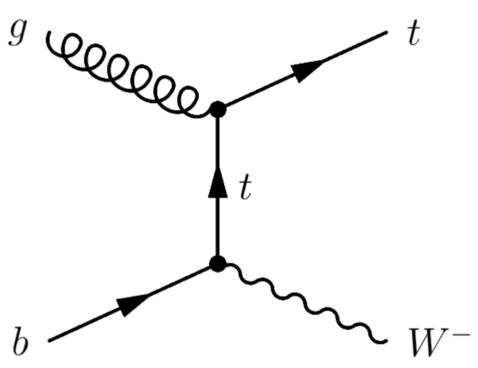

tW inclusive and differential cross section measurements at 13.6 TeV

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ON BEHALF OF THE CMS COLLABORATION

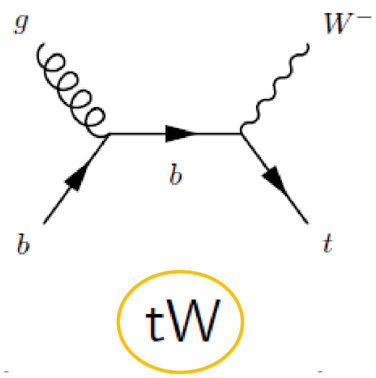
LHC TOP WG meeting 24-26 April 2024

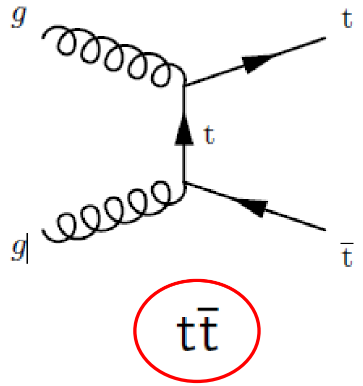
Overview

- **Objective**: perform the first **inclusive and differential** cross section measurements at 13.6 TeV of the **tW** process using Run 3 data collected in 2022.
  - Integrated luminosity: $34.7\ \mathrm{fb}^{-1}$.
- First single top measurement performed in Run 3.
- **Main challenge:** irreducible **$t\bar{t}$** background largely dominates signal contribution.
- **$t\bar{t}$** was measured at 13.6 TeV using a smaller dataset of $1.21\ \mathrm{fb}^{-1}$ (2022 data): JHEP08(2023)204.
- Previous measurements:
  - JHEP 07 (2023) 046: Inclusive and differential cross section measurements of tW using full Run 2.
  - PAS TOP-19-003: Differential cross section measurements of tW using 2016 data.
  - JHEP 10 (2018) 117: Inclusive cross section measurement of tW using 2016 data.

Reference: PAS-TOP-23-008.

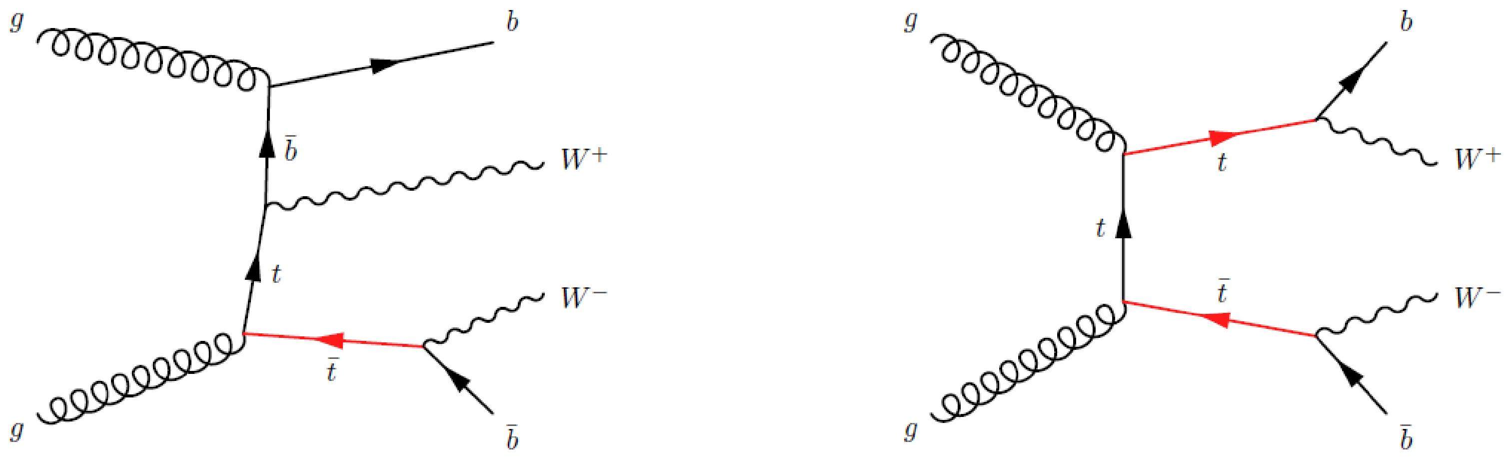
Result **presented** in **MoriondEW** 2024: Indico.





tW vs $t\bar{t}$

- **tW** interferes with $t\bar{t}$ at NLO in QCD → DR and DS schemes used to define **tW** to avoid double counting of diagrams.



