8th Red LHC Workshop

28 – 30 May 2024 @ U. Complutense (Madrid)

Early top quark measurements with Run3 data by the CMS experiment

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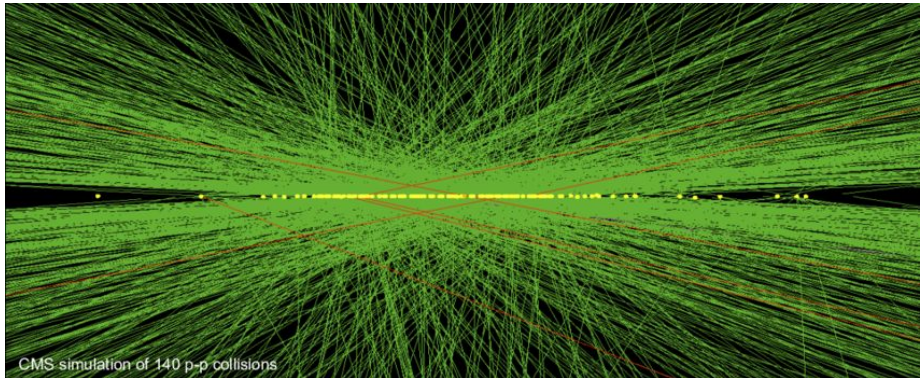
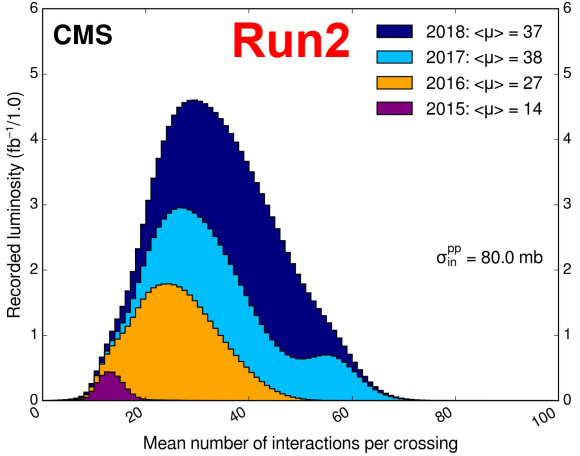
Universidad de Oviedo

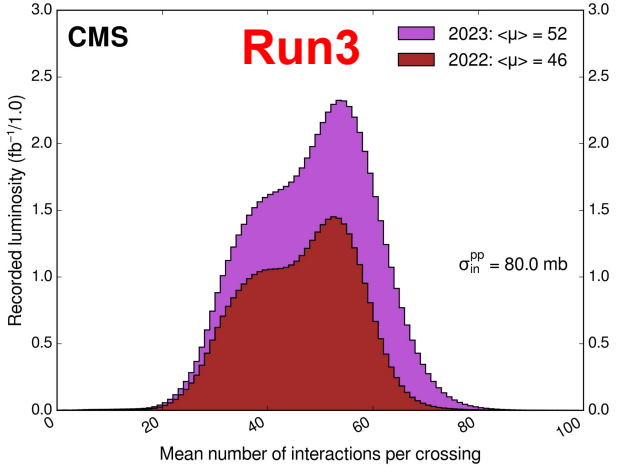
Grant PID2020-113341RB-100 funded by

LHC Run3 Data

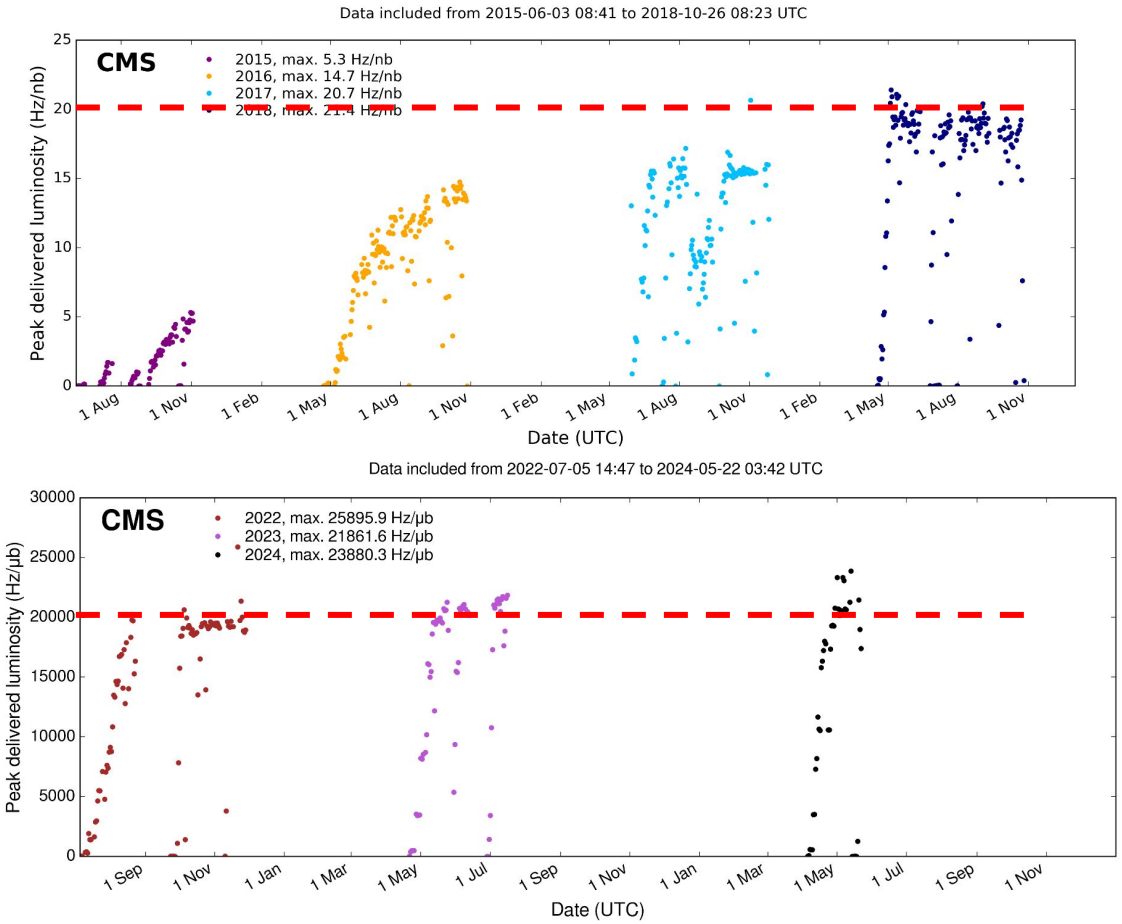
- During Run 3 the LHC is expected to run at higher instantaneous luminosity
  - Achieved by increasing the **number of interactions per bunch crossing**
- **Harder conditions:**
  - **Higher rate of background**
  - **Increased of pile-up**
- Higher rate of **interesting events** but more **challenging** to identify signal events







