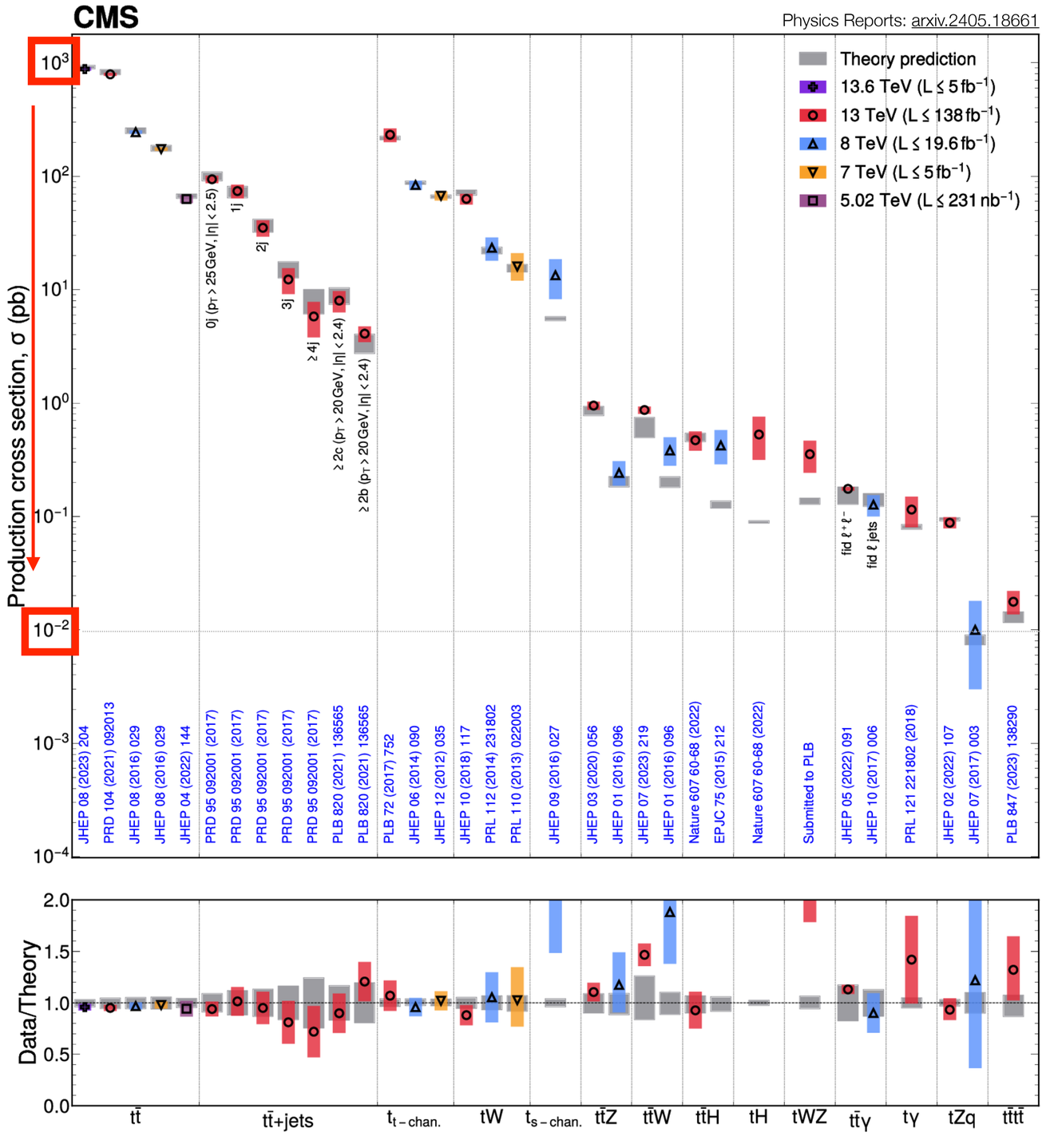
# Electroweak and associated top-quark production at CMS

Beatriz Ribeiro Lopes, on behalf of the CMS collaboration

# Electroweak and associated top quark production




- Top quark measurements central to LHC program
- Deep connection to both EW and QCD sectors
- **t(t̄) + vector boson** processes all accessible with Run 2 data

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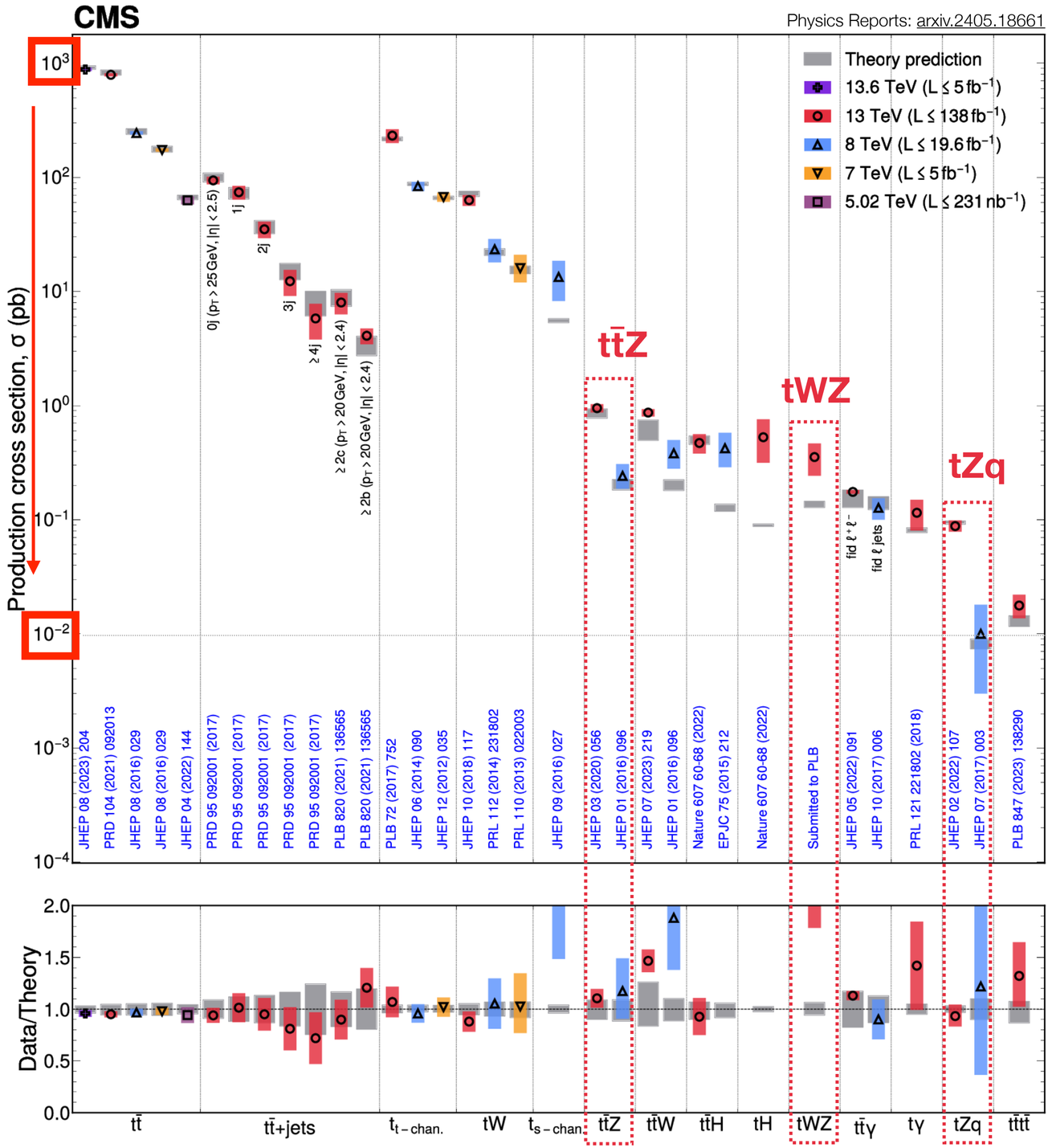


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  - Observation or at least evidence for all processes
  - Most of them entered the precision era
  - Differential distributions give access to regions of the phase space where new physics effects may be enhanced - ideal for Effective Field Theory

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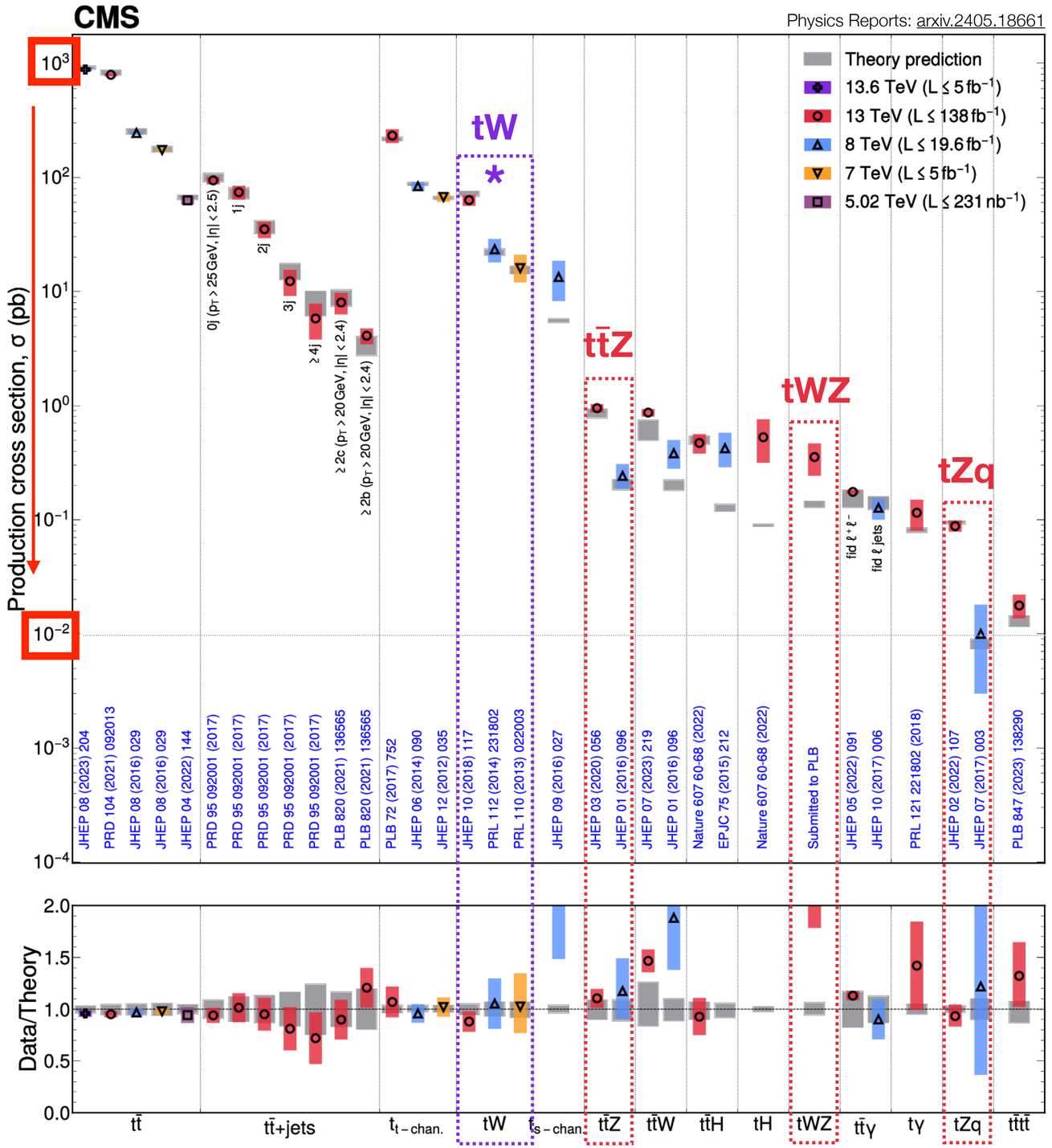