- The matrix element for the final state WWbb: $|\mathcal{M}_{WWb\bar{b}}|^2 = |\mathcal{M}_{\text{singly}}|^2 + |\mathcal{M}_{\text{doubly}}|^2 + 2Re\left(\mathcal{M}^*_{\text{singly}}\mathcal{M}_{\text{doubly}}\right)$
- Besides the nominal sample of tW generated with powheg-pythia8 with the **DR** method we consider (for the differential measurement comparisons):
  - Powheg DS-pythia8, Powheg DR-Herwig7, amcatnlo DR-pythia8, amcatnlo DR2-pythia8, amcatnlo DS-pythia8 and amcatnlo DS dyn.-pythia8.

tW: Kinematic Selection

- Summary of the **object selection**:

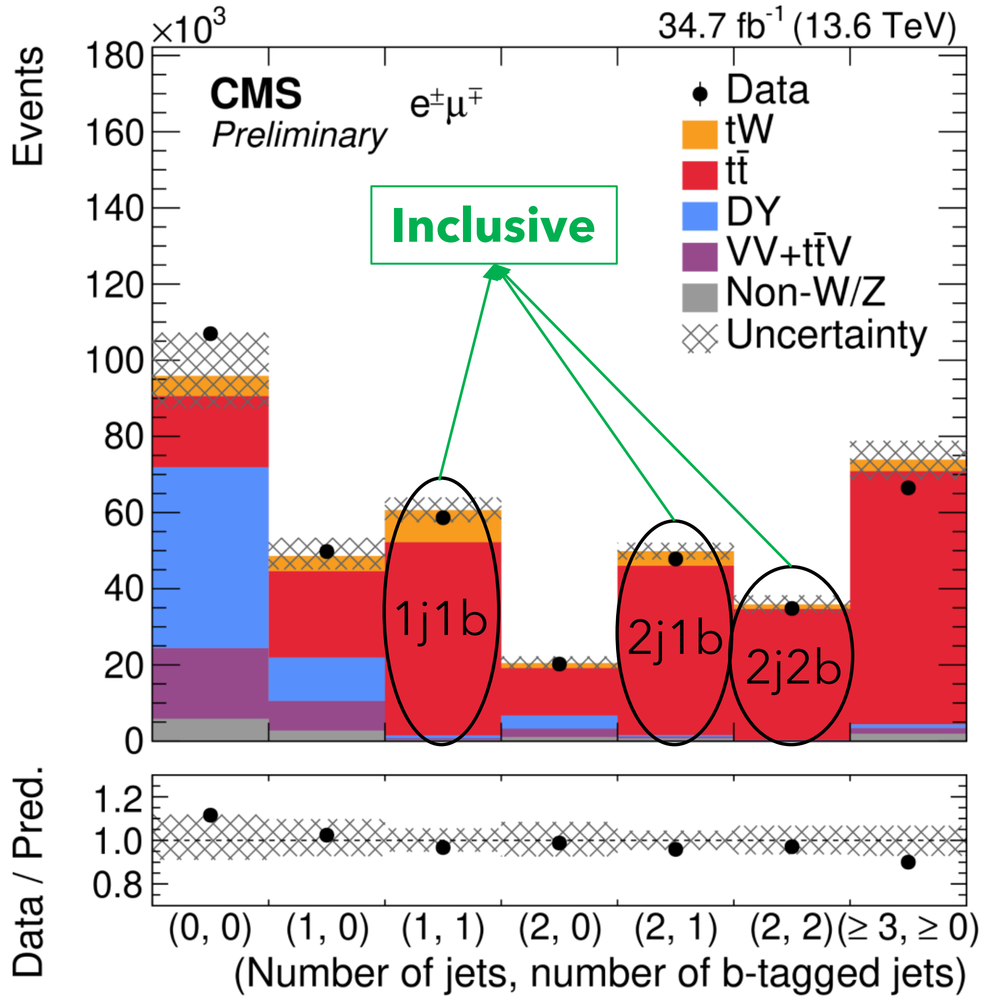
Leptons	Jets	MET	b tagging
$p_T > 20$ GeV & $\|\eta\| < 2.4$ Tight ID Cut-based (electrons: JINST 16 (2021) P05014, muons: JINST 13 (2018) P06015)	$p_T > 30$ GeV & $\|\eta\| < 2.4$ Tight ID for Puppi Jets (JINST 15 (2020) P09018)	Puppi MET(JINST 15 (2020) P09018)	ParticleTransformer (arXiv:2202.03772)

- We define **loose jets** with the same selection as the main jets but with $p_T \ \varepsilon \ [20, 30]$ GeV.

- **Event selection:**
  - **At least two leptons in the event.**
  - Leading lepton $p_T > 25$ GeV.
  - All lepton pairs must satisfy $m(\ell_1, \ell_2) > 20$ GeV.
  - Channel:
    - $\boldsymbol{e^{\pm}\mu^{\mp}}$(the two leading leptons must be an electron and a muon of opposite charge).