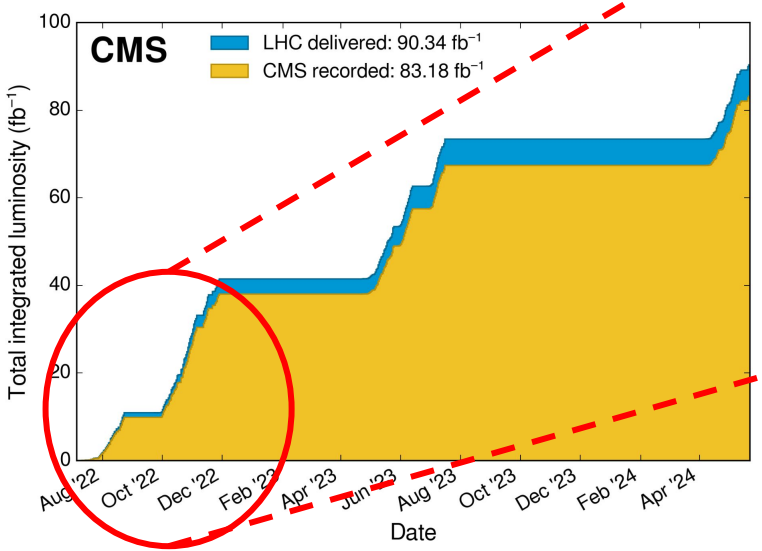
LHC Run2 v Run3 Instantaneous Luminosity



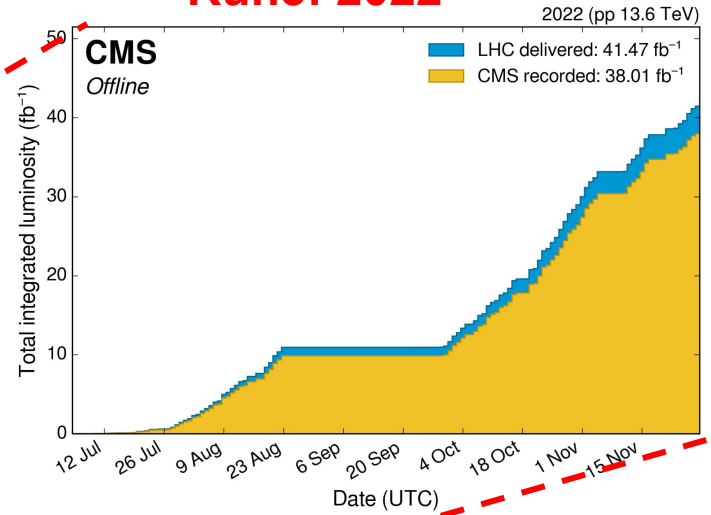
Run3 data-taking started at the maximum values of inst. luminosity reached at **Run2**

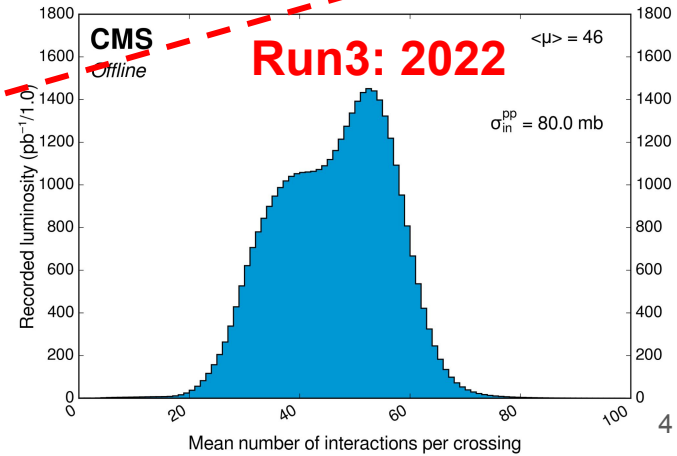
LHC Run3 Luminosity and Pile-up

Run3: 2022-2024



Run3: 2022





CMS and ATLAS Run3 Publications/Public Notes

CMS

- ttbar cross section JHEP 08 (2023) 204
- LLPs decaying to final states with a pair of muons JHEP 05 (2024) 047
- tW inclusive and differential cross section CMS-PAS-TOP-23-008
- W^+W^- inclusive and differential CMS-PAS-SMP-24-001 (Alicia's talk)
- Inclusive cross section of Z boson production CMS-PAS-SMP-22-017
- Low-mass LLPs decaying to displaced jets CMS-PAS-EXO-23-013
- Luminosity measurement in proton- proton collisions in 2022 at CMS CMS-PAS-LUM-22-001
- Development of the CMS detector for the CERN LHC Run 3 JINST 19 P05064

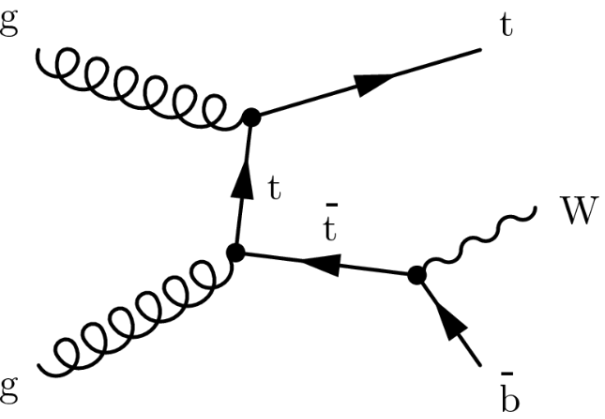
ATLAS

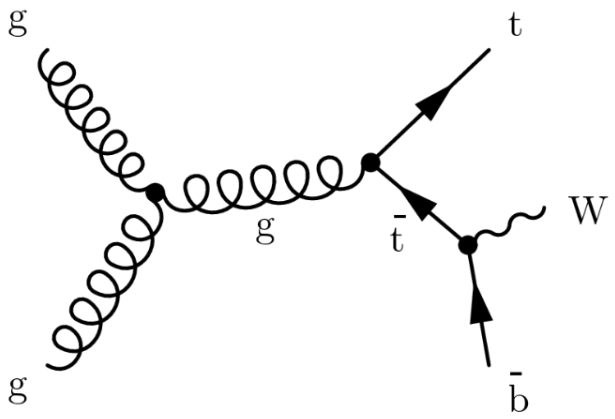
- The ATLAS detector for the LHC Run-3 ***Accepted by JINST***
- H→yy and H→ZZ→4l cross sections Eur. Phys. J. C 84 (2024) 78
- Measurement of tt cross section and tt/Z cross section ratio Phys. Let. B 848 (2024) 138376
- Measurement of ZZ production cross sections in the four-lepton final state ***Submitted to PLB***
- Measurement of vector boson production cross sections and their ratios **Accepted by PLB**
- Few more on performance, computing… (full list on back-up)

