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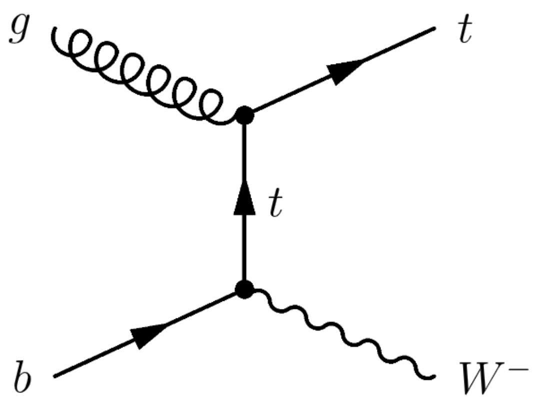

Measurement of inclusive and differential cross sections of tW at 13.6 TeV

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ON BEHALF OF THE CMS COLLABORATION

XVI CPAN DAYS

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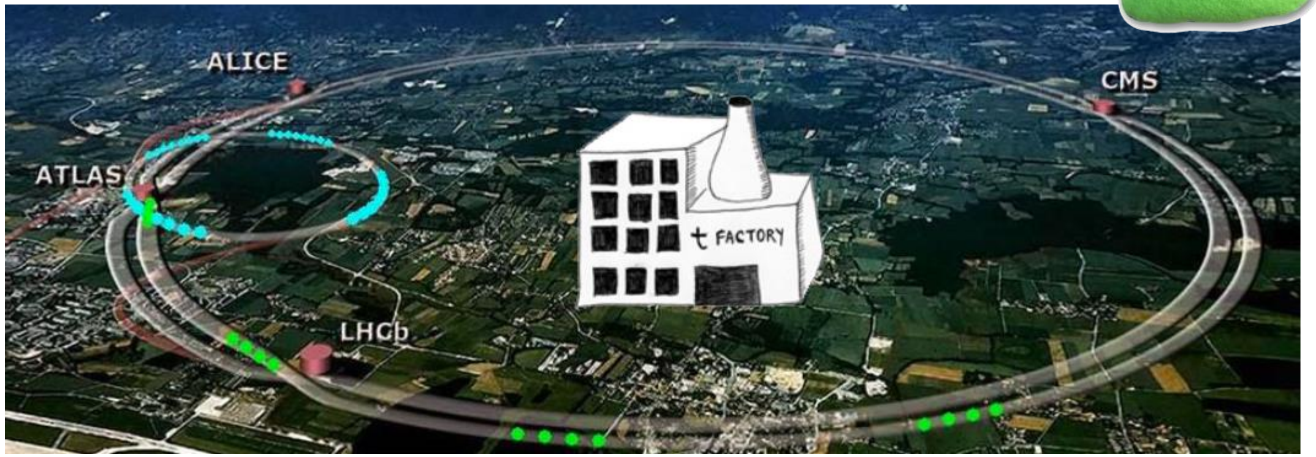
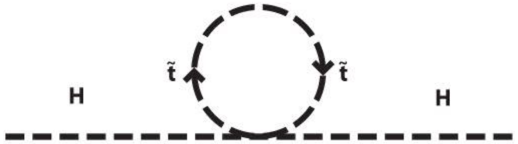
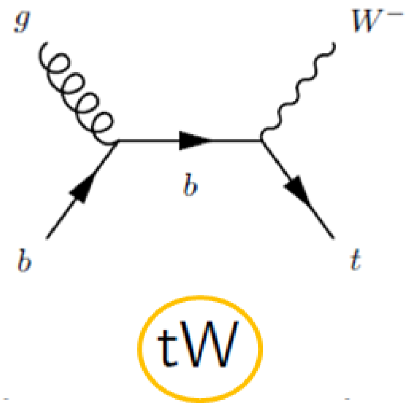
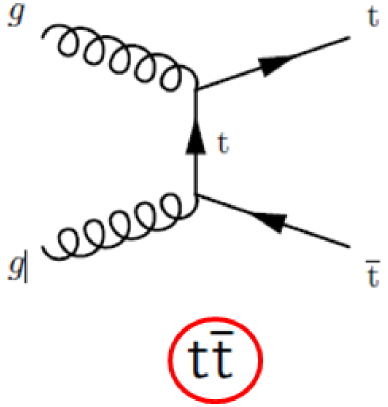
An introduction to the top quark

- **Top quark is heavy:**
  - The heaviest known fundamental particle, ~36 times heavier than the bottom quark.
  - Largest Yukawa coupling to the Higgs boson.
- **Top quark is unique:**
  - Extremely short lifetime 5×10^{-25} s.
  - Decays before hadronization.
- Many production modes:
  - **Top pair** (QCD), **single top** production (EW), but also…
  - They can be produced in association with bosons (W, Z, H, γ).
  - Even four top production!
- Top quark may play an important role in BSM physics.
  - Its SUSY partner can be fundamental to explain the Higgs mass.
  - Many top processes are sensitive to **EFT** operators.









Overview of the analysis

- **First** measurement of the **tW** process at $\mathbf{13.6\ TeV}$ and one of the first measurements done in Run 3 using the full 2022 dataset with $34.7\ \mathrm{fb}^{-1}$ of int. luminosity.
- **tW** has the second biggest cross section of single top production.

Reference: arXiv:2409.06444 (submitted to **JHEP**).