Inclusive measurement - strategy

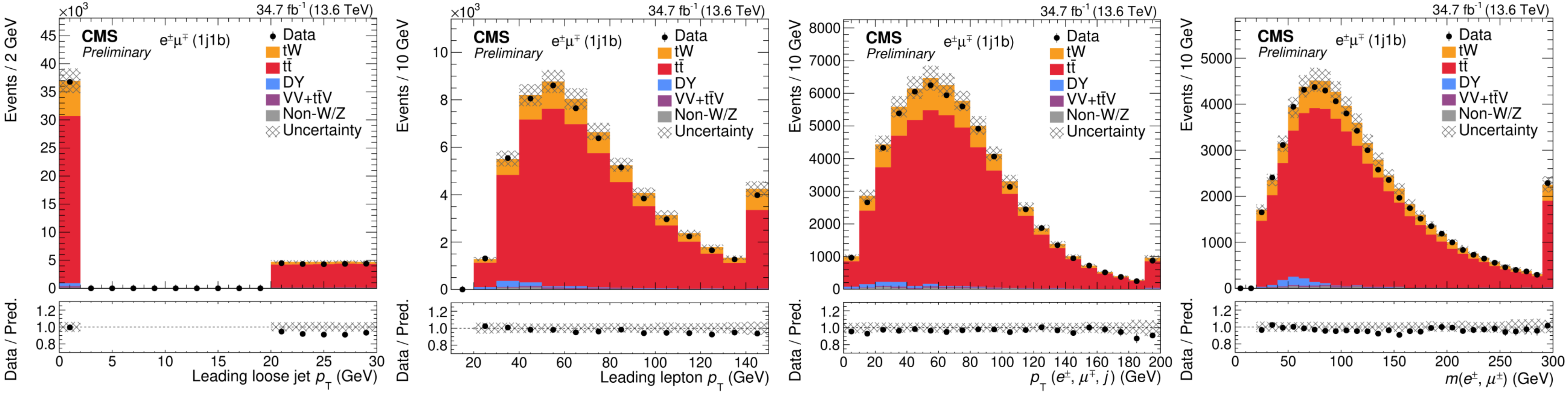
- **Inclusive** measurement:
  - **1j1b** (SR).
  - **2j1b** (SR).
  - **2j2b** (tt̄ CR).
- A ML fit to extract the inclusive cross section is performed to the following distributions:
  - **1j1b**: Random Forest (RF) multiclassifier to discriminate DY vs tt̄ vs **tW**.
  - **2j1b**: RF multiclassifier to discriminate tt̄ semileptonic vs tt̄ vs **tW**.
  - **2j2b**: subleading jet p_T.



Inclusive measurement -MVAs

- **8 variables are selected for each RF based on**:
  - Good discriminating power.
  - Data/MC agreement.
    - The agreement between the observed data and the simulation is measured using a goodness-of-fit test based on the saturated model. If the p-value is under 5%, the variable is rejected.

- For the RF in the 1j1b region the **four most discriminating variables** are:



Uncertainties – Experimental and normalisation

- **Jet energy scale and resolution**: varying both within its p_T and η bin uncertainties.
- **Lepton and trigger**: varying the data-to-simulations SFs by their uncertainties.
- **Electron scale and smearing**: the momenta of the electrons is varied by their uncertainties, taken from the electron scale and smearing corrections.
- **Luminosity** (1.4%) LUM-22-001 and **pileup** (varying $\pm 4.6\%$ the pp inelastic cross section).
- **Unclustered energy**: the effect from unclustered energy from the calorimeters is taken into account through the momentum resolution of the various PF candidates.
- **b-tagging** and **mistagging**: varying the data-to-simulations SFs by their uncertainties.
- $t\bar{t}$: 3.5% (from JHEP08(2023)204).
- VV, $t\bar{t}$V: 50% (from JHEP07(2023)046).
- DY: 10% (from JHEP07(2023)046).
- Non-W/Z (W+jets, $t\bar{t}$ semileptonic): 50% (from JHEP07(2023)046).

Uncertainties – modelling I

- All uncertainties in this slide are considered for $t\bar{t}$ and **tW**.

  We will indicate whether they are correlated or uncorrelated between $t\bar{t}$ and **tW**.

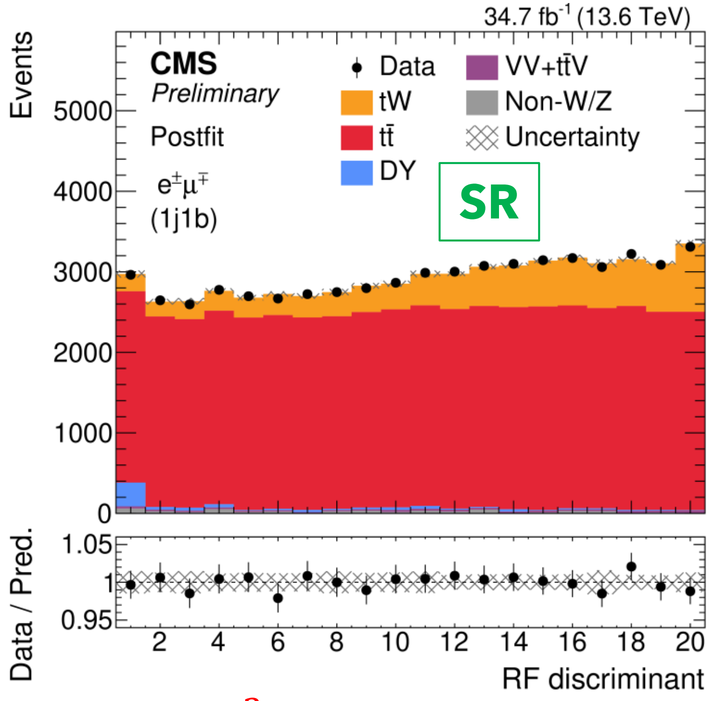
- **PDF+α_S** (correlated)**:** determined by reweighting the samples according to the 100 NNPDF3.1 replicas. For PDFs the variations are summed quadratically to obtain its uncertainty. α_S variations are not added to the PDFs and and they are considered as a separate nuisance.
- **μ_R/μ_F scales** (uncorrelated)**:** we take the difference w.r.t. scaling μ_R and μ_F by 2 and 0.5 relative to their common nominal value. We take separate nuisances for μ_R and μ_F.
- **UE** (correlated)**:** using dedicated samples that vary the Pythia parameters that tune the measurements to the UE.
- **CR** (correlated)**:** using various models (CR1/QCD-inspired, CR2/gluon move and with early resonance decays activated/ERDon). The different models are included as separate nuisances.
- **m_{top}** (correlated)**:** using ± 3 GeV varied samples and extrapolated to ± 1 GeV assuming linearity.
- **ISR** (uncorrelated)**:** using the dedicated weights that vary the PS scales by a factor of two.
- **FSR** (correlated)**:** using the dedicated weights that vary the PS scales by a factor of two.

