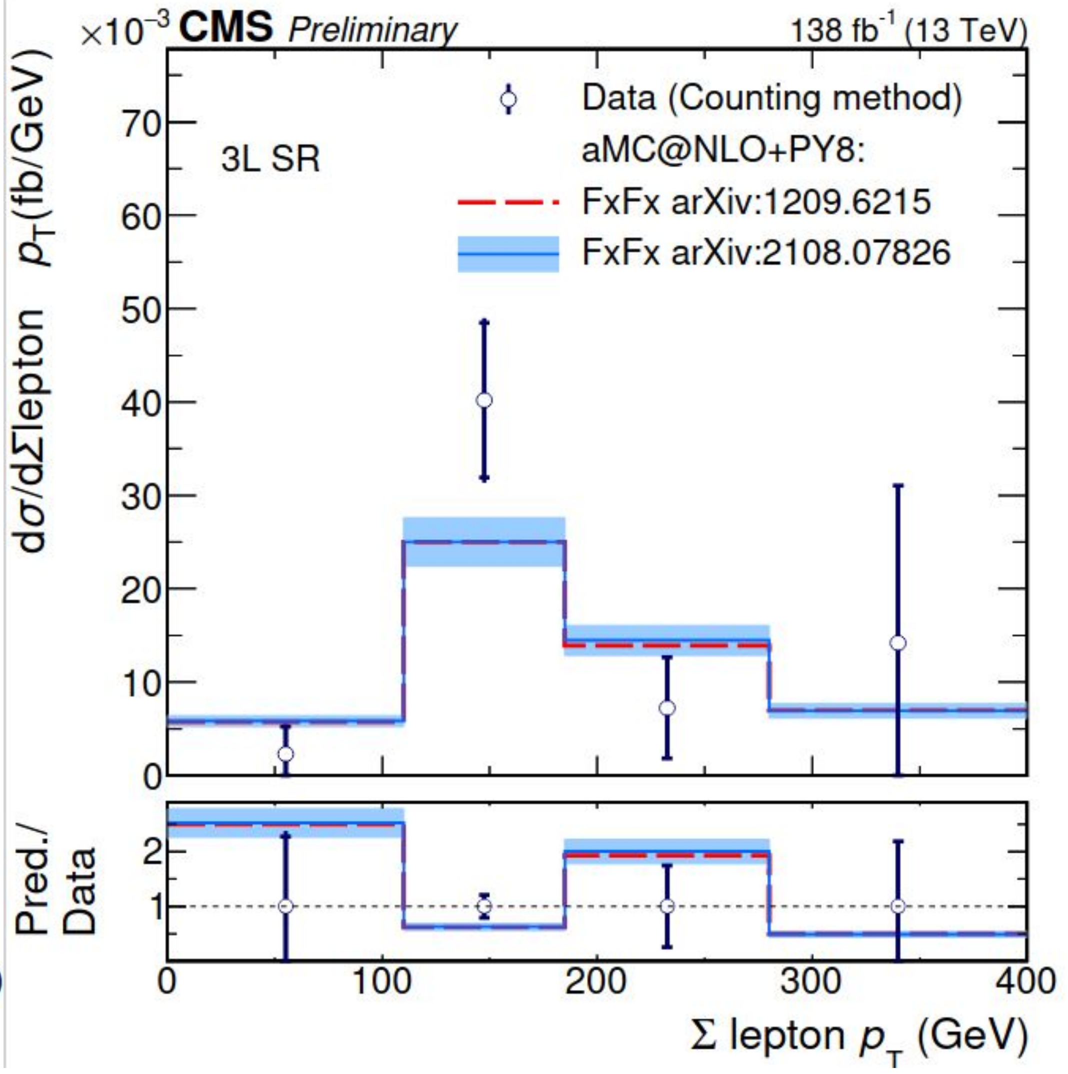


Uncertainties

	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	✓	—

ttW differential 3 lepton





ttW state of the art MC

NLO QCD FxFx@2j + NLO EWK

● MadGraph with new FxFx merging [JHEP11 (2021) 029]

● treats EWK jets by ME below merging scale