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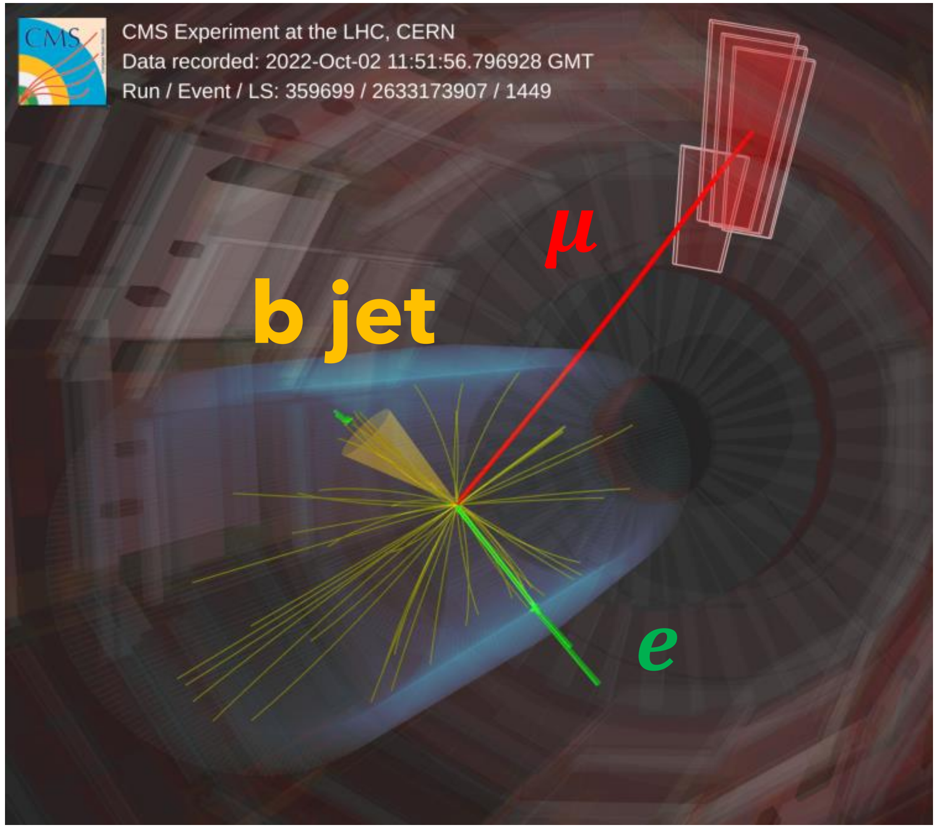
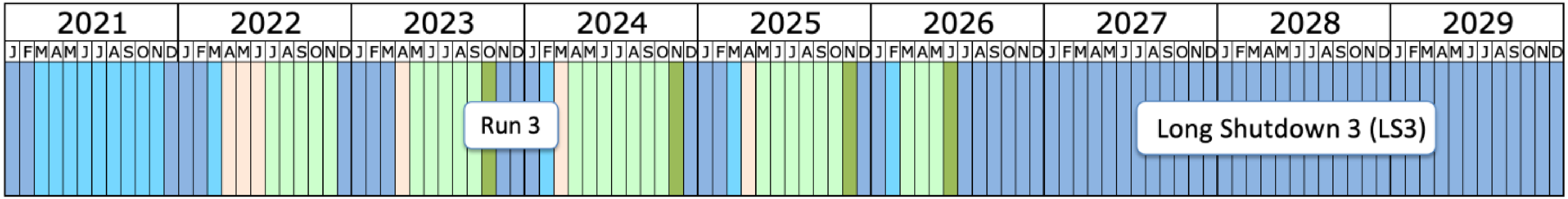
$$\sigma_{tW}^{SM}(13.6\ \mathrm{TeV}) = 87.9^{+2.0}_{-1.9}(\mathrm{scale}) \pm 2.4(\mathrm{PDF} + \alpha_S)\ \mathrm{pb}$$

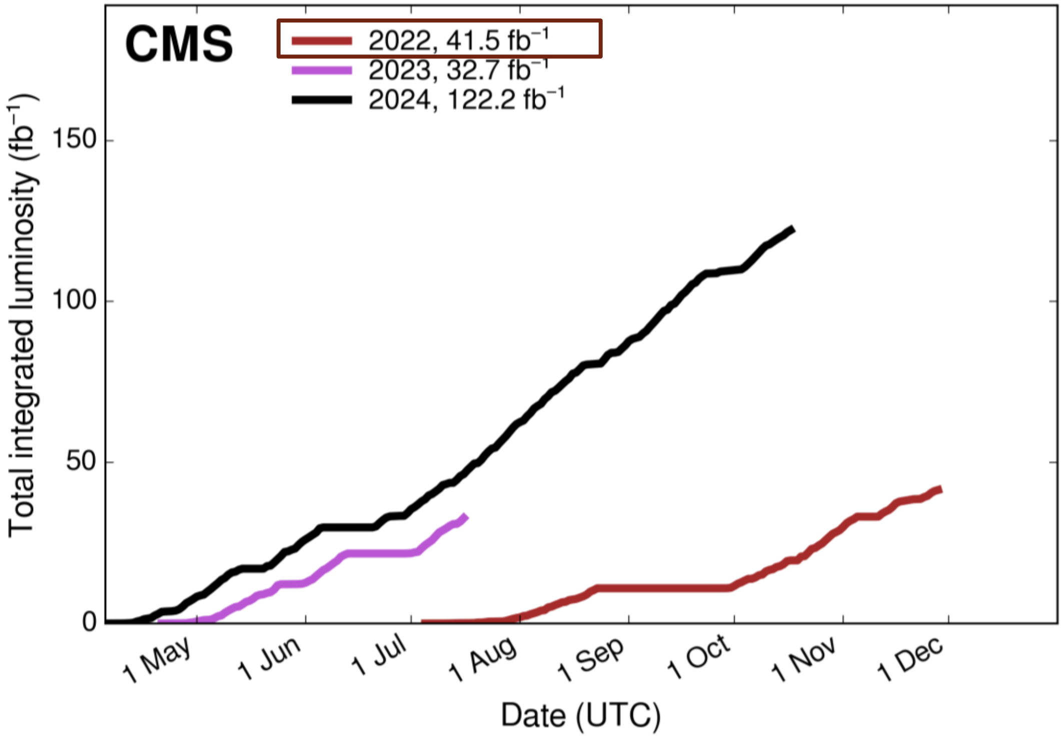
- **Main challenge:** irreducible $\mathbf{t\bar{t}}$ background largely dominates signal contribution.
  - ~10 times the **tW** cross section.
- $\mathbf{t\bar{t}}$ was measured at 13.6 TeV using a smaller dataset of $1.21\ \mathrm{fb}^{-1}$ (2022 data): JHEP08(2023)204.
  - Next step: measure single top processes.
- Previous measurement:
  - JHEP 07 (2023) 046: Inclusive and differential cross section measurements of tW using full Run 2.