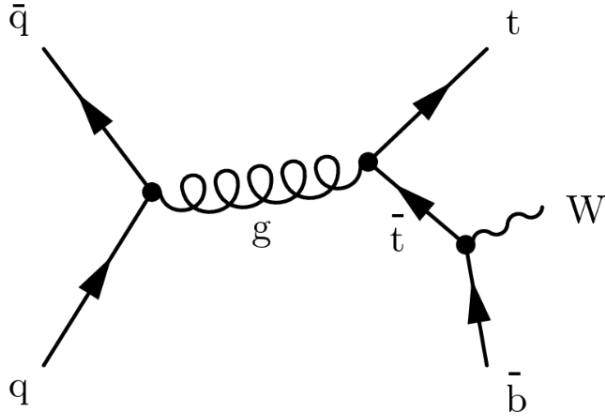
Motivation and Introduction

- Top quarks keep playing a key role on LHC physics
  - The most massive elementary particle
  - Relevant for EWK symmetry breaking
- Top quarks are produced in abundance at the LHC
- Dominant production modes:
  - **Pair (tt) production** via **QCD interactions**: ~10 Hz for 13.6 TeV
  - **Single production** via **EW interactions**:~1 Hz for 13.6 TeV
- **This talk focuses on:**
  - tt inclusive cross section JHEP 08 (2023) 204
  - tW inclusive and differential cross section CMS-PAS-TOP-23-008
  - Extra: WZ analysis on-going

top-antitop (tt)







Reference: Top++v2.0 program (M.Czakon, A. Mitov, Comput.Phys.Commun. 185 (2014) 2930)

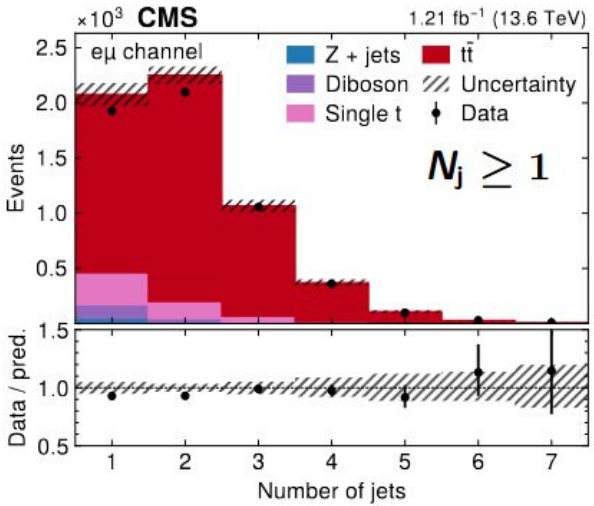
$\sqrt{s}$	$\sigma_{t\bar{t}}$ (NNLO + NNLL)
13 TeV	$833.9^{+29.4}_{-36.6}$ pb (4.4%)
13.6 TeV	$923.6^{+32.1}_{-40.4}$ pb (4.4%)

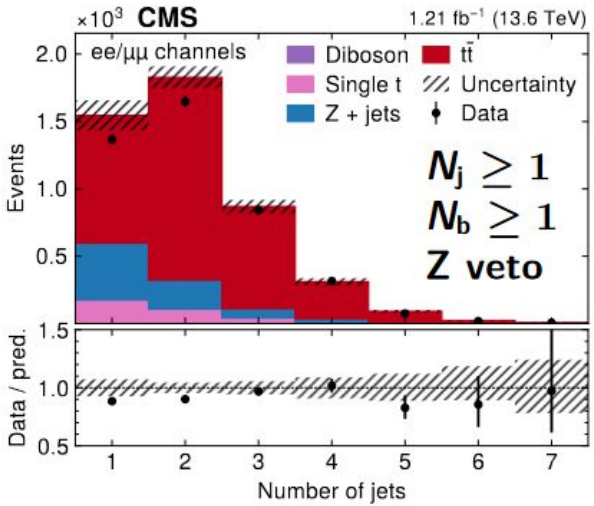
11% increase

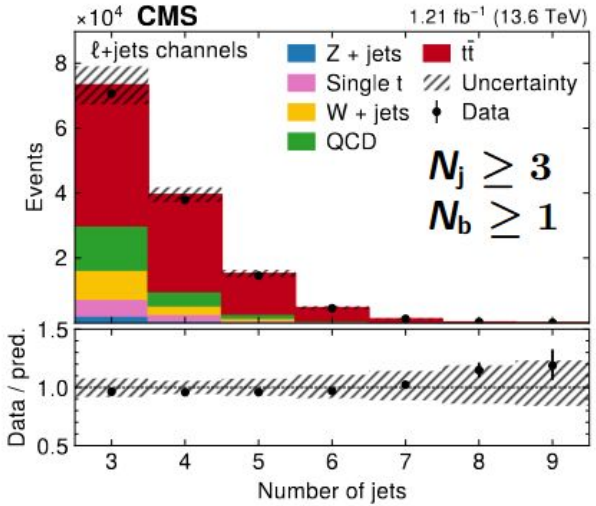
tt at 13.6 TeV

JHEP 08 (2023) 204

- **Early measurement:** Data from 27 July to 03 August 2022 ⇒ **1.21 fb^{-1}**
- **Combined analysis:**
  - Dilepton (eμ, ee, μμ) and lepton+jets (e+jets, μ+jets) channels
- **Event categories:** lepton number & flavor, N_j, N_b (*shown in next slide*)