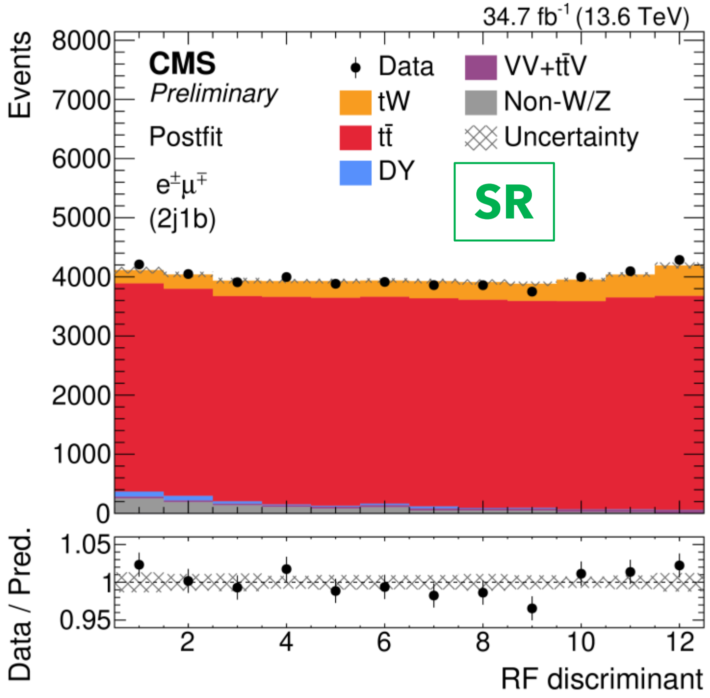
Uncertainties – modelling II

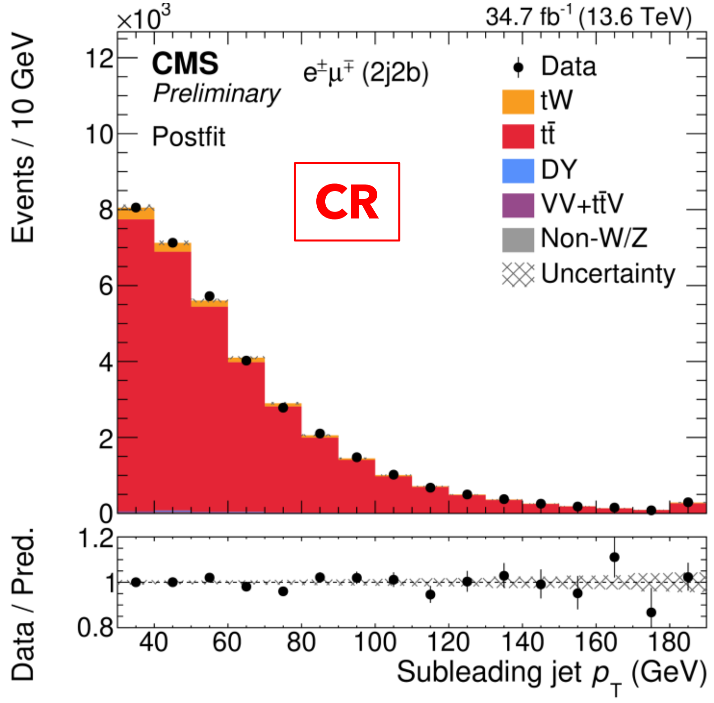
- **ME/PS matching** (h_{damp}) considered for $t\bar{t}$ only**:** using dedicated samples that vary the Powheg h_{damp} parameter by its uncertainty. The nominal value used for h_{damp} (250 GeV) is taken as the rounded average of ATLAS (258.75 GeV) and CMS (237.8775 GeV) values. For the variations (158 GeV and 418 GeV), they are obtained doing a translation of the old values (150.7305 GeV, 237.8775 GeV and 397.6125GeV).
- **Top quark p_T modelling** considered for $t\bar{t}$ only**:** estimated by taking the difference between reweighted and unweighted distributions. Using data-to-NLO weights derived following result from: Phys. Rev. D 95, 092001 and PAS-TOP-16-011.
- **DS** considered for **tW** only**:** using dedicated samples, we take the difference w.r.t. nominal (i.e. DR) values.

Inclusive cross section measurement

- To discriminate between **tW** and $t\bar{t}$ events, two RFs, one in the **1j1b** region and the other in the **2j1b** region, are trained using the kinematic properties of the events.
- To extract the signal, a ML fit is performed using the two RF outputs and the subleading jet p_T in the **2j2b** region.