Run 3 data taking

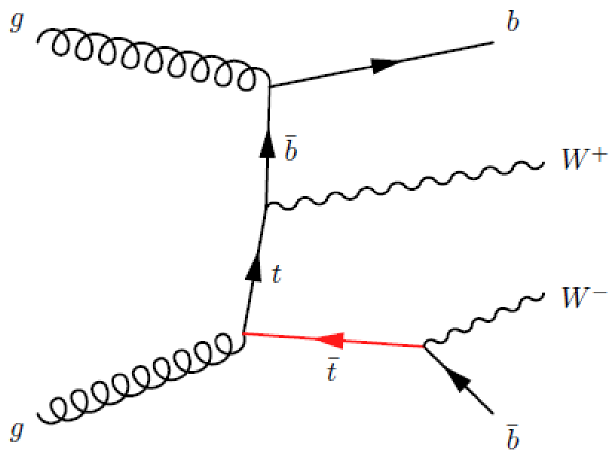


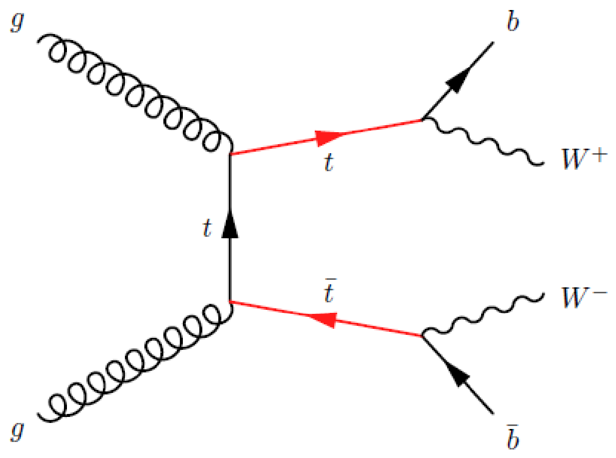
- Collisions: pp @ 13.6 TeV.
- Huge amount of data delivered so far **~196** $\mathbf{fb^{-1}}$.
  - For comparison, in Run 2 the LHC delivered **~164** $\mathbf{fb^{-1}}$.
- With the new data we can extend further our knowledge of the standard model.
  - First measurements are also important to test the **performance** of the **CMS** detector and the **calibrations**.
- The analysis presented here will make use of the 2022 dataset.
- Target final state of **tW** $\rightarrow e^{\pm}\mu^{\mp}\, b\,\mathrm{jet} + \mathrm{MET}$.
  - Involves all subdetectors.



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**:

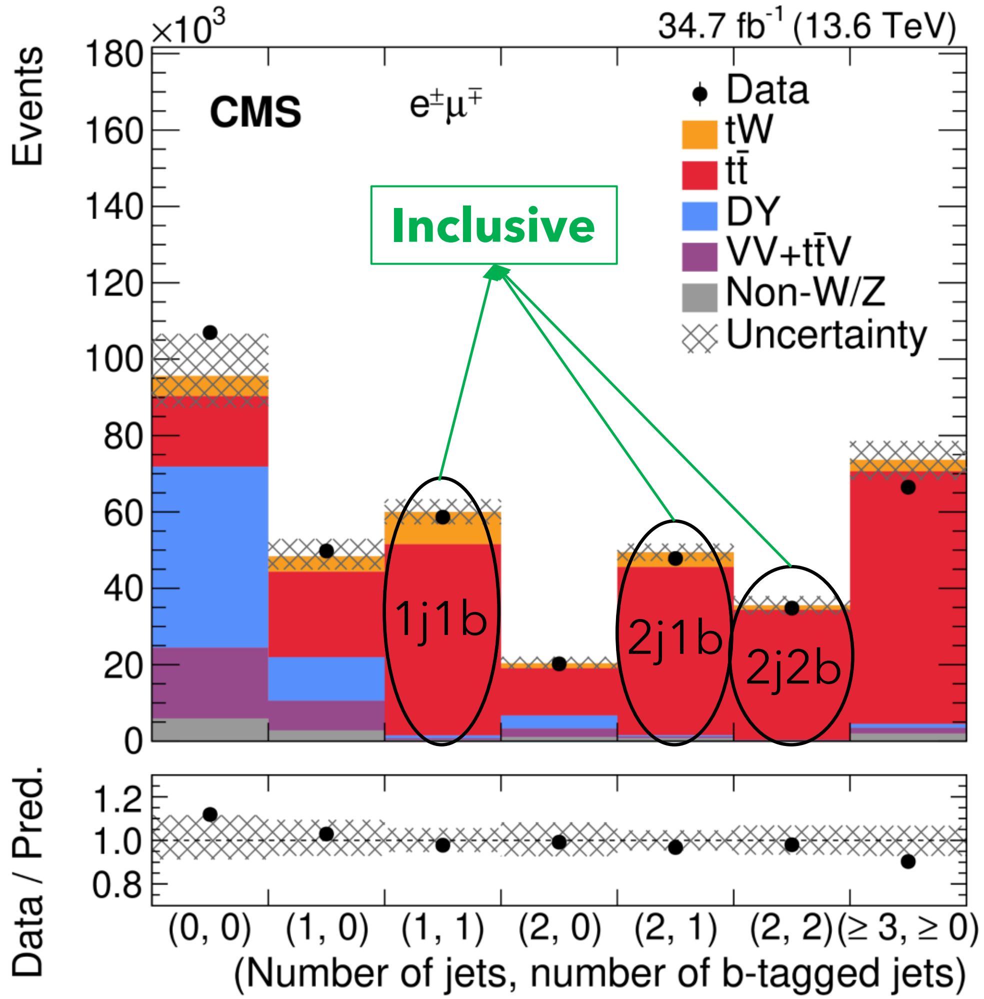
Leptons	Jets	MET	b tagging
$p_T > 20$ GeV & $\|\eta\| < 2.4$ Tight ID Cut-based (electrons: JINST 16 (2021) P05014, muons: JINST 13 (2018) P06015)	$p_T > 30$ GeV & $\|\eta\| < 2.4$ Tight ID for Puppi Jets (JINST 15 (2020) P09018)	Puppi MET(JINST 15 (2020) P09018)	ParticleTransformer (arXiv:2202.03772)