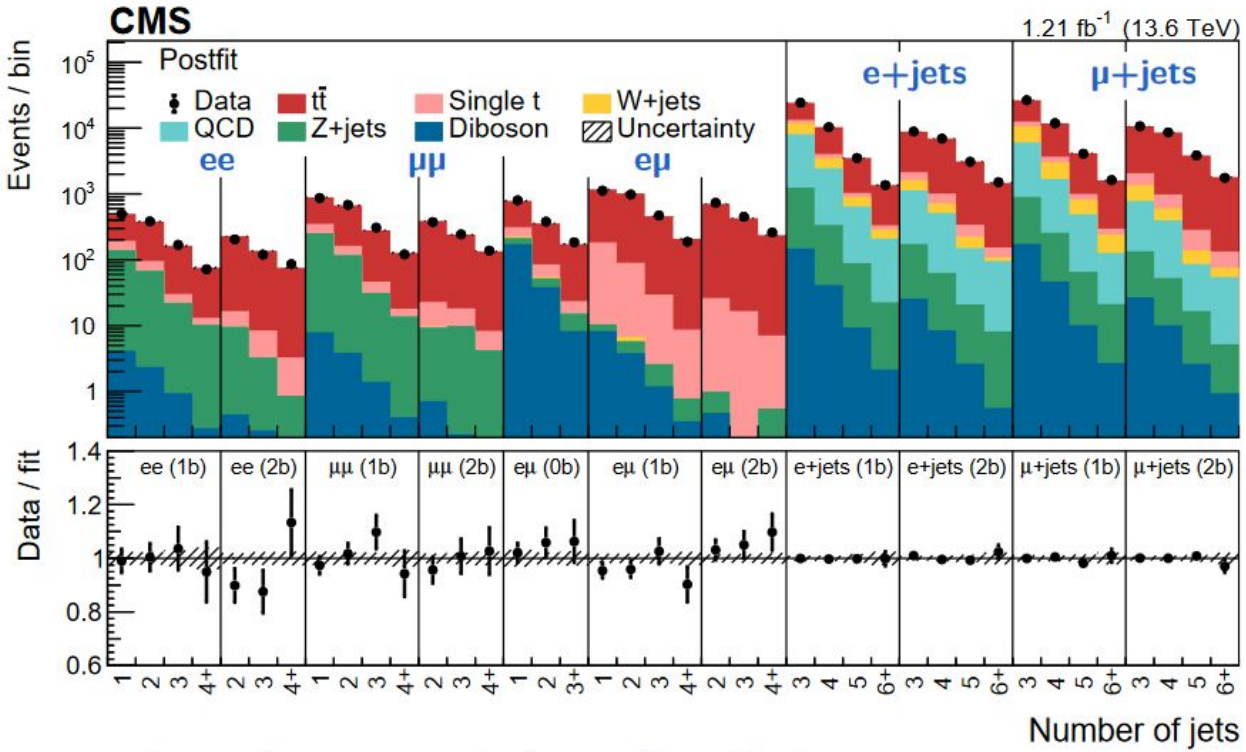


- A **maximum likelihood fit** is performed in **event categories** after Z+jets and QCD normalization **corrections** from side-band regions
- A **cut-and-count analysis** is also performed

tt at 13.6 TeV

JHEP 08 (2023) 204

Source	Uncertainty (%)
Lepton ID efficiencies	1.6
Trigger efficiency	0.3
JES	0.7
b tagging efficiency	1.1
Pileup reweighting	0.5
ME scale, $t\bar{t}$	0.6
ME scale, backgrounds	0.1
ME/PS matching	0.1
PS scales	0.3
PDF and α_S	0.3
Single t background	1.0
Z+jets background	0.3
W+jets background	0.0
Diboson background	0.5
QCD multijet background	0.3
Statistical uncertainty	0.5
Combined uncertainty	2.6
Integrated luminosity	2.3



$$\sigma_{t\bar{t}} = 882 \pm 23\,(\text{stat+syst}) \pm 20\,(\text{lumi})\ \text{pb}$$

$$\sigma_{t\bar{t}}^{C\&C} = 888 \pm 34\,(\text{stat+syst}) \pm 20\,(\text{lumi})\ \text{pb}$$

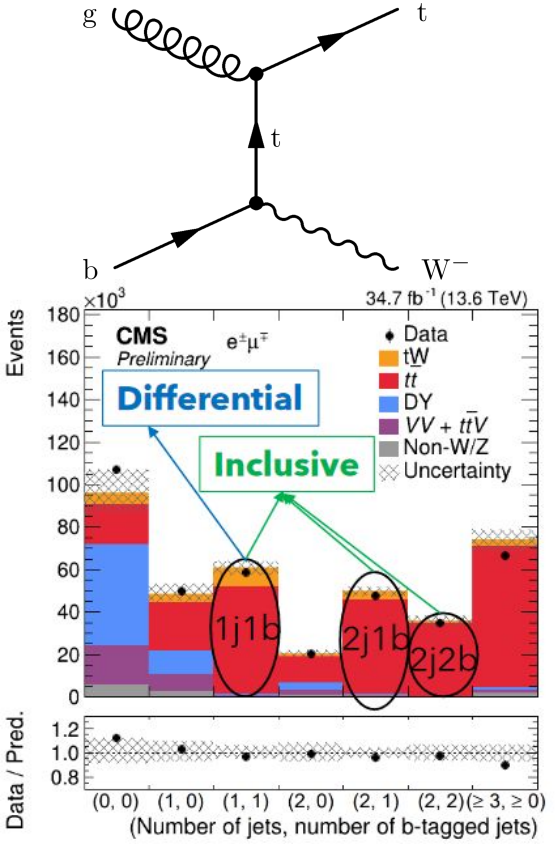
- **Lepton ID efficiencies:** from T&P method from Z+jets events plus extrapolation factor
- **b tagging efficiencies:** free fit parameter, constrained from using N_b= 0,1,2 categories

tW at 13.6 TeV

CMS-PAS-TOP-23-008

First measurement of the tW process at **13.6 TeV** using the full 2022 dataset with 34.7 fb^{-1}

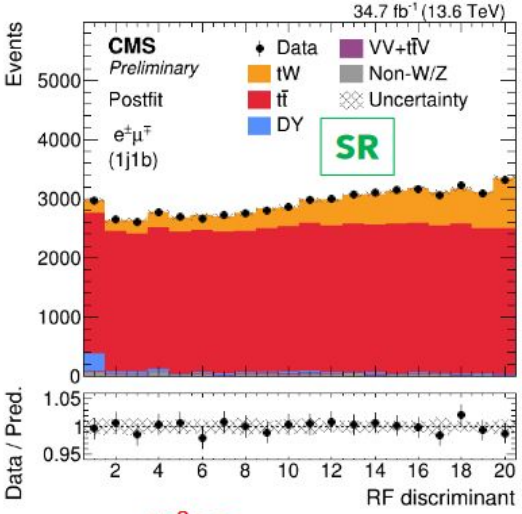
- Measure the inclusive cross section of tW
- Measure the differential cross sections as a function of several observables
- **Main challenges:**
  - Irreducible **tt** background largely dominates signal contribution
  - **NLO** interference between tW and tt (*DR and DS samples*)
- **Event selection:**
  - $e^{\pm}\mu^{\mp}$: the two leading leptons must be an electron and a muon of opposite charge (OSOF)
  - Leading lepton p_T > 25 GeV and subleading lepton p_T >20 GeV
  - All lepton pairs must satisfy $m(\ell 1, \ell 2)$ > 20 GeV