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  - Observation or at least evidence for all processes
  - Most of them entered the precision era
  - Differential distributions give access to regions of the phase space where new physics effects may be enhanced - ideal for Effective Field Theory
- **First tW measurement using data from Run 3*** (not shown in plot)

# Summary of recent CMS measurements

Now published in PLB!

ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2023-146
2023/12/20

CMS-TOP-22-008

## Evidence for tWZ production in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ in multilepton final states

The CMS Collaboration*

**Abstract**

The first evidence for the standard model production of a top quark in association with a W boson and a Z boson is reported. The measurement is performed in multilepton final states, where the Z boson is reconstructed via its decays to electron or muon pairs and the W boson decays either to leptons or hadrons. The analysed data were recorded by the CMS experiment at the CERN LHC in 2016–2018 in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$, and correspond to an integrated luminosity of $138\,\text{fb}^{-1}$. The measured cross section is $354 \pm 54\,(\text{stat}) \pm 95\,(\text{syst})$ fb, and corresponds to a statistical significance of 3.4 standard deviations.

*Submitted to Physics Letters B*

tWZ

Available on the CERN CDS information server **CMS PAS TOP-23-004**

CMS Physics Analysis Summary

Contact: cms-pag-conveners-top@cern.ch 2024/03/27

## Inclusive and differential measurement of top quark cross sections in association with a Z boson

The CMS Collaboration

**Abstract**

A measurement is presented of the inclusive and differential cross sections for top quark production in association with a Z boson, in pairs ($t\bar{t}Z$) or with a single top quark (tZq and tWZ). The data were recorded in pp collisions at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of $138\,\text{fb}^{-1}$. Events with exactly three leptons, electrons or muons, are selected. A deep neural network is trained to separate the signal processes and the backgrounds. The $t\bar{t}Z$ and tWZ pro-

tWZ $t\bar{t}Z$ tZq

Available on the CERN CDS information server **CMS PAS TOP-23-008**

CMS Physics Analysis Summary

Run 3

Contact: cms-pag-conveners-top@cern.ch 2024/03/27

## Measurement of inclusive and differential cross sections for single top quark production in association with a W boson in proton-proton collisions at $\sqrt{s} = 13.6$ TeV

The CMS Collaboration

**Abstract**

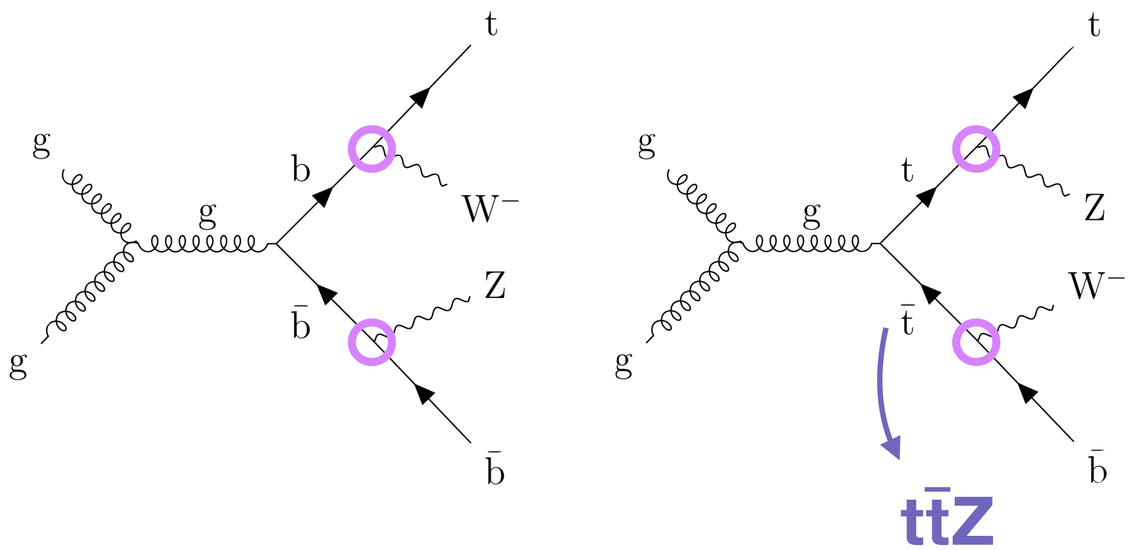
The first measurement of the inclusive and normalised differential cross sections for the production of single top quarks in association with a W boson in proton-proton collisions at a centre-of-mass energy of 13.6 TeV are presented. The data used were recorded with the CMS detector at the LHC during 2022, and correspond to an integrated luminosity of $34.7\,\text{fb}^{-1}$. The analyzed events contain one muon and one

tW

# tWZ production

- Explore two top quark electroweak couplings in one process

**tWZ:**




- Challenges:
  - Very rare process: exp. cross section ~136 fb (NLO in QCD)
  - Overwhelming and irreducible $t\bar{t}Z$ background
  - Interference with the $t\bar{t}Z$ process within the SM beyond the leading order

# tWZ production

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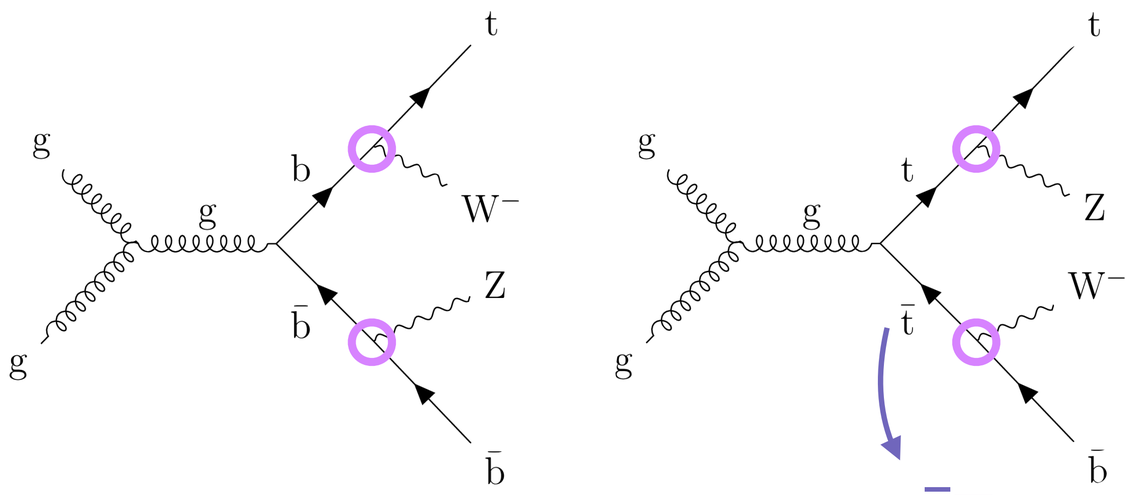
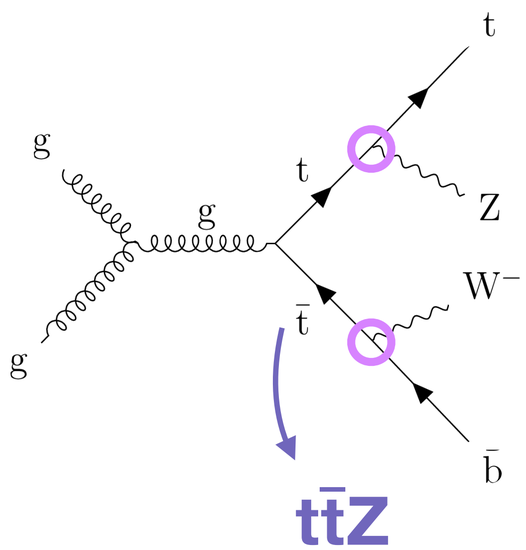



**tt̄Z**

- Challenges:
  - Very rare process: exp. cross section ~136 fb (NLO in QCD)
  - Overwhelming and irreducible tt̄Z background
  - Interference with the tt̄Z process within the SM beyond the leading order