- 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).

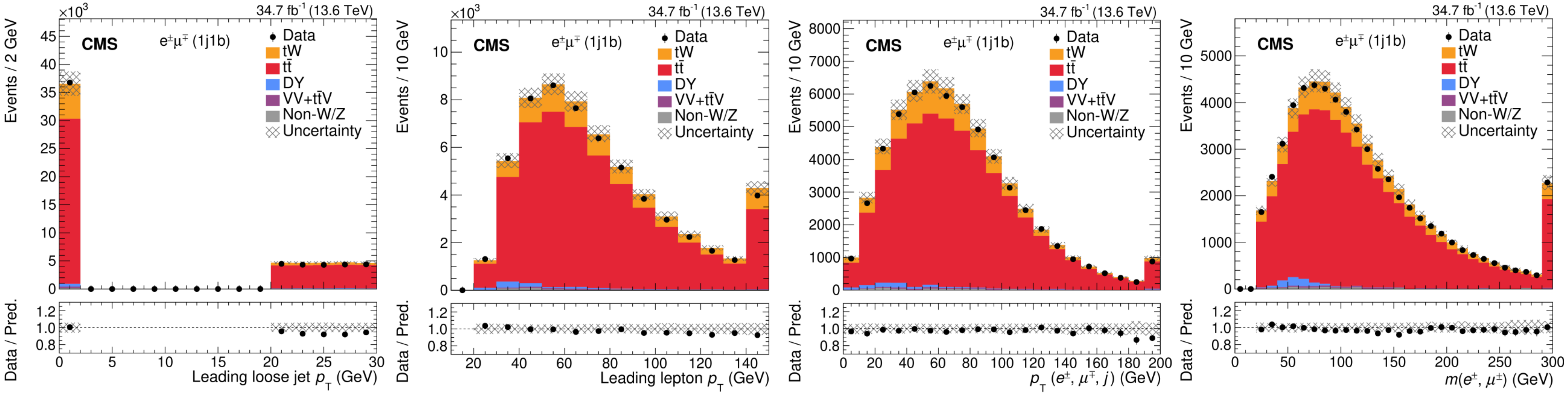
Inclusive measurement - strategy

- **Inclusive** measurement:
  - **1j1b** (SR).
  - **2j1b** (SR).
  - **2j2b** ($t\bar{t}$ 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 $t\bar{t}$ vs **tW**.
  - **2j1b**: RF multiclassifier to discriminate $t\bar{t}$ semileptonic vs $t\bar{t}$ vs **tW**.
  - **2j2b**: subleading jet p_T.



Inclusive measurement -MVAs

- **8 variables are selected for each RF based on**:
  - Good discrimination power.
  - Data/MC agreement.
- For the RF in the 1j1b region the **four most discriminating variables** are:



Uncertainties – Experimental and normalisation

- **Jet energy scale and resolution.**
- **Lepton and trigger** efficiencies**.**
- **Electron scale and smearing.**
- **Luminosity** (1.4%) LUM-22-001 and **pileup** (varying $\pm 4.6\%$ the pp inelastic cross section).
- **Unclustered energy.**
- **b-tagging** and **mistagging** efficiencies**.**

- $t\bar{t}$: 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): 15% (taken from an estimation performed with data in a region where the selected leptons have the same electric charge).

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**.