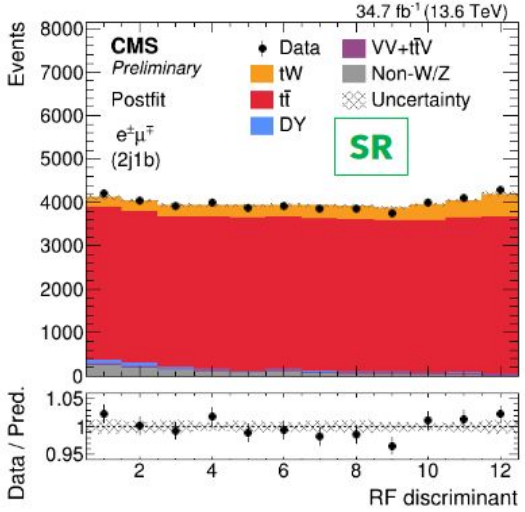


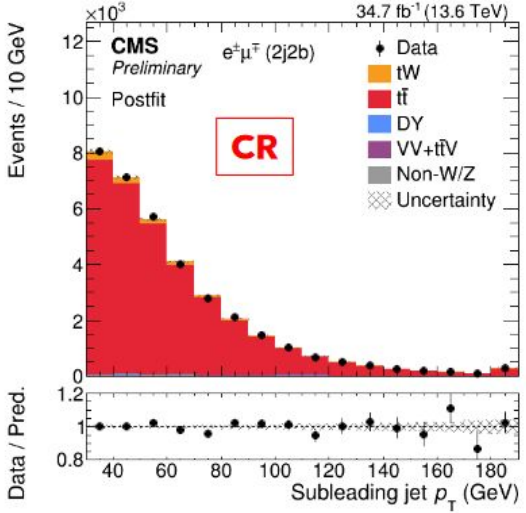
tW inclusive cross section at 13.6 TeV

CMS-PAS-TOP-23-008

- To discriminate between **tW** and **tt** events, two **Random Forest** (RF), in the **1j1b** and **2j1b** regions are trained using the kinematic properties of the events
- ML fit performed to extract the signal using the two RFs and the subleading jet p_T (**2j2b**)







aN^{3}LO

JHEP05 (2021) 278

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

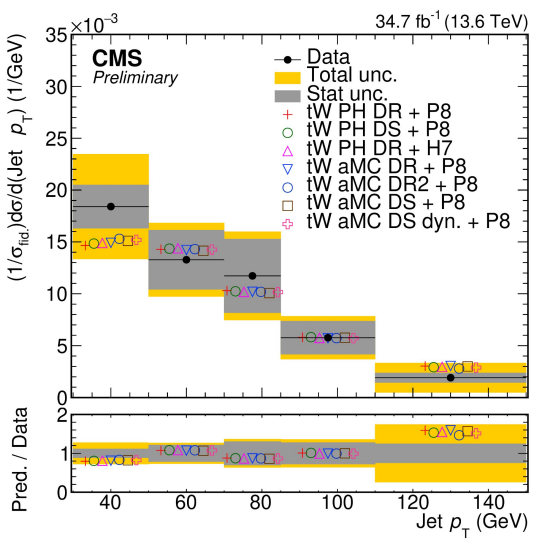
$\sigma_{tW}^{obs} = 84.1 \pm 2.1(\text{stat})^{+9.8}_{-10.2}(\text{syst}) \pm 3.3(\text{lum})$ pb

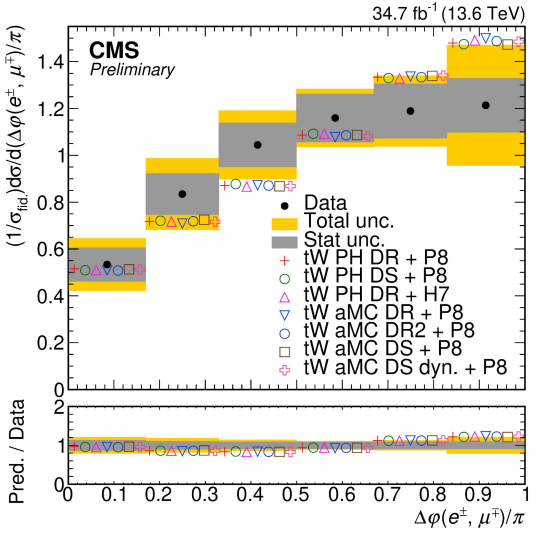
Main systematic uncertainties: jet energy scale, b tagging and non-W/Z (misidentified leptons) normalization

tW differential cross section at 13.6 TeV

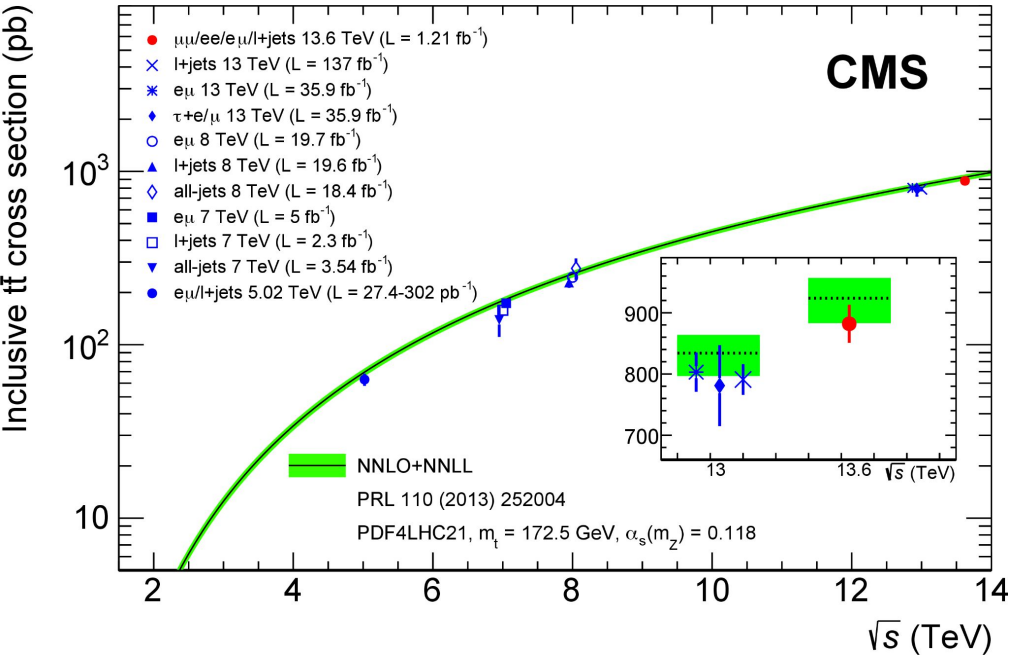
- Measurement performed in the **1j1b** region **vetoing** events with **low energy jets** (loose jets)
- Signal extraction is performed by background subtraction
- Unfolding from detector level to particle level is performed using TUnfold (JINST 7 (2012) T10003)
- **Measure the following 6 observables** (all in back-up):
  - p_T of the leading lepton and of the jet
  - $\Delta\phi(e, \mu)$
  - $p_z(e, \mu, \text{jet})$
  - $m(e, \mu, \text{jet})$
  - $m_T(e, \mu, \text{jet}, p_T^{\text{miss}})$
- Results **normalized** to fiducial cross section
- **Compared unfolder data with predictions:**
  - POWHEG (PH) vs MADGRAPH5_aMC@NLO (aMC)
  - PYTHIA8 (P8) vs HERWIG7 (H7)
  - Different schemes to treat the tW and tt interference