aN^{3}LO

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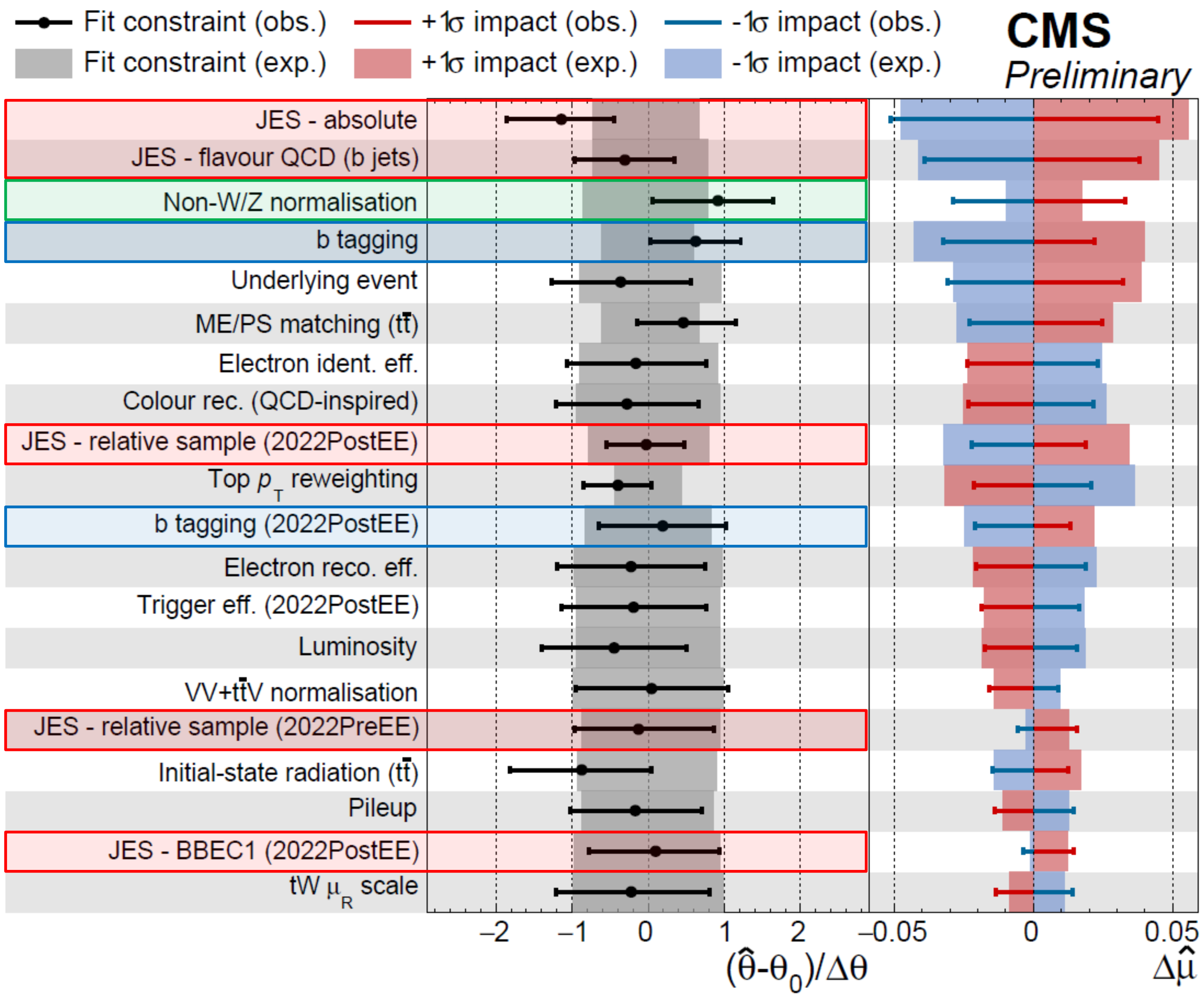
$$\sigma_{tW}^{SM} = 87.9^{+2.0}_{-1.9}(\text{scale}) \pm 2.4(\text{PDF} + \alpha_S)\ \text{pb}$$

$$\sigma_{tW}^{obs} = 84.1 \pm 2.1(\text{stat})^{+9.8}_{-10.2}(\text{syst}) \pm 3.3(\text{lum})\ \text{pb}$$