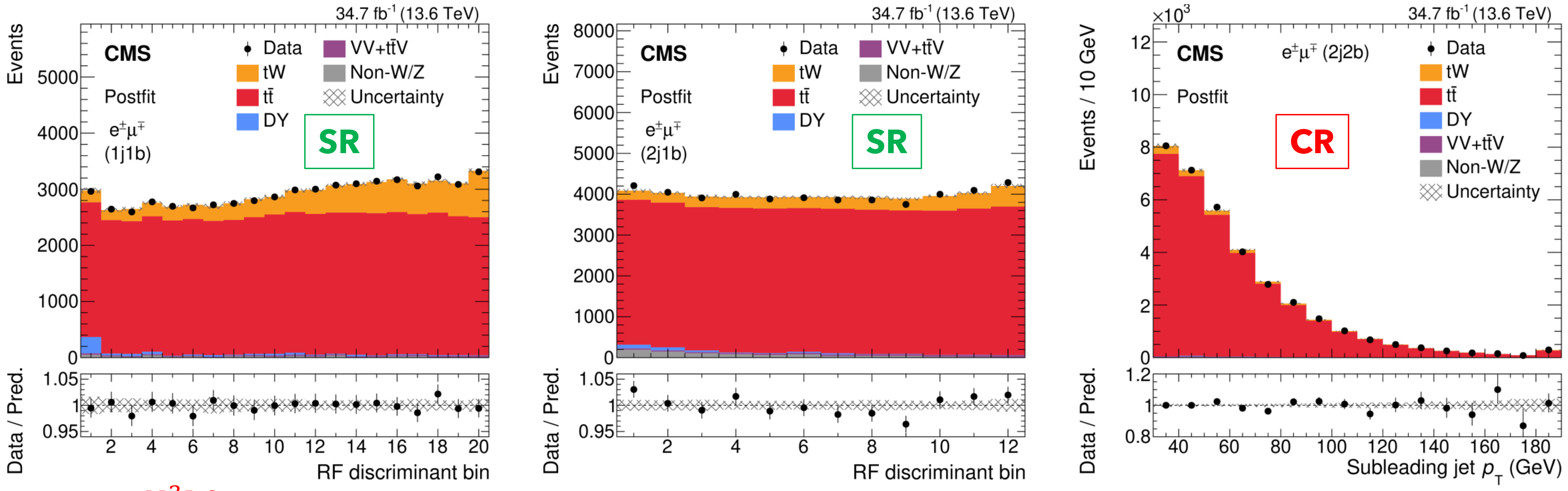
  - **PDF+α_S** (correlated)**:** determined by reweighting the samples according to the 100 NNPDF3.1 replicas.
  - **μ_R/μ_F scales** (uncorrelated)**:** vary the μ_R and μ_F scales by a factor of two. We take separate nuisances for μ_R and μ_F.
  - **UE** (correlated)**:** using dedicated samples that **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 ± 0.33 GeV (Phys. Rev. Lett. 132 (2024) 261902) assuming linearity.
  - **ISR** (uncorrelated)**:** vary the PS scales by a factor of two.
  - **FSR** (correlated)**:** vary the PS scales by a factor of two.

Uncertainties – modelling II

- **ME/PS matching** ($\boldsymbol{h_{damp}}$) considered for $t\bar{t}$ only**:** using dedicated samples that vary the Powheg h_{damp} parameter by its uncertainty (following common MC settings for ATLAS and CMS: CMS-NOTE-2023-004).
- **Top quark $\boldsymbol{p_T}$ modelling** considered for $t\bar{t}$ only**:** estimated by taking the difference between reweighted and unweighted distributions. Using NNLO-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 extract the signal, a ML fit is performed using the two RF outputs and the subleading jet p_T in the **2j2b** region.



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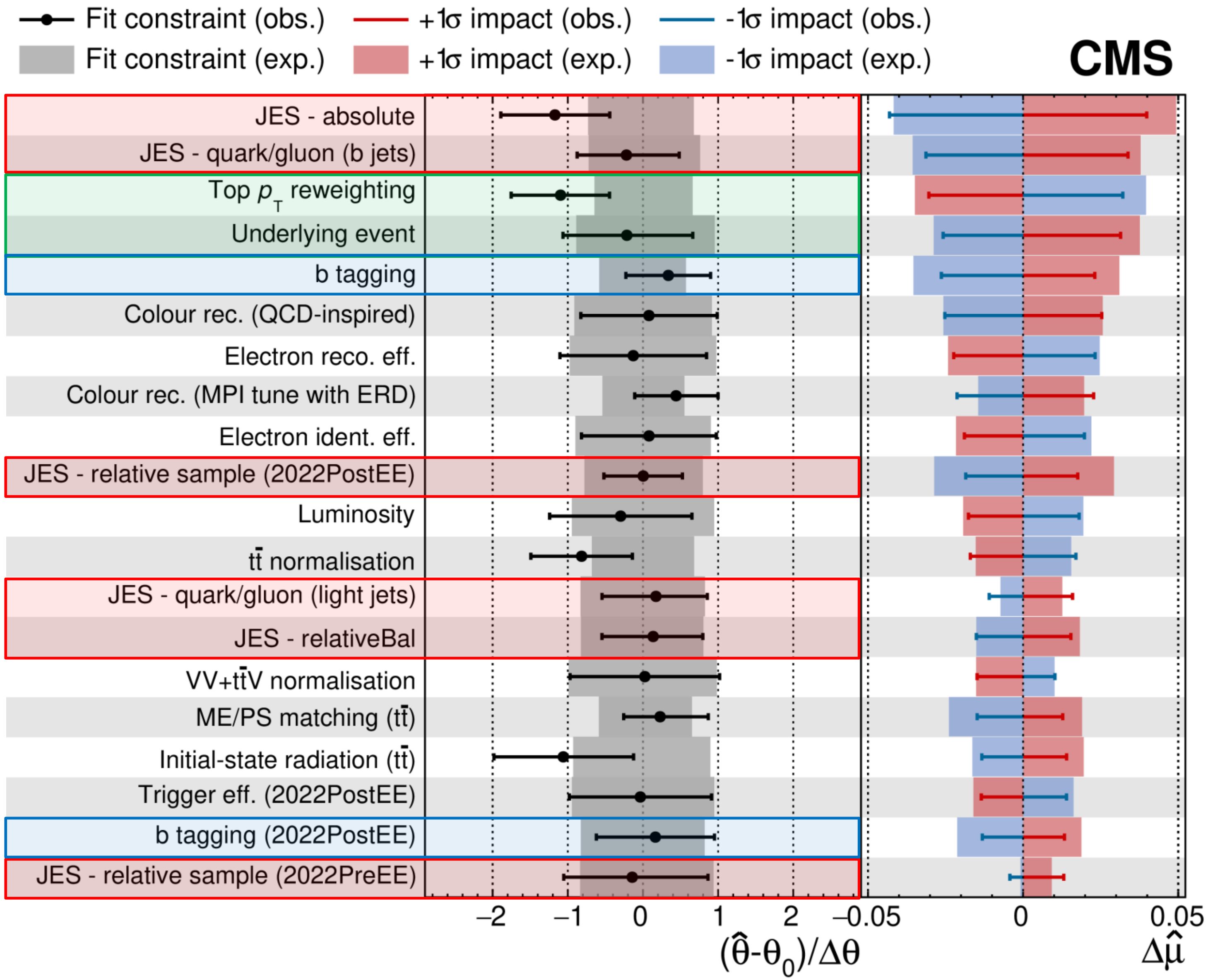
$$\sigma_{tW}^{SM} = 87.9^{+2.0}_{-1.9}(\text{scale}) \pm 2.4(\text{PDF} + \alpha_S)\ \text{pb}$$