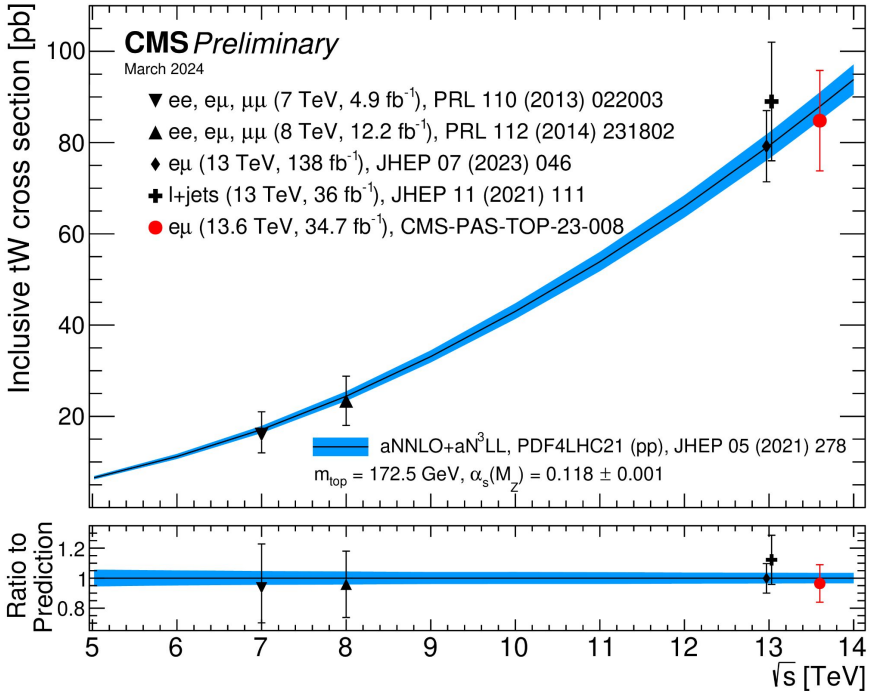
CMS-PAS-TOP-23-008





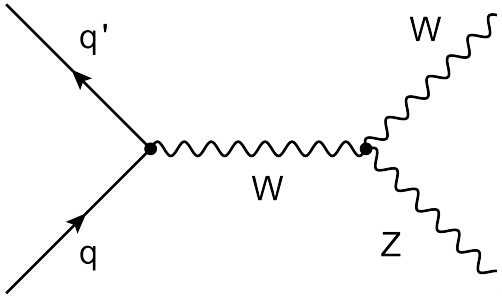
Results

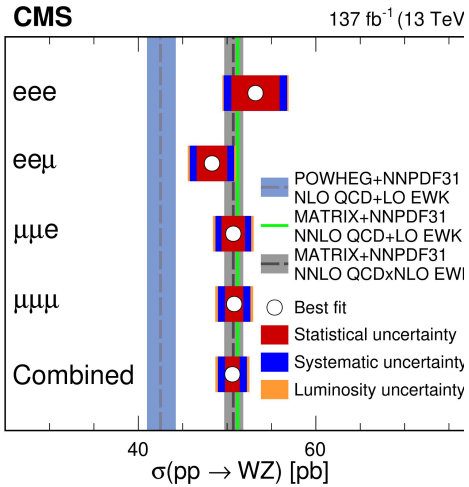

CMS
μμ/eeeμ/l+jets 13.6 TeV (L = 1.21 fb-1)
l+jets 13 TeV (L = 137 fb-1)
eμ 13 TeV (L = 35.9 fb-1)
τ+e/μ 13 TeV (L = 35.9 fb-1)
eμ 8 TeV (L = 19.7 fb-1)
l+jets 8 TeV (L = 19.6 fb-1)
all-jets 8 TeV (L = 18.4 fb-1)
eμ 7 TeV (L = 5 fb-1)
l+jets 7 TeV (L = 2.3 fb-1)
all-jets 7 TeV (L = 3.54 fb-1)
eμ/l+jets 5.02 TeV (L = 27.4-302 pb-1)
NNLO+NNLL
PRL 110 (2013) 252004
PDF4LHC21, mt = 172.5 GeV, αs(mZ) = 0.118
Inclusive tt̄ cross section (pb)
√s (TeV)

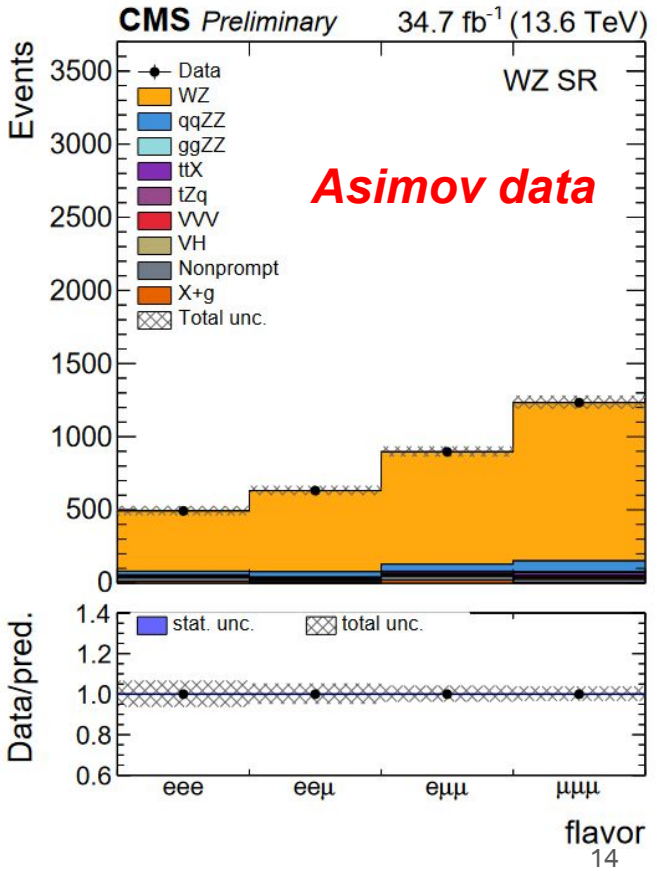

CMS Preliminary
March 2024
ee, eμ, μμ (7 TeV, 4.9 fb-1), PRL 110 (2013) 022003
ee, eμ, μμ (8 TeV, 12.2 fb-1), PRL 112 (2014) 231802
eμ (13 TeV, 138 fb-1), JHEP 07 (2023) 046
l+jets (13 TeV, 36 fb-1), JHEP 11 (2021) 111
eμ (13.6 TeV, 34.7 fb-1), CMS-PAS-TOP-23-008
aNNLO+aN3LL, PDF4LHC21 (pp), JHEP 05 (2021) 278
mtop = 172.5 GeV, αs(MZ) = 0.118 ± 0.001
Inclusive tW cross section [pb]
Ratio to Prediction
√s [TeV]

On-going: WZ cross section at 13.6 TeV

- Working on measuring WZ cross section at 13.6 TeV
- **Three-lepton analysis:**
  - eee, eeμ, μμe, μμμ
- **Very clean final state**
- Aiming for a similar precision of Run2 (JHEP 07 (2022) 032):
  - **~4% level**
- Compare with high order predictions:
  - POWHEG at NLO in QCD
  - MATRIX at NNLO in QCD

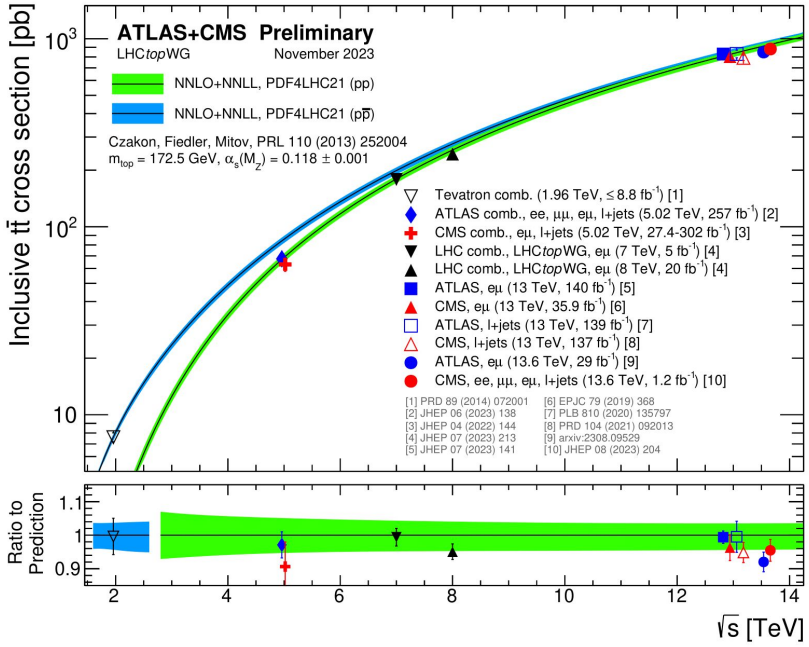


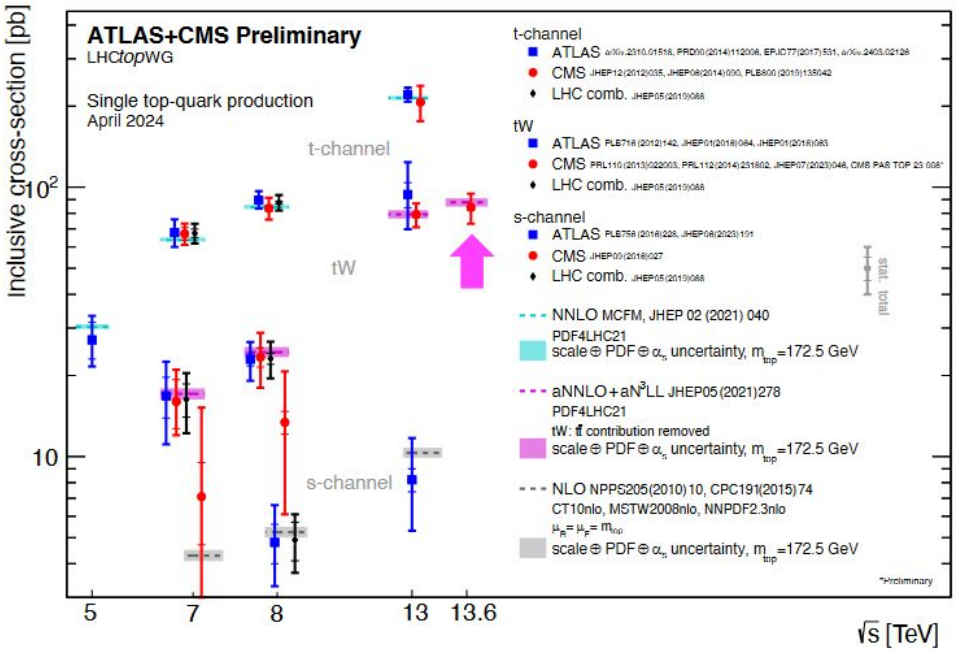




Summary

- Successful **Run3** data-taking
- **Precision measurements** performed to keep testing **SM accuracy** and as a window the **new physics**
- **Differential** and **fiducial** measurements are key inputs to improve **MC modeling**





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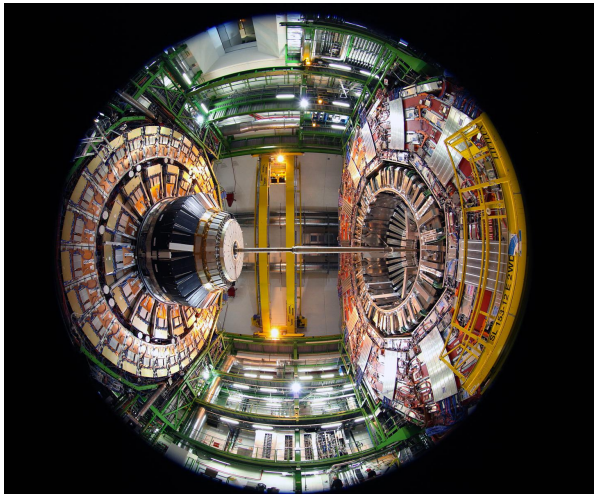
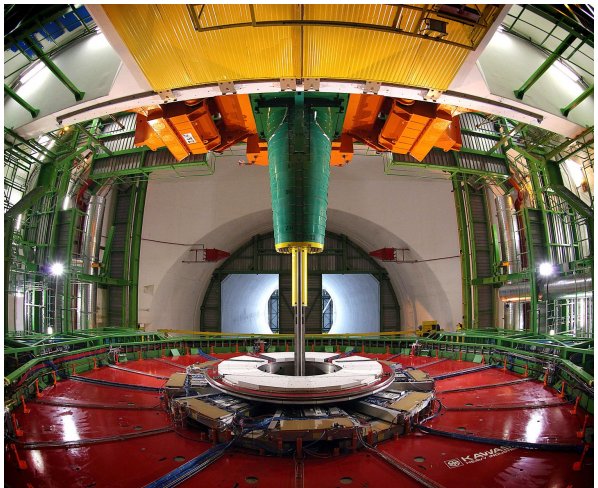
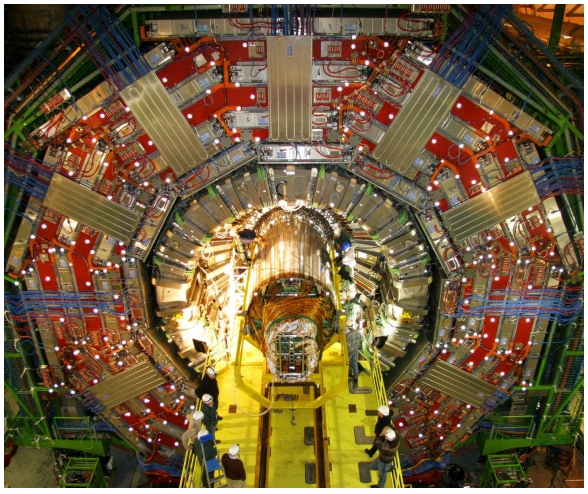
28 – 30 May 2024 @ U. Complutense (Madrid)

BACK-UP SLIDES



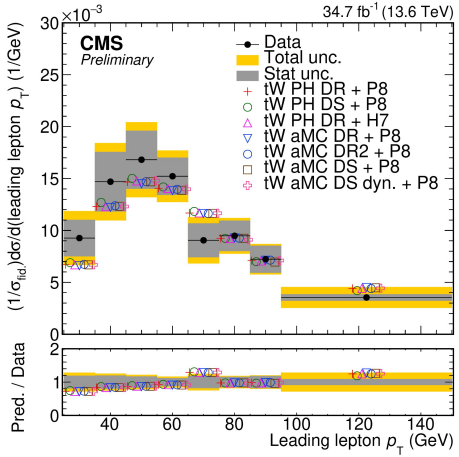


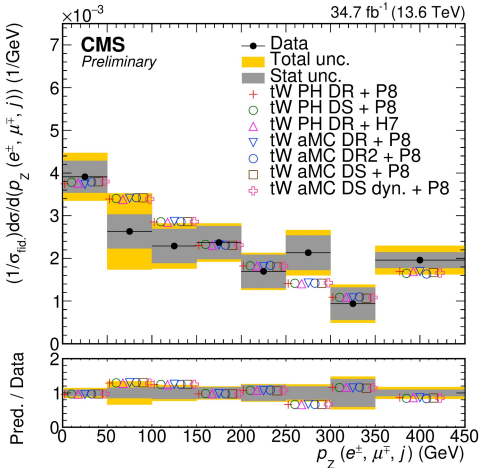


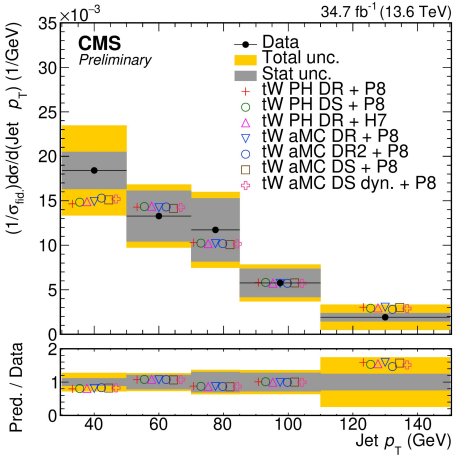
ATLAS Run 3 Publications

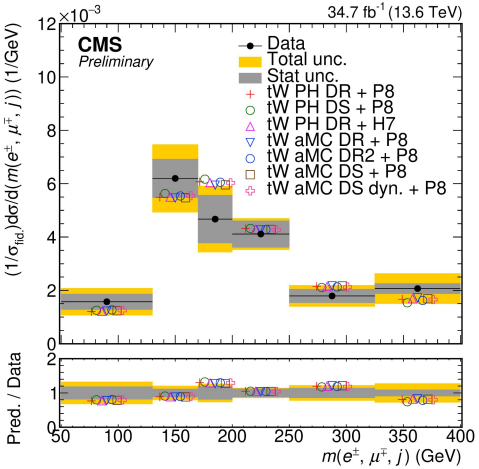
ATLAS Google Project: Total Cost of Ownership NEW	SOFT	Submitted to CSBS	2024-05-22	13.6		Documents | Internal
Run 3 Software and Computing	SOFT	Submitted to EPJC	2024-04-09	13.6		Documents | 2404.06335 Inspire | Internal
Measurement of vector boson production cross sections and their ratios	STDM	Accepted by PLB	2024-03-19	13.6	29 fb^{-1}	Documents | 2403.12902 Inspire | Briefing | Internal
Performance of the ATLAS Trigger System in 2022	TRIG	Submitted to JINST	2024-01-12	13.6	30 fb^{-1}	Documents | 2401.06630 Inspire | Internal
Measurement of ZZ production cross-sections in the four-lepton final state	STDM	Submitted to PLB	2023-11-16	13.6	29 fb^{-1}	Documents | 2311.09715 Inspire | HepData Internal
Track reconstruction software performance in Run 3	IDTR	Comput Softw Big Sci 8, 9 (2024)	2023-08-18	13.6		Documents | 2308.09471 Inspire | Internal
Measurement of tt cross-section and tt/Z cross-section ratio at sqrt(s) = 13.6 TeV	TOPQ	Phys. Let. B 848 (2024) 138376	2023-08-18	13.6	29 fb^{-1}	Documents | 2308.09529 Inspire | HepData Internal
H→yy and H→ZZ→4l cross-sections at sqrt(s) = 13.6 TeV	HIGG	Eur. Phys. J. C 84 (2024) 78	2023-06-20	13.6	29 fb^{-1}	Documents | 2306.11379 Inspire | Internal
Fast b-jet identification algorithms in the ATLAS High Level Trigger for LHC Run 3	TRIG	JINST 18 (2023) 001 P11006	2023-06-16	13.6	6.3 fb^{-1}	Documents | 2306.09738 Inspire | Internal
The ATLAS detector for the LHC Run-3	GENR	Accepted by JINST	2023-05-26	13.6		Documents | 2305.16623 Inspire | Internal

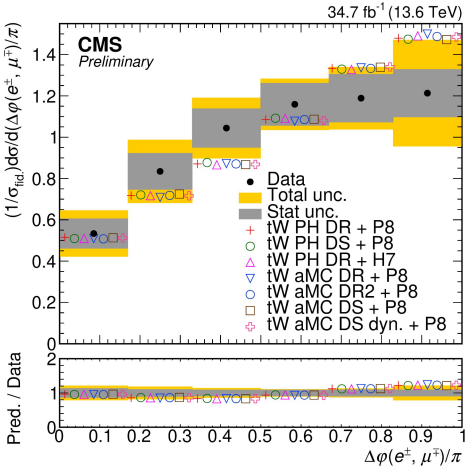
tW differential cross section at 13.6 TeV

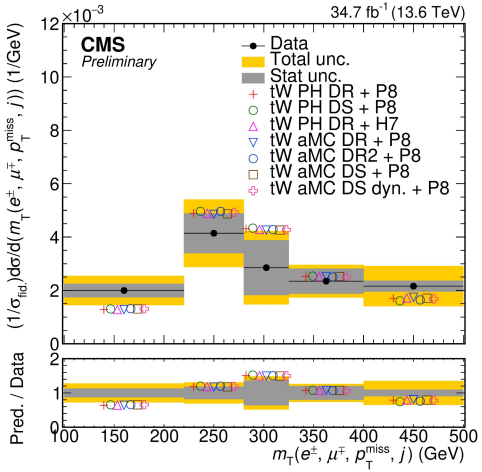












We measure the following observables:

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