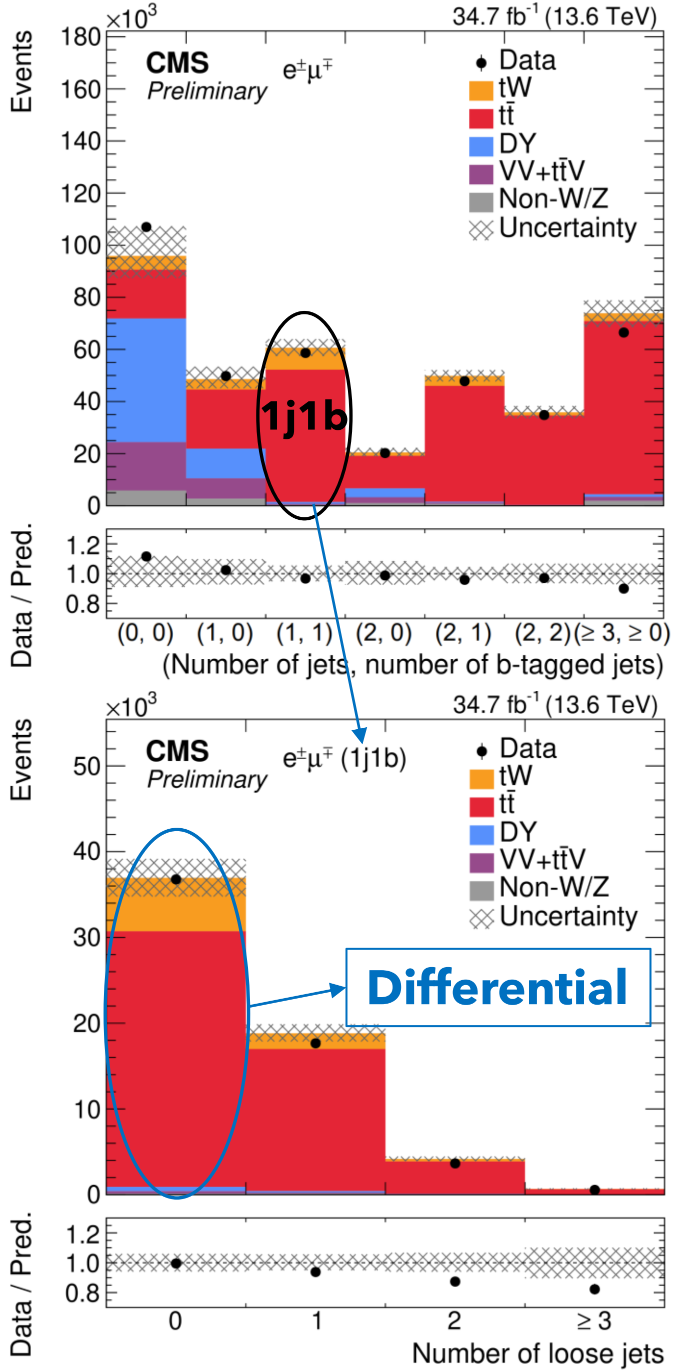
Inclusive cross section measurement

- Measurement dominated by **systematic** uncertainties.
- The main difference between $t\bar{t}$ and **tW** is the additional b jet that is present in $t\bar{t}$, thus:
  - The leading uncertainties are the ones associated with the energy of the jets and b tagging. But also, the normalisation of the second leading background: Non-W/Z (misidentified leptons).

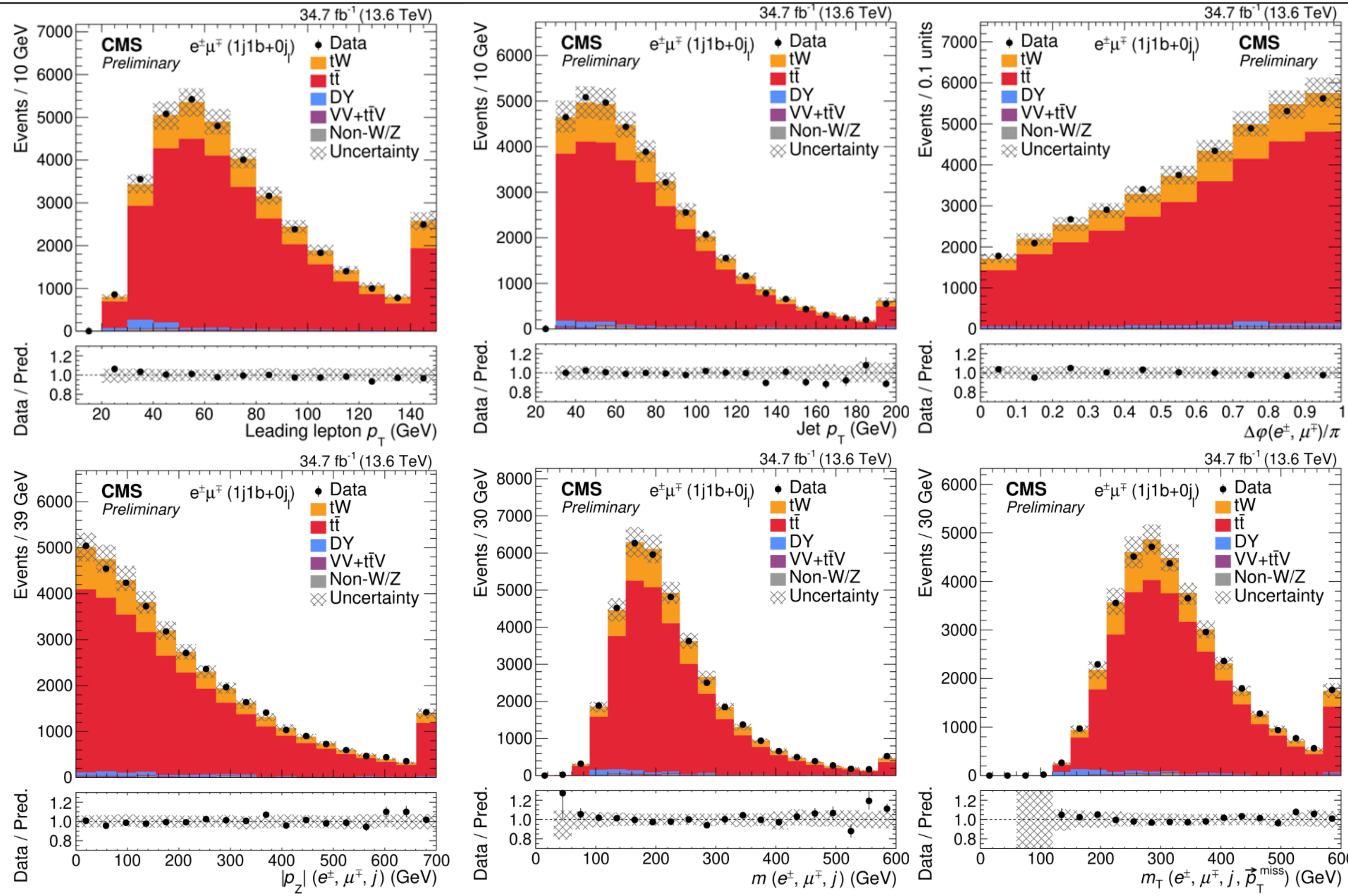


Differential measurements

- Measurement performed in the **1j1b** region **vetoing events with low energy jets (loose jets)**.
- Signal extraction is performed by **background subtraction**.
- Unfolding from detector level to particle level is performed using **TUnfold** (JINST 7 (2012) T10003).
- We measure the following observables:
  - p_T of the leading lepton.
  - p_T of the jet.
  - $\Delta\phi(e, \mu)$.
  - $p_z(e, \mu, \text{jet})$.
  - $m(e, \mu, \text{jet})$.
  - $m_T(e, \mu, \text{jet}, p_T^{\text{miss}})$.