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

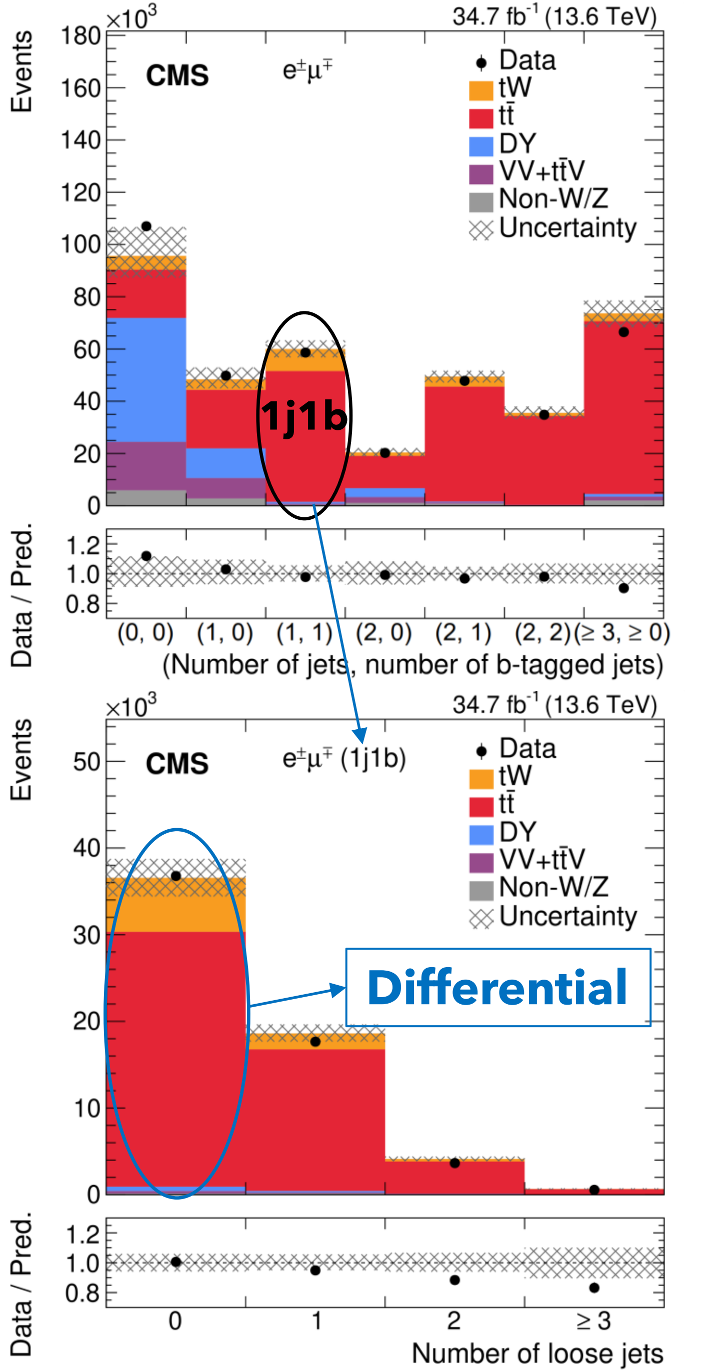
Inclusive cross section measurement

- 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 modelling uncertainties: top pT modelling and underlying event.