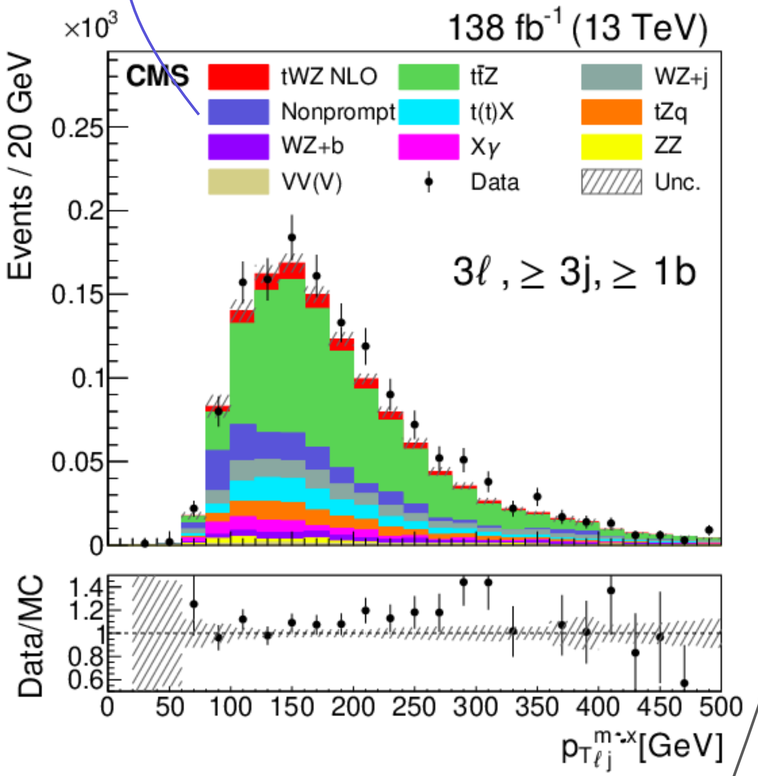
First analysis using state-of-the-art tWZ signal modeling at NLO, consistently treating the interference

# Analysis strategy for tWZ

- Two regions of the phase space considered:
  - ✓ Low top quark $p_T$ (**resolved**): higher stat., sensitive to the SM tWZ production
  - ✓ Top quark with $p_T$ > 270 GeV (**boosted**): enhanced sensitivity for new phenomena
- Signal and control regions built based on number of leptons and b jets
  - Resolved: 3 leptons, 2j, ≥ 1b
    **3 leptons, ≥ 3j, ≥ 1(2)b**
    4 leptons, ≥ 1b
  - Boosted: hadronic top decay (fat jet)
    leptonic top decay (lep. top tagger)
  - Diboson CRs: 4 leptons (ZZ)
    3 leptons, 0b (WZ)

**Simultaneous fit of 7 distributions**

Nonprompt lepton background estimated from data




Other backgrounds taken from simulation and some (WZ, ZZ) constrained with CRs

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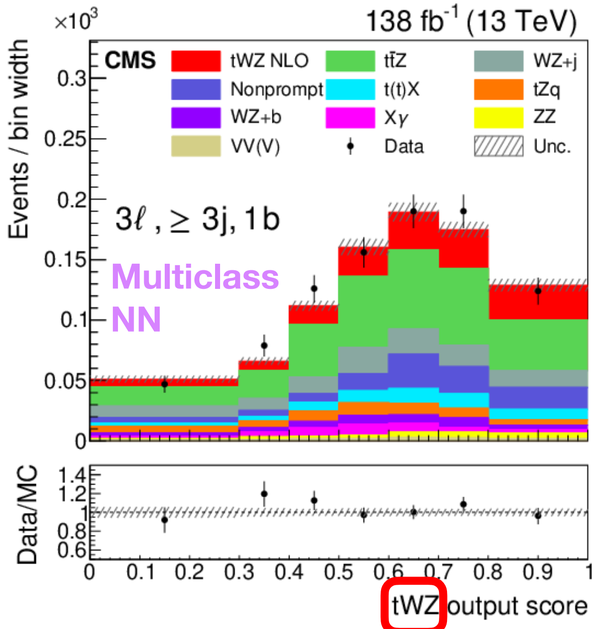
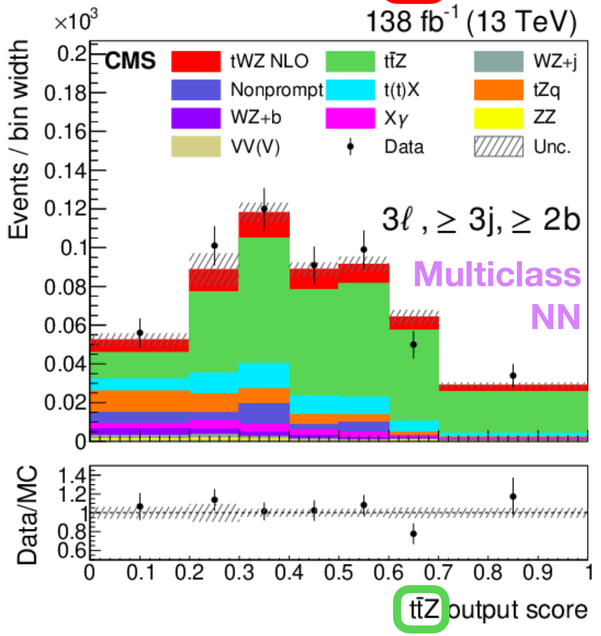
  - ✓ Low top quark $p_T$ (**resolved**): higher stat., sensitive to the SM tWZ production
  - ✓ Top quark with $p_T$ > 270 GeV (**boosted**): enhanced sensitivity for new phenomena
- Signal and control regions built based on number of leptons and b jets
  - Resolved: 3 leptons, 2j, ≥ 1b → **Binary NN**
    3 leptons, ≥ 3j, ≥ 1(2)b → **Multiclass NN**
    4 leptons, ≥ 1b
  - Boosted: hadronic top decay (fat jet)
    leptonic top decay (lep. top tagger)
  - Diboson CRs: 4 leptons (ZZ)
    3 leptons, 0b (WZ)

**Simultaneous fit of 7 distributions**



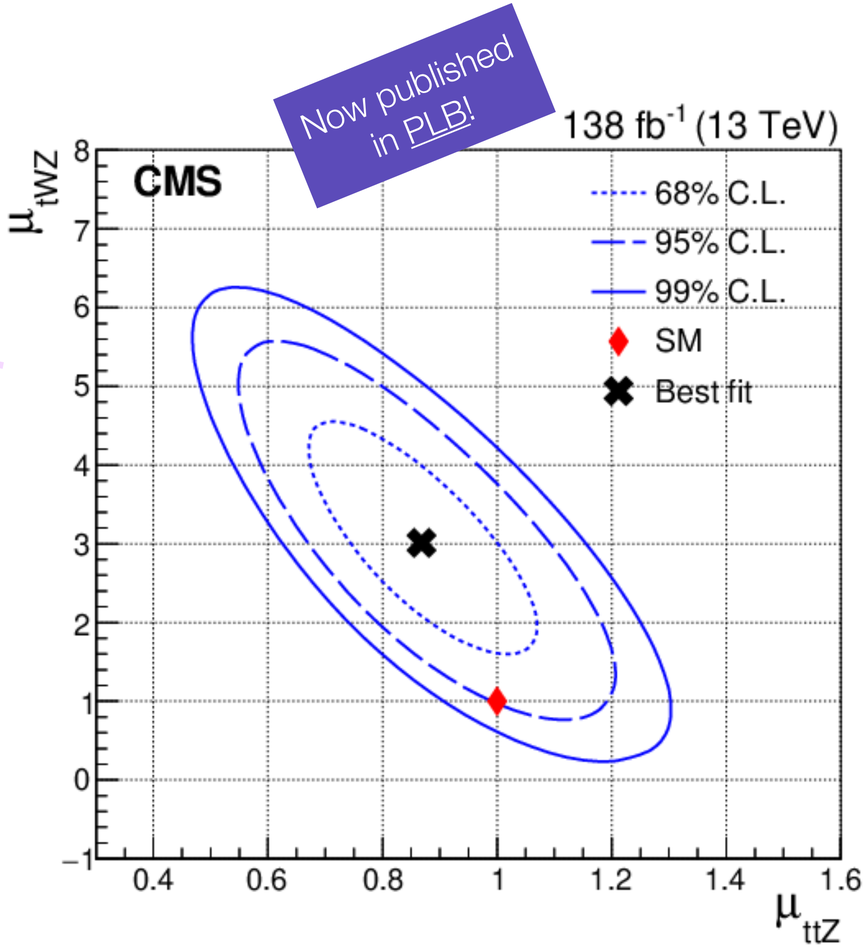



# Inclusive tWZ cross section

- Observed (expected) significance of 3.4σ (1.4σ) → **evidence!**

$\sigma_{tWZ}$ = 354 ± 54 (stat) ± 95 (syst) fb

(two s.d. above the SM)

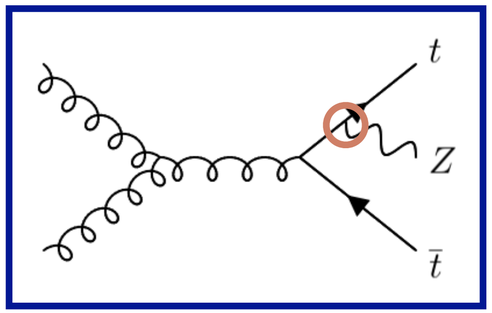


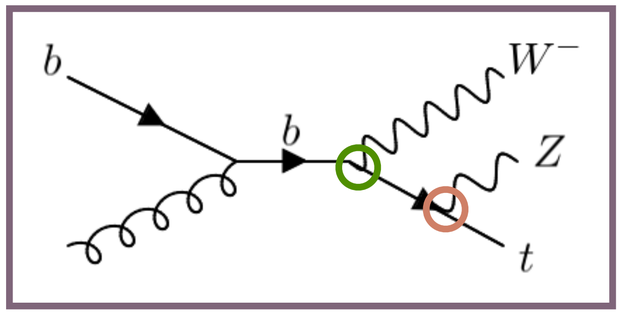

- Dominant systematic uncertainties:
  - **$t\bar{t}Z$** normalization: 18% - strongly anti-correlated with the signal