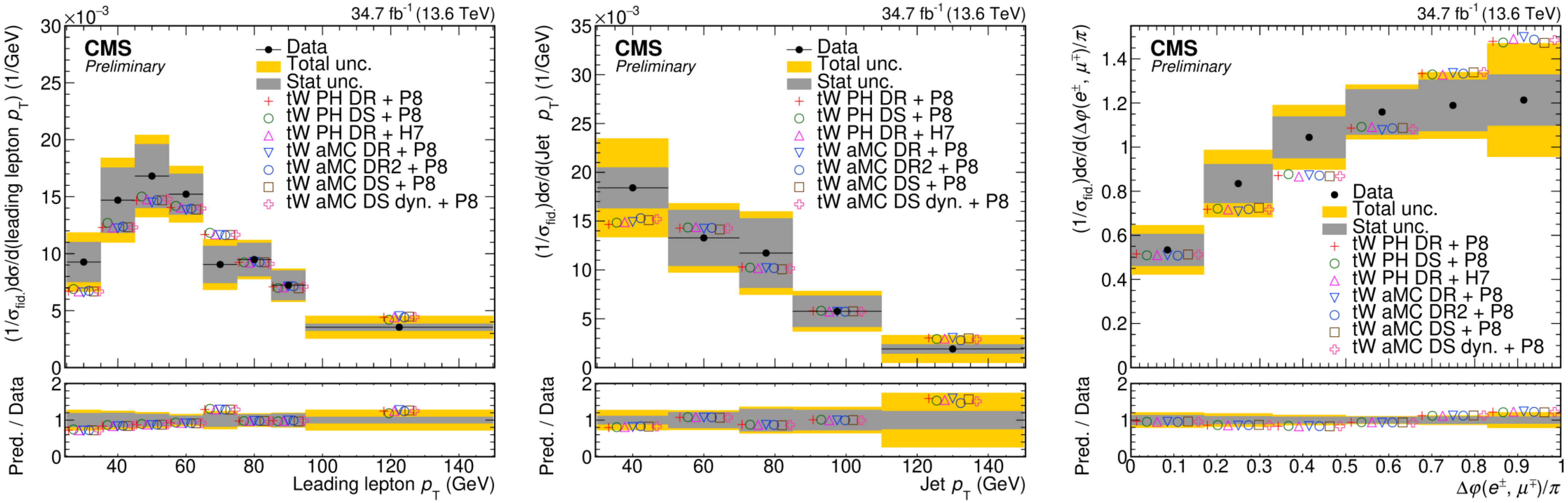


Differential measurements – data/MC comparison



Differential measurements – results

- Results are normalised to the fiducial cross section and bin width.
- There is **good agreement** between the measurements and the predictions from the different event generators:
  - `POWHEG` vs `MADGRAPH5_aMC@NLO`.
  - `PYTHIA8` vs `HERWIG7`.
  - Different schemes to treat the interference between **tW** and $t\bar{t}$.



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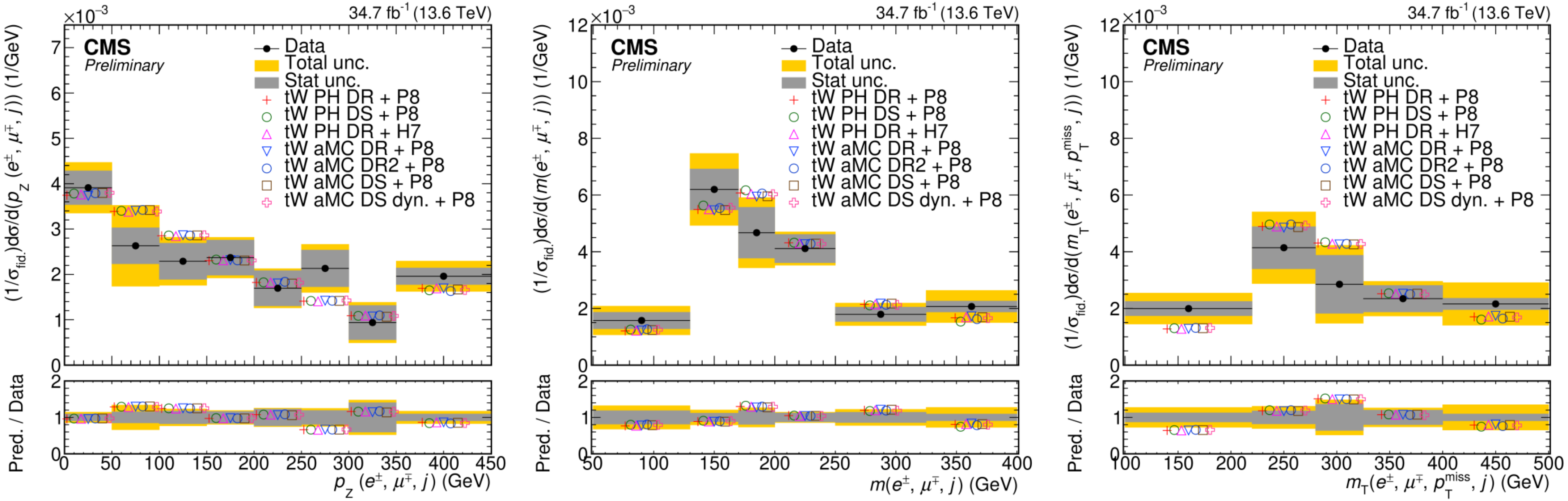


Differential measurements – GOF test

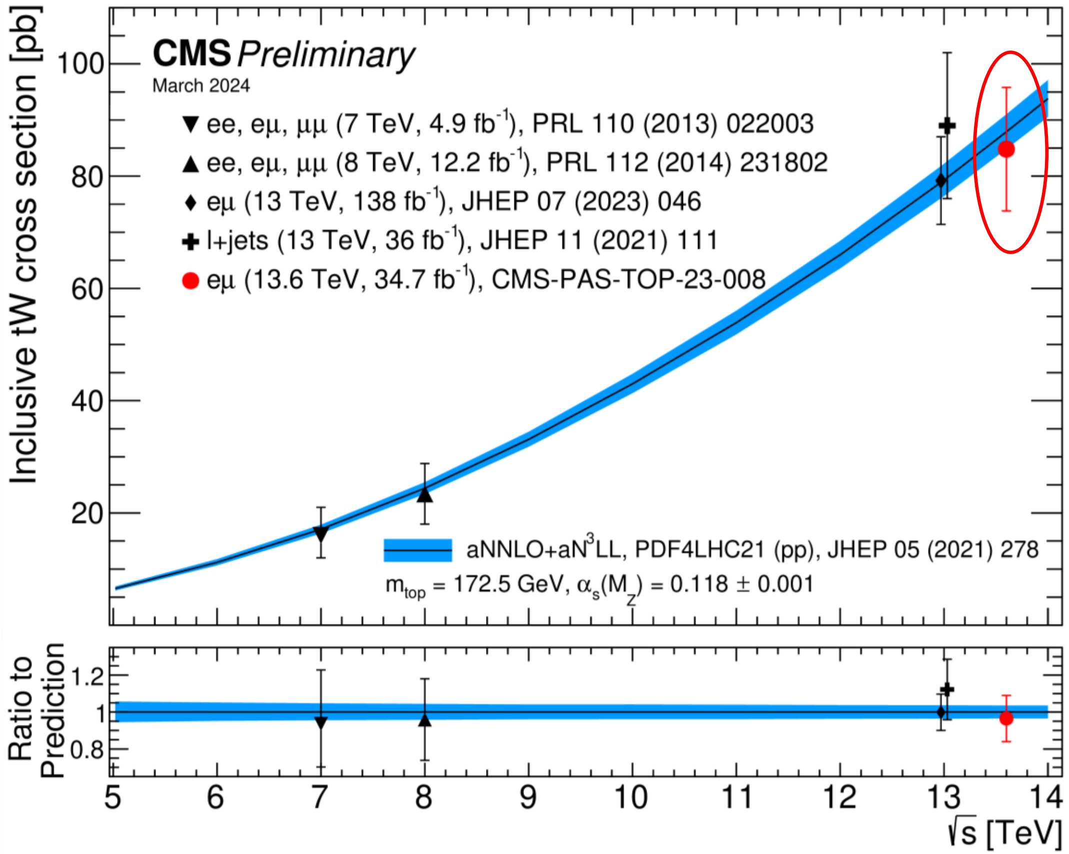
- We perform a χ^2 GOF test for the differential distributions to compare the observed result with the different MC generators.
- Performed using the full covariance matrix as well as statistical uncertainties of the predictions.
- We tabulate the p-values of the test:

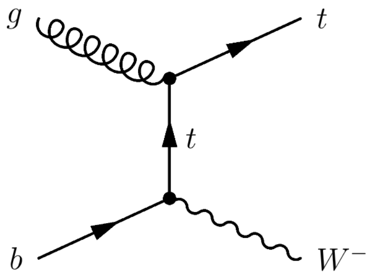
Variable	PH DR + P8	PH DS + P8	PH DR + H7
Leading lepton p_{T}	0.96	0.98	0.96
Jet p_{T}	0.96	0.97	0.97
$\Delta\varphi(\mathrm{e}^{\pm},\mu^{\mp})/\pi$	0.94	0.94	0.93
$p_{z}(\mathrm{e}^{\pm},\mu^{\mp},j)$	0.96	0.96	0.96
$m_{\mathrm{T}}(\mathrm{e}^{\pm},\mu^{\mp},j,\vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	0.78	0.75	0.79
$m(\mathrm{e}^{\pm},\mu^{\mp},j)$	0.95	0.93	0.95

Variable	aMC DR + P8	aMC DR2 + P8	aMC DS + P8	aMC DS dyn. + P8
Leading lepton p_{T}	0.94	0.96	0.95	0.96
Jet p_{T}	0.96	0.98	0.97	0.99
$\Delta\varphi(\mathrm{e}^{\pm},\mu^{\mp})/\pi$	0.93	0.93	0.94	0.93
$p_{z}(\mathrm{e}^{\pm},\mu^{\mp},j)$	0.96	0.96	0.96	0.96
$m_{\mathrm{T}}(\mathrm{e}^{\pm},\mu^{\mp},j,\vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	0.80	0.77	0.80	0.79
$m(\mathrm{e}^{\pm},\mu^{\mp},j)$	0.96	0.95	0.96	0.96

Summary

- The **first** inclusive and differential cross section measurements of the **tW** process at **13.6 TeV** have been presented: CMS-PAS-TOP-23-008.
- The measured inclusive cross section $\sigma_{tW}^{obs} = 84.1 \pm 2.1(\text{stat})^{+9.8}_{-10.2}(\text{syst}) \pm 3.3(\text{lum})$ pb is compatible with the SM prediction $\sigma_{tW}^{SM} = 87.9^{+2.0}_{-1.9}(\text{scale}) \pm 2.4(\text{PDF} + \alpha_S)$ pb (JHEP05 (2021) 278).
- With respect to the differential measurements, compatible results between the SM expectations and the measured cross sections are also observed.





Thanks!

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