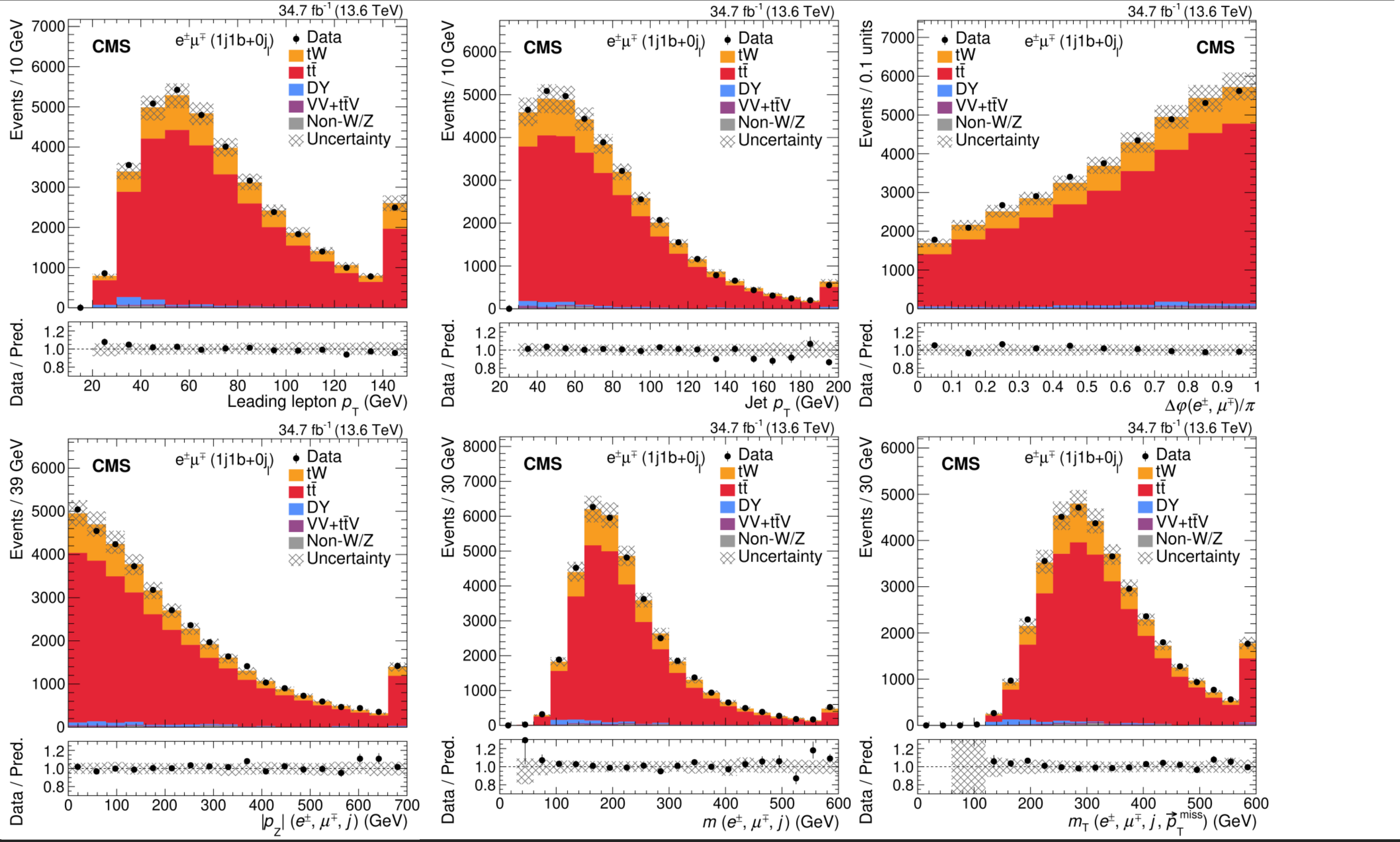


Differential measurements

- 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.
  - $\Delta\phi(e,\mu)$.
  - $p_z(e,\mu,\text{jet})$.
  - $m(e,\mu,\text{jet})$.
  - $m_T(e,\mu,\text{jet},p_T^{\text{miss}})$.