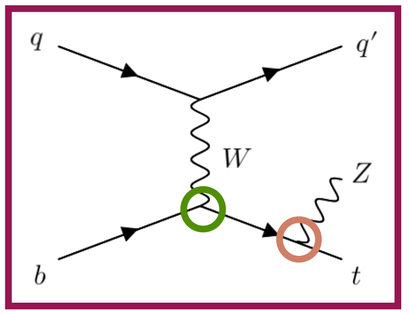
    **Additional studies showed that when fixing the $t\bar{t}Z$ cross section to the previously measured value, the significance stays above 3σ**
  - Other background normalization
- Sensitivity driven by resolved SRs, especially the SR with **3 leptons, ≥ 3j, ≥ 1b**

# Simultaneous measurement of $t\bar{t}Z$, tWZ, and tZq

- **$t\bar{t}Z$** and **tZq** already measured, inclusively and differentially
- Evidence for **tWZ** production (previous slides)
- Significant interference between tWZ and $t\bar{t}Z$ beyond leading order



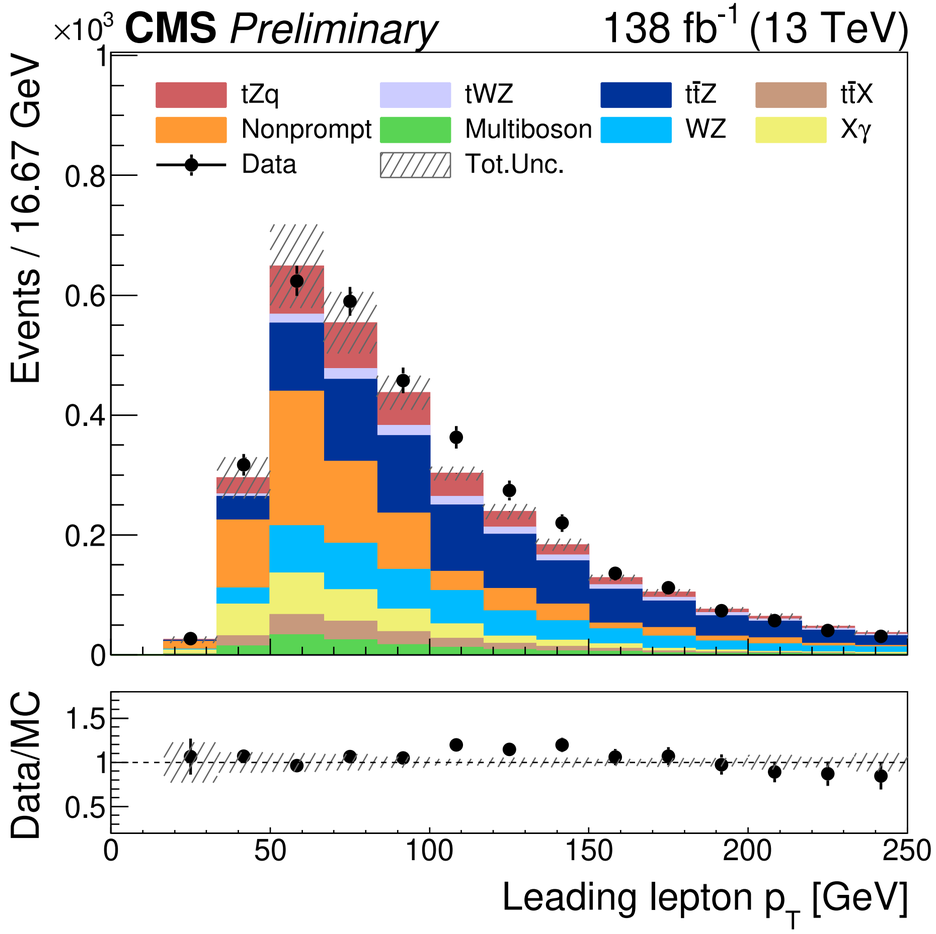



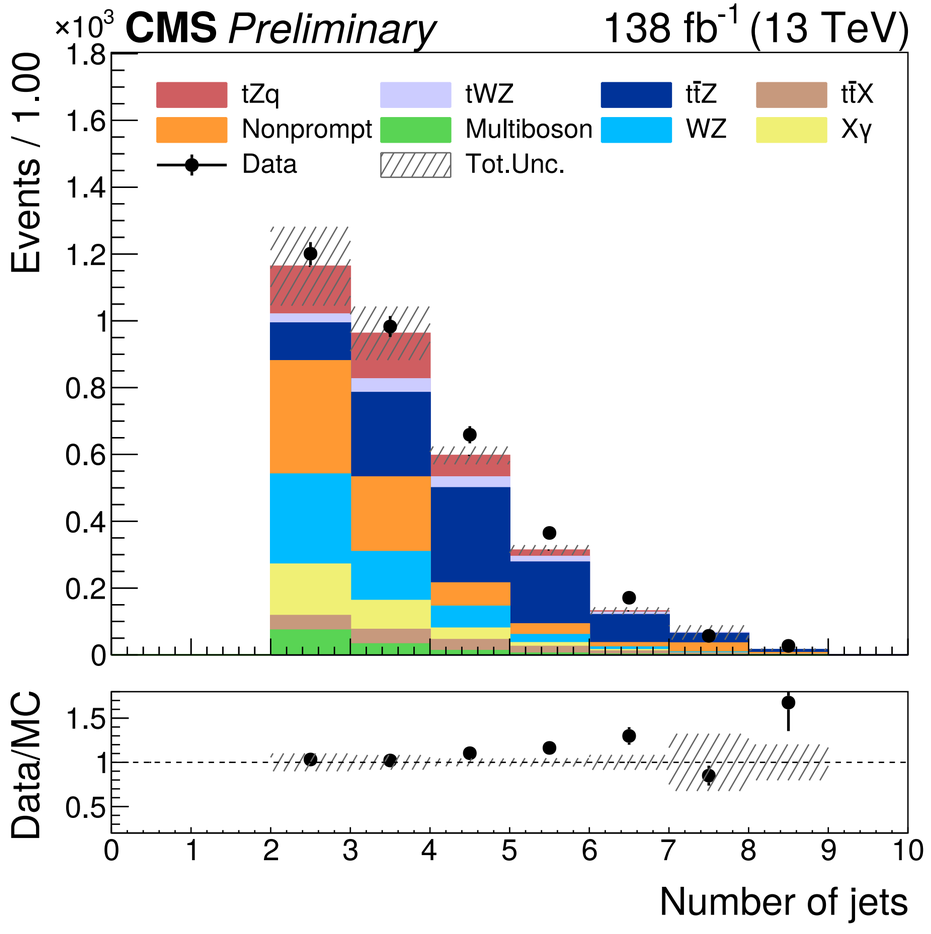




- Simultaneous measurement:
  - less dependency on signal modelling assumptions
  - processes are major backgrounds to each other
  - consistently treat correlations between systematic uncertainties
  - ✦ enhance sensitivity to deviations from SM that affect all processes (e.g. anomalous tZ, tbW couplings)
- **Strategy: Measure $t\bar{t}Z$ + tWZ together, and simultaneously with tZq**

# Selection strategy for $t\bar{t}Z$, tWZ, and tZq

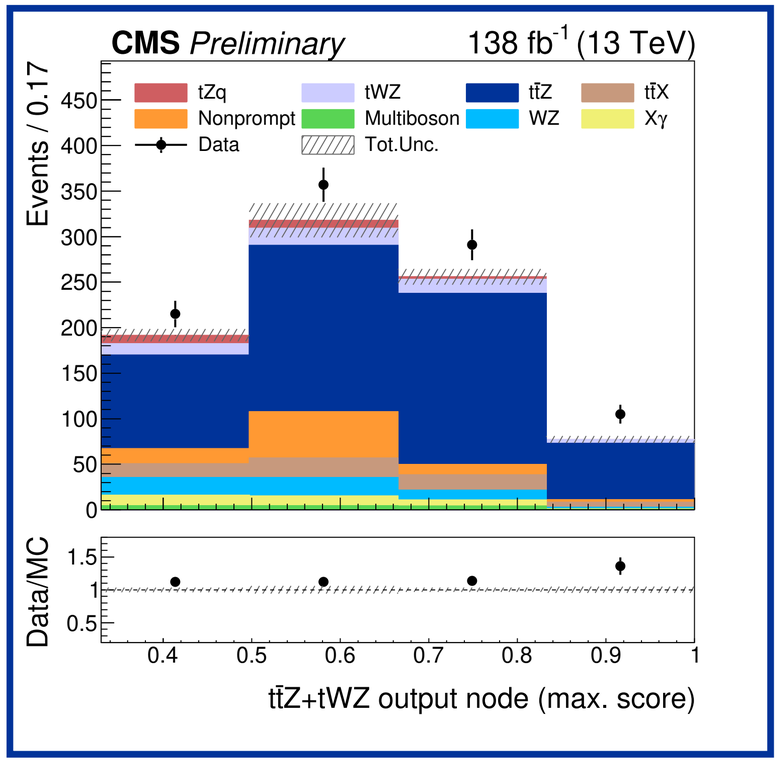
- Signal region with three leptons (e or $\mu$), $\geq$2 jets, $\geq$1 b-tagged jet
- **Nonprompt lepton contribution** is estimated from data, **WZ** and other smaller backgrounds from simulation

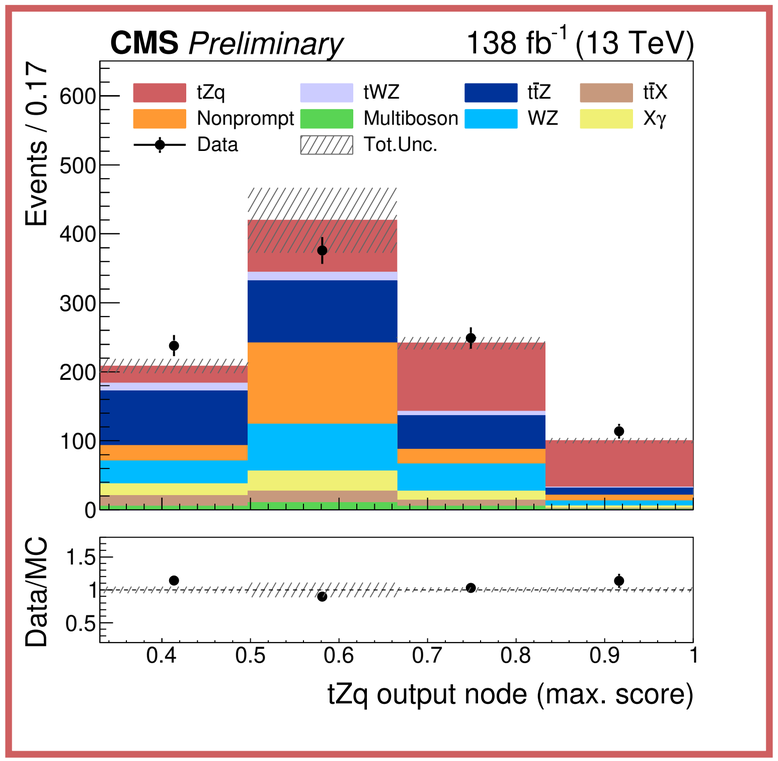


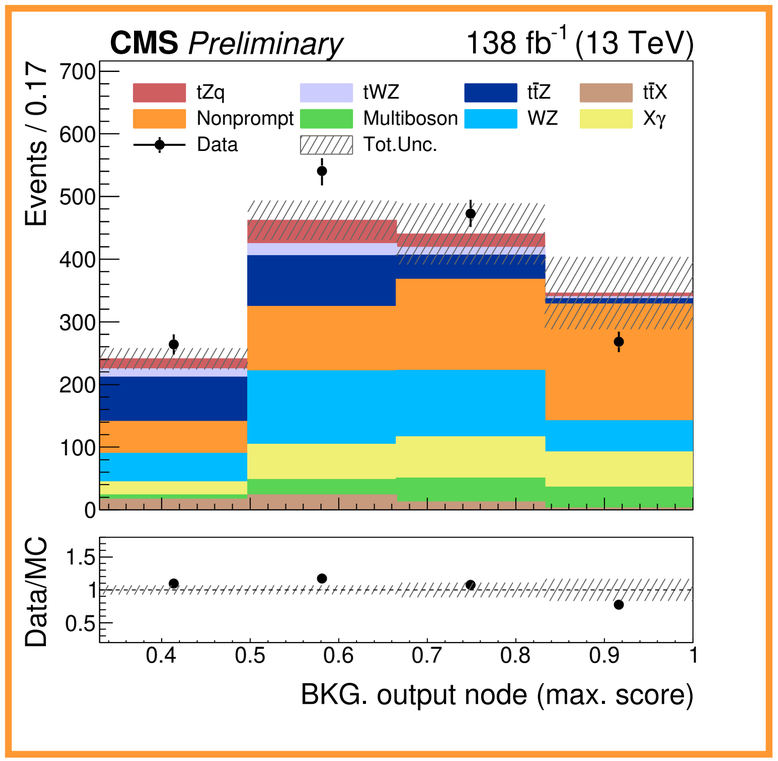



# Signal/background discrimination

- Neural network (multi-class classifier) to disentangle different signals and backgrounds
  - 3 output nodes for $t\bar{t}Z$+tWZ, tZq, and background (maximum-score splitting to build fit categories)



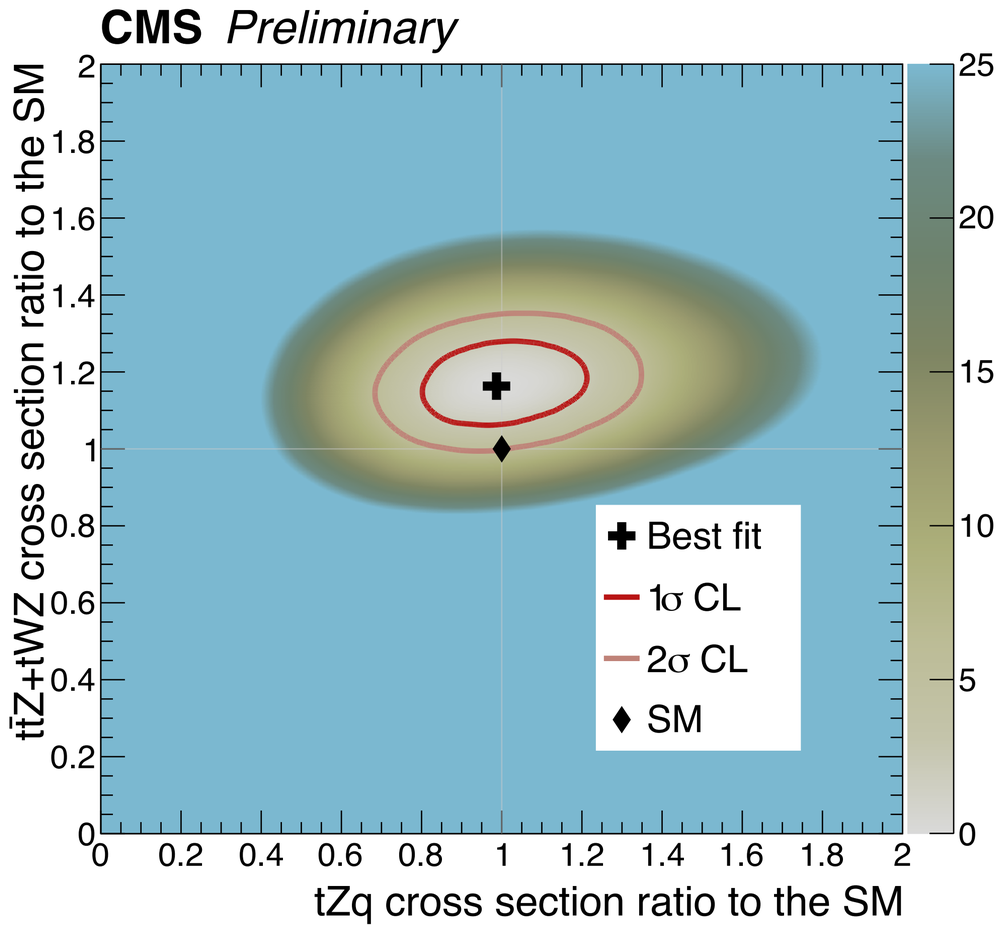



# Inclusive measurement

- Simultaneous fit to 3 max-score output nodes (SR) and two CRs
- Profiled likelihood fit
- Limited by statistics, main syst. uncertainties on background modelling and b tagging
- Inclusive cross sections measured to be:

$$\sigma_{t\bar{t}Z+tWZ} = 1.14 \pm 0.07 \text{ pb}$$

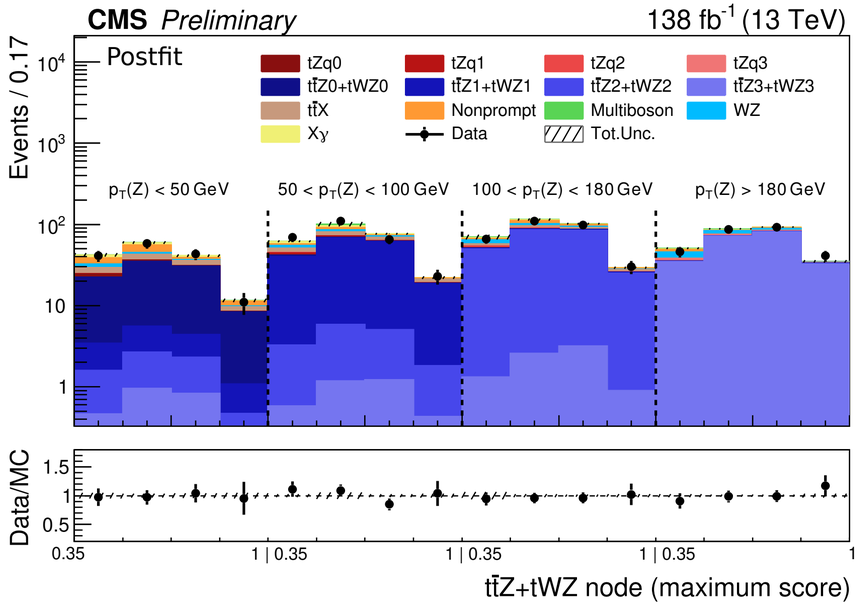
$$\sigma_{tZq} = 0.89 \pm 0.10 \text{ pb}$$



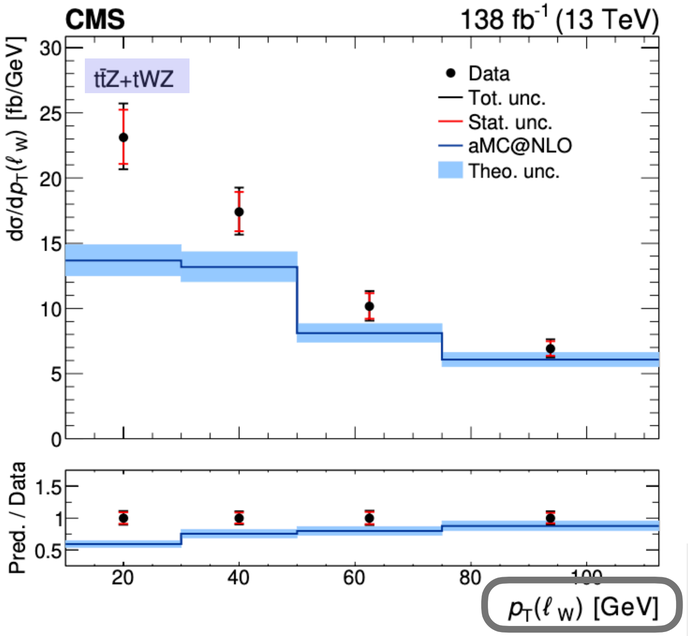

consistent with SM for **tZq,**
slight excess for **$t\bar{t}$Z+tWZ**

# Differential measurements

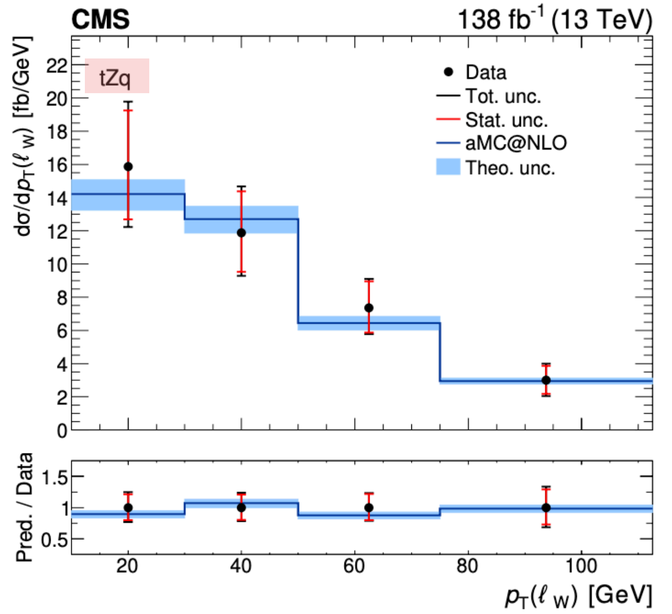
- Cross sections measured as function of lepton and Z observables
- Maximum likelihood unfolding




- Measurements compared to predictions from aMC@NLO
- Good agreement overall for tZq, excess for tt̄Z+tWZ at low lepton $p_T$




$p_T$ of the lepton from the W



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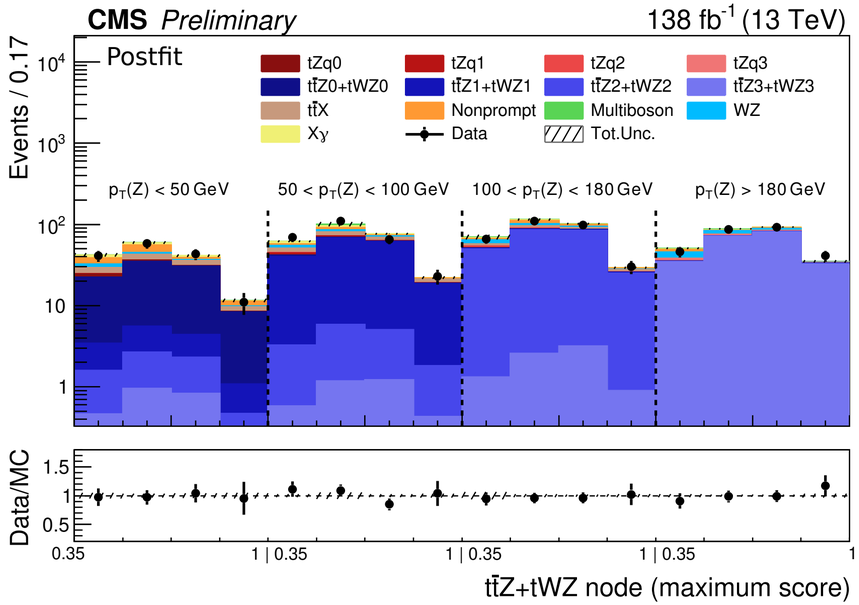


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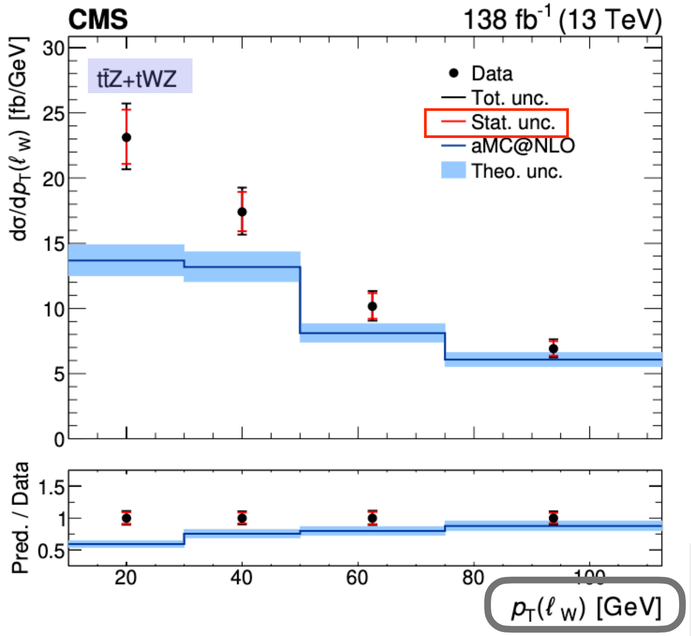
**First simultaneous measurement of these processes, useful for theory and EFT interpretations**

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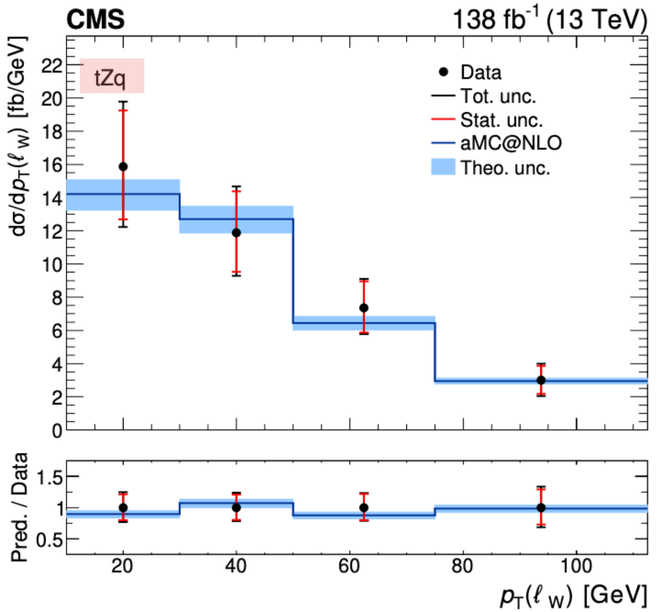
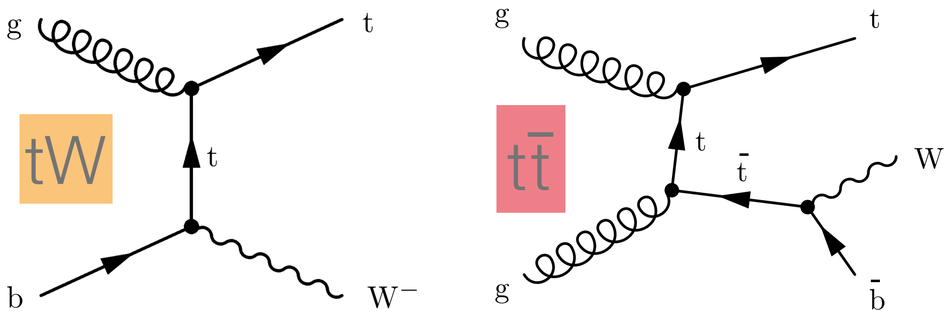


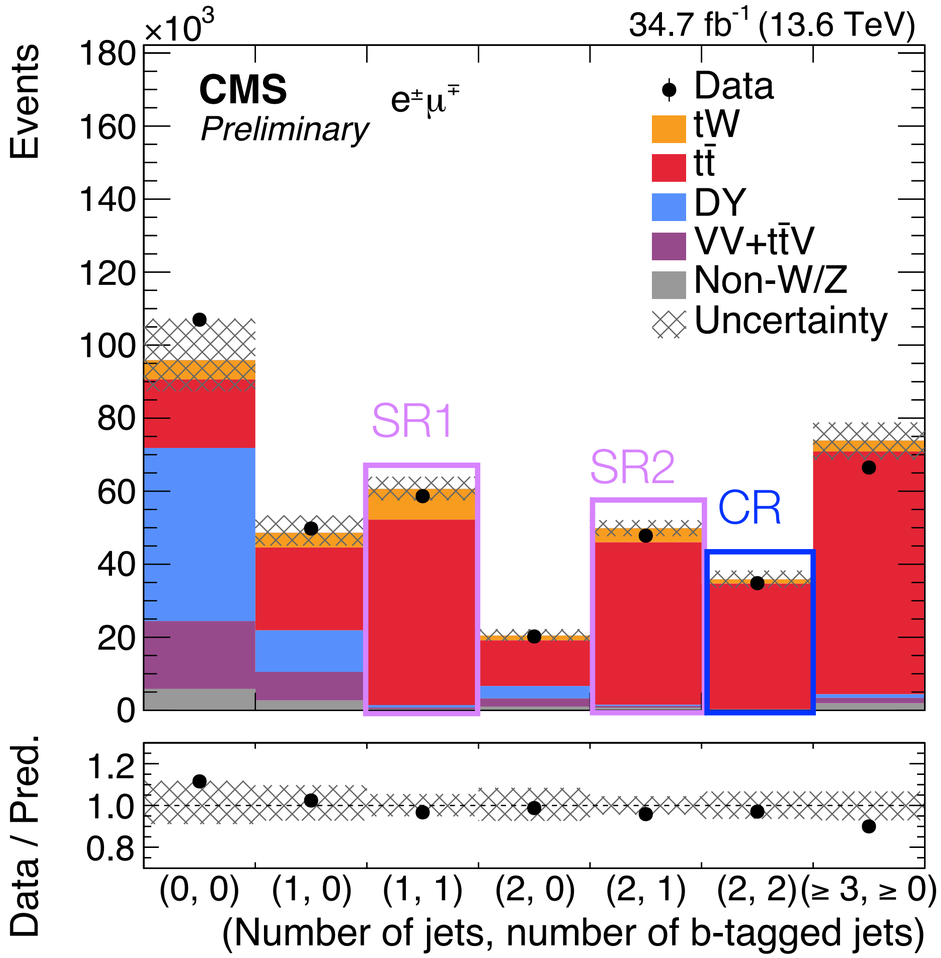
# The tW process at the LHC Run 3

- First tW measurement at 13.6 TeV, using full 2022 dataset (34.7 fb$^{-1}$)




- Focusing on $e\mu$ final states

- Two SRs and CR defined based on number of jets and b jets



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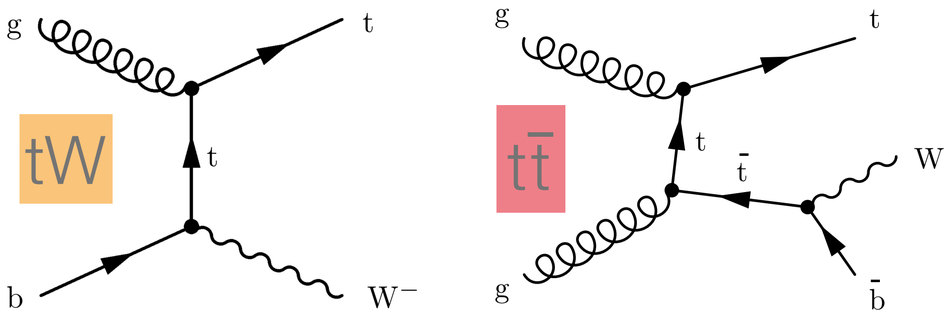
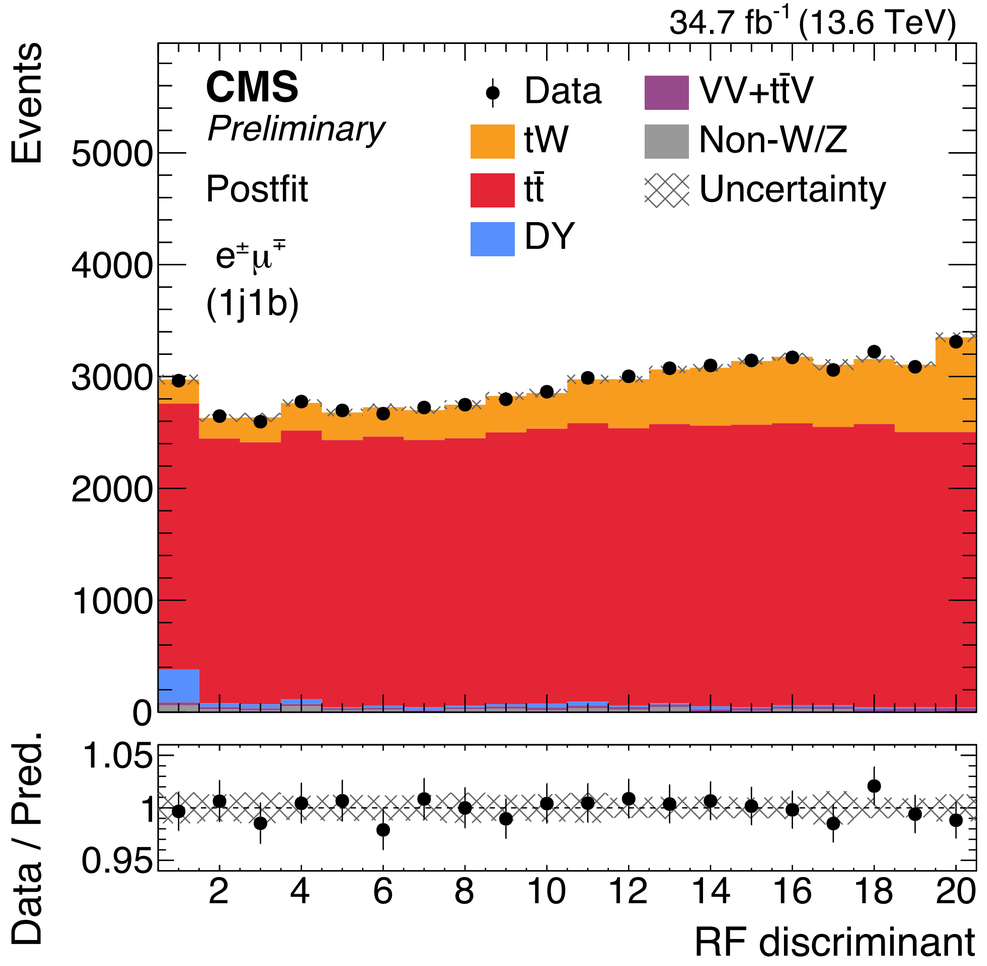



- Focusing on $e\mu$ final states

- Two SRs and CR defined based on number of jets and b jets

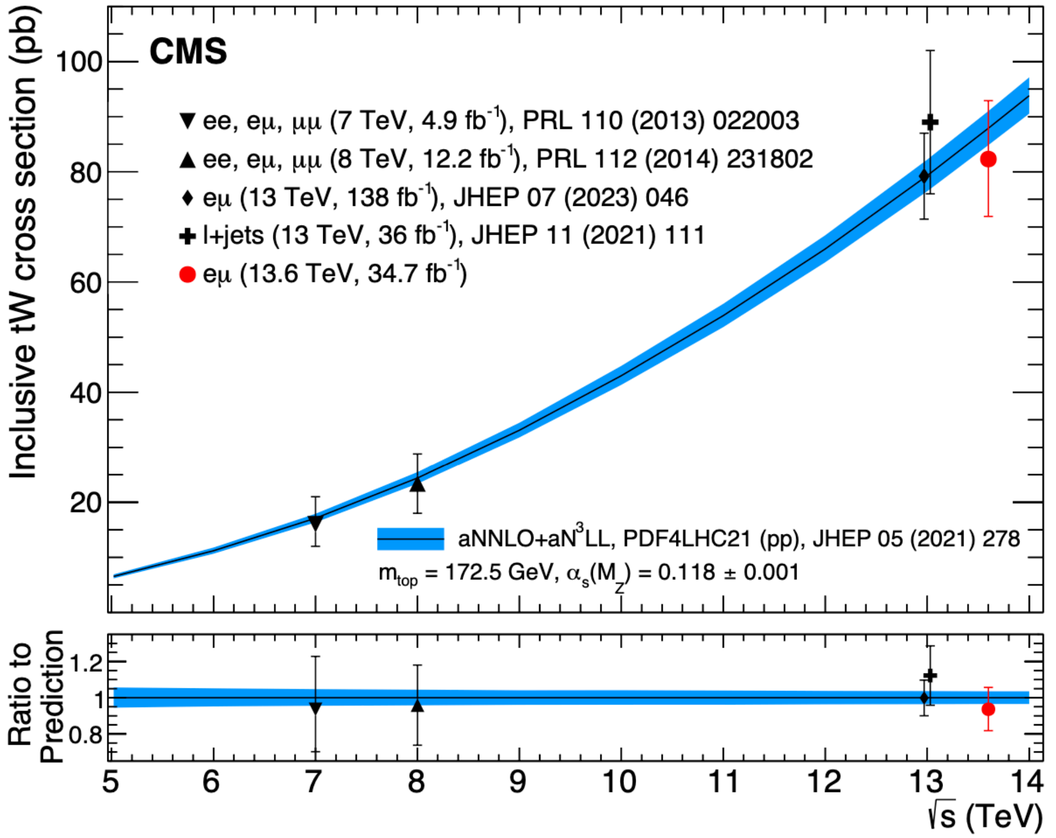
- MVA classifiers (Random Forests) to separate tW from irreducible tt̄ background in SRs



# Inclusive tW cross section at 13.6 TeV

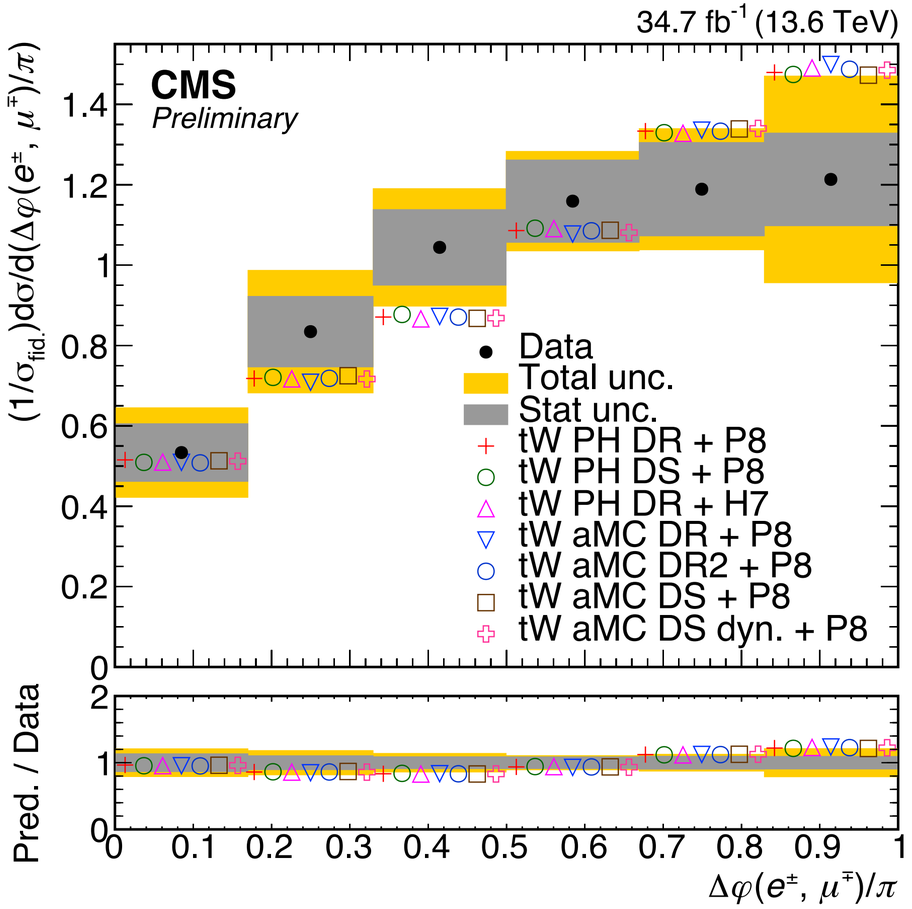
- Result: $\sigma_{tW} = 84.1 \pm 2.1(\text{stat.})^{+9.8}_{-10.2}(\text{syst.}) \pm 3.3(\text{lum})\ \text{pb}$

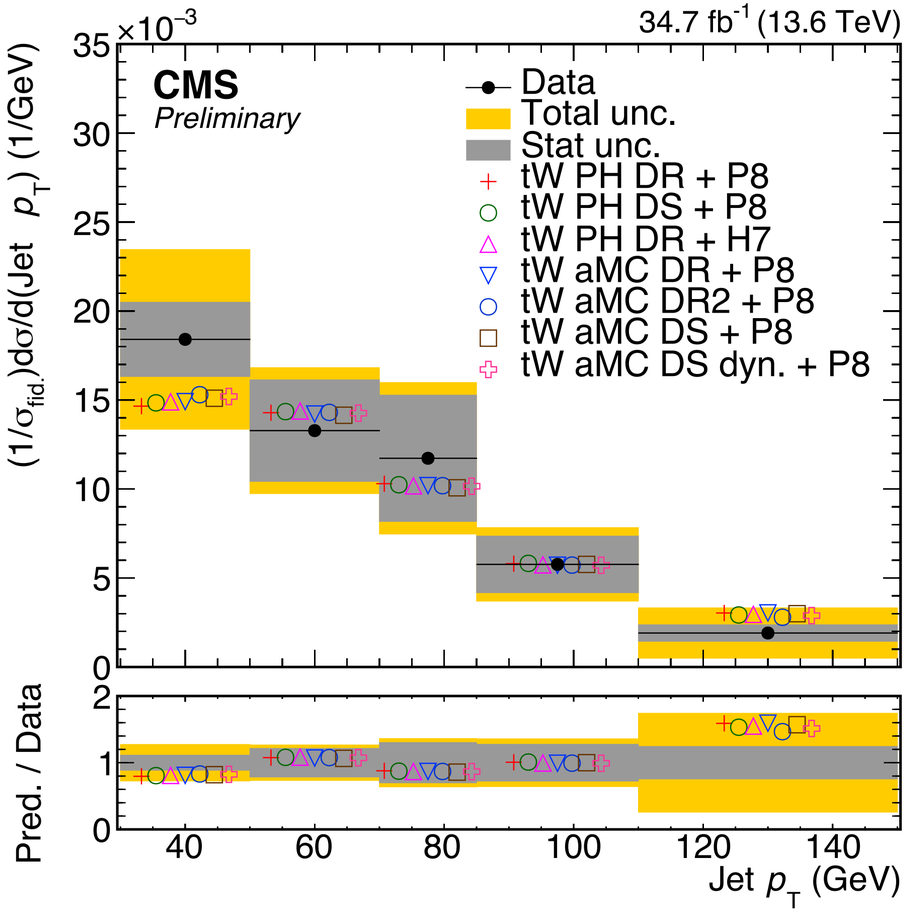
- Compatible with SM N$^3$LO prediction
- Limited by systematic uncertainties:
  - mainly jet energy scale, b tagging and background modelling



# Differential tW cross sections at 13.6 TeV

- Differential cross sections measured in 1j1b region, with veto on jets with $p_T$ 20-30 GeV
- Several jet and lepton observables unfolded to particle level using TUnfold [1]
- Good agreement with predictions from different generators, and different schemes for treating the interference between $t\bar{t}$ and tW




[1] [arXiv:1205.6201]

# Summary

- Putting the SM to the test with processes involving top quark EW couplings
- Simultaneous measurements enhance sensitivity to BSM effects
- Run 2 and Run 3 data give access to **very rare top+V** processes
- **Shown today:**
  - First evidence for **tWZ**
  - First simultaneous measurement of **$t\bar{t}$Z+tWZ** and **tZq** → **Statistically limited, can still improve with more data!**
  - First inclusive and differential **tW** measurement in Run 3

**More results on their way: stay tuned!**

# BACKUP

# Treating the interference between tWZ and ttZ

MadSTR plugin used for removal through diagram removal schemes

Amplitude A divided into A(res) and A(non-res)

- **DR1**: removes A(res) in A, used for **nominal**
- DR2: removes $|A(res)|^2$ in $|A|^2$ (leaves interference term) for uncertainty
- DS: subtraction term, lies between DR1 and DR2

## Overview of diagram removal/subtraction schemes

Frixione et al., JHEP12(2019)008

NLO process $a + b \longrightarrow \delta + \gamma + X$ with a possible resonance $\beta \longrightarrow \delta + \gamma$

$$\mathcal{A}_{ab\to\delta\gamma X} = \mathcal{A}^{(\not\beta)}_{ab\to\delta\gamma X} + \mathcal{A}^{(\beta)}_{ab\to\delta\gamma X}$$

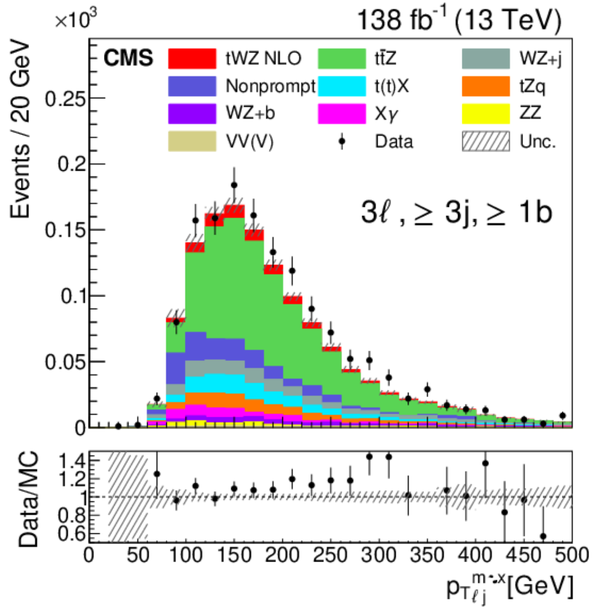
non-resonant resonant

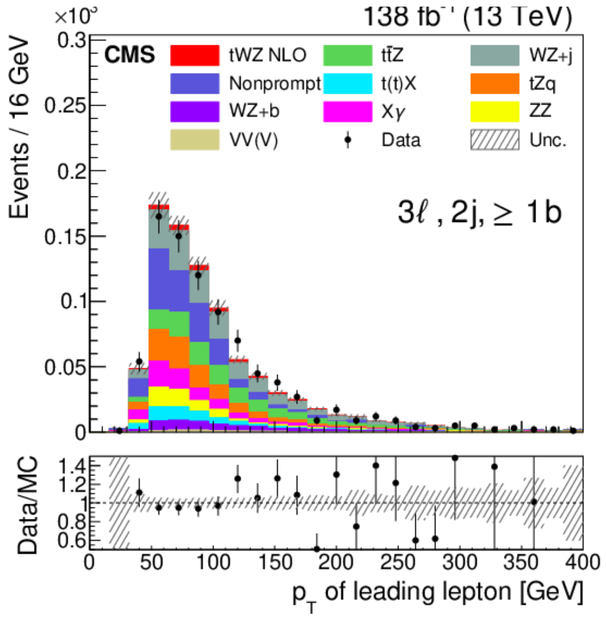
$$|\mathcal{A}_{ab\to\delta\gamma X}|^2 = \left|\mathcal{A}^{(\not\beta)}_{ab\to\delta\gamma X}\right|^2 + 2\Re\left(\mathcal{A}^{(\not\beta)}_{ab\to\delta\gamma X}\mathcal{A}^{(\beta)\dagger}_{ab\to\delta\gamma X}\right) + \left|\mathcal{A}^{(\beta)}_{ab\to\delta\gamma X}\right|^2$$

- DR+I (DR1): removes both resonance and interference term
- DR2: removes only the resonant term
- The diagram subtraction (DS) scheme implements removal at the cross section level

A. Saggio
LHCTopWG meeting
07/06/2023

# More on the tWZ selection




| | $SR_{3\ell,3j}$ | $SR_{3\ell,2j}$ | $SR_{4\ell}$ | $SR^{Boosted}$ | $CR_{WZ}$ | $CR_{ZZ}$ |
|---|---|---|---|---|---|---|
| tWZ signal | $77.47 \pm 0.12$ | $28.19 \pm 0.07$ | $15.98 \pm 0.06$ | $5.44 \pm 0.02$ | $31.96 \pm 0.08$ | $2.39 \pm 0.02$ |
| $t\bar{t}Z$ | $657.9 \pm 1.6$ | $122.76 \pm 0.61$ | $113.86 \pm 0.64$ | $59.03 \pm 0.50$ | $112.41 \pm 0.73$ | $14.44 \pm 0.23$ |
| Nonprompt leptons | $139 \pm 42$ | $170 \pm 51$ | $1.02 \pm 0.31$ | $1.94 \pm 0.58$ | $1450 \pm 430$ | $23.0 \pm 7.0$ |
| tZq | $86.45 \pm 0.78$ | $108.69 \pm 0.71$ | $0.29 \pm 0.04$ | $4.37 \pm 0.17$ | $74.84 \pm 0.67$ | $0.05 \pm 0.01$ |
| ZZ | $22.7 \pm 2.4$ | $60.6 \pm 4.1$ | $20.0 \pm 2.3$ | $0.30 \pm 0.29$ | $597 \pm 12$ | $2202 \pm 22$ |
| WZ | $166.4 \pm 3.3$ | $227.8 \pm 4.0$ | $0.59 \pm 0.19$ | $6.84 \pm 0.66$ | $10610 \pm 25$ | $0.68 \pm 0.16$ |
| VV(V) | $15.51 \pm 0.11$ | $10.55 \pm 0.09$ | $1.35 \pm 0.03$ | $0.64 \pm 0.02$ | $166 \pm 14$ | $16.52 \pm 0.07$ |
| $t(\bar{t})X$ | $108.30 \pm 0.99$ | $49.4 \pm 1.2$ | $17.32 \pm 0.34$ | $6.26 \pm 0.19$ | $39.4 \pm 1.8$ | $1.08 \pm 0.07$ |
| $X\gamma$ | $54.1 \pm 2.6$ | $78.3 \pm 3.7$ | $6.92 \pm 0.95$ | $1.08 \pm 0.31$ | $519 \pm 11$ | $2.53 \pm 0.60$ |
| Total backgrounds | $1249 \pm 42$ | $822 \pm 51$ | $159.9 \pm 2.6$ | $80.8 \pm 1.1$ | $13520 \pm 430$ | $2028 \pm 23$ |
| Data | 1463 | 849 | 180 | 77 | 12743 | 2352 |

- Nonprompt lepton contribution estimated from data:
  - Weights derived from simulated QCD multimeter samples