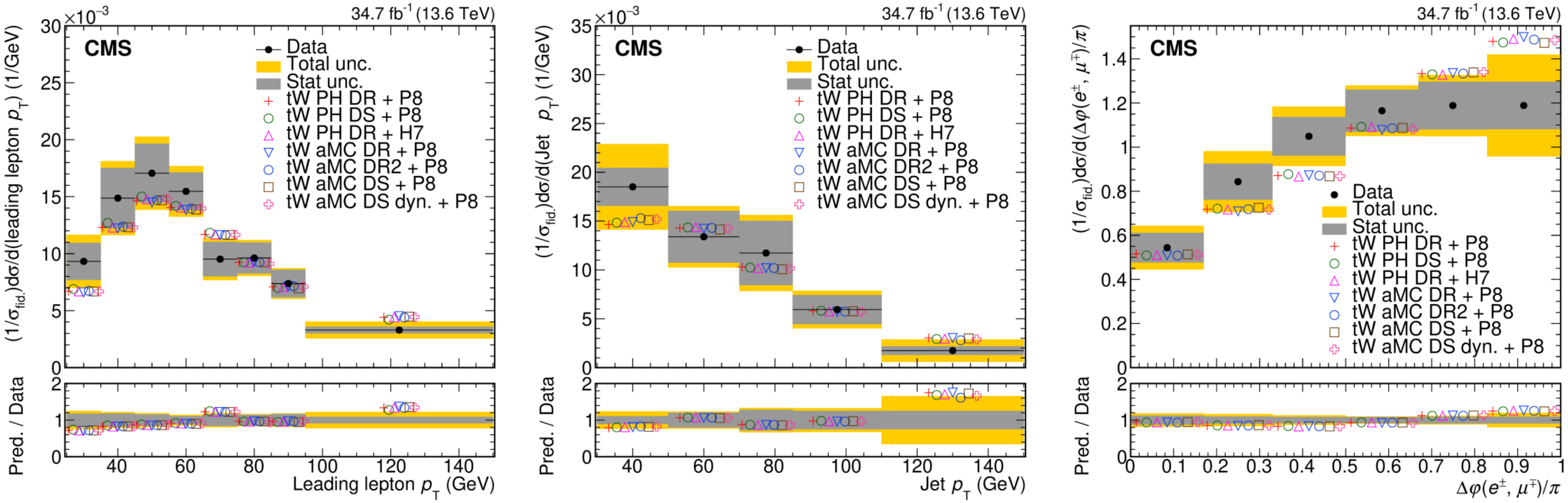


Differential measurements – data/MC comparison



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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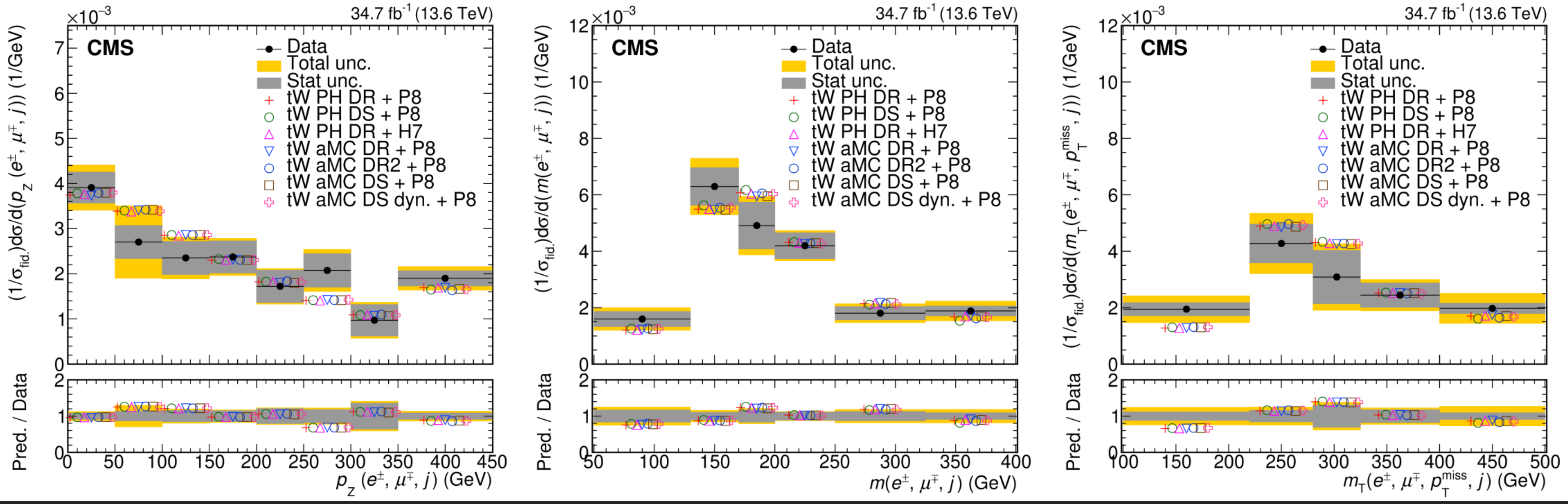
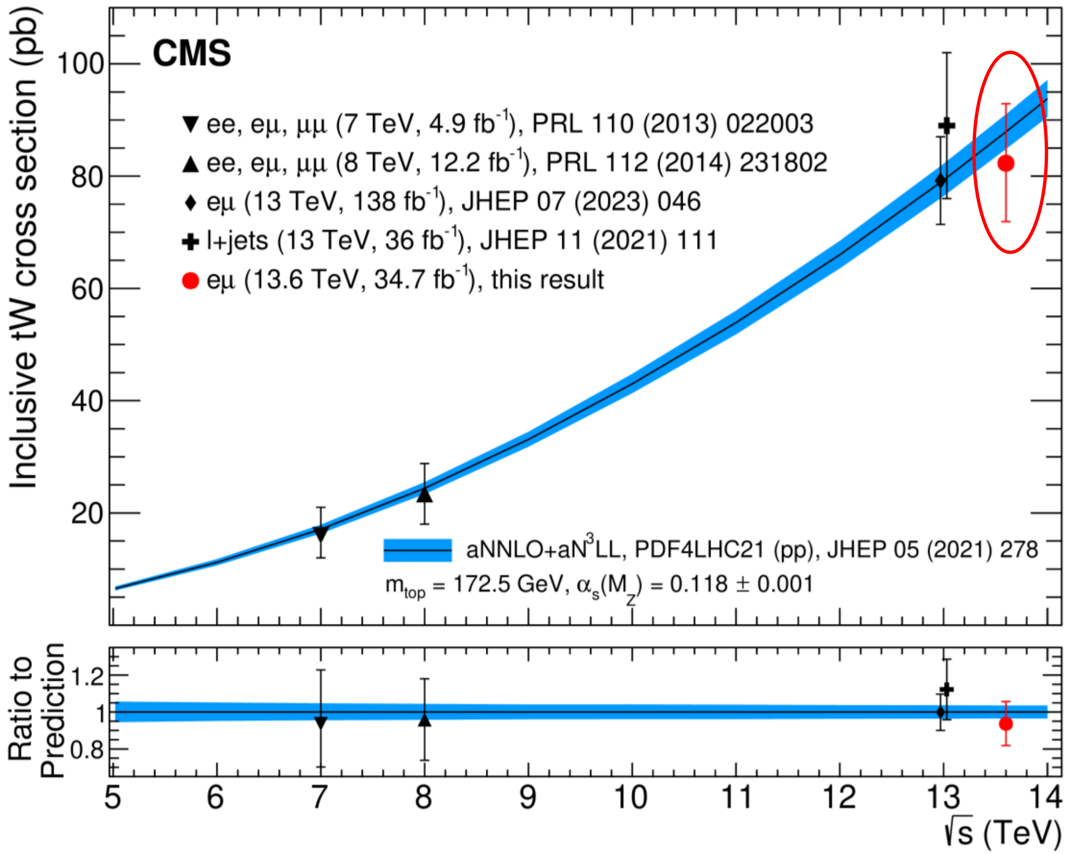
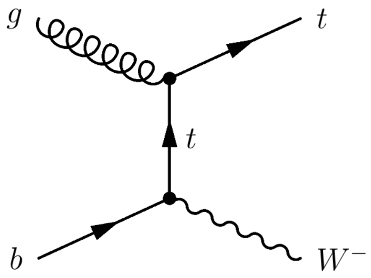


Summary

- The **first** inclusive and differential cross section measurements of the **tW** process at **13.6 TeV** have been presented: arXiv:2409.06444 .
- The measured inclusive cross section $\sigma_{tW}^{obs} = 82.3 \pm 2.1(\text{stat})^{+9.9}_{-9.7}(\text{syst}) \pm 3.3(\text{lum})$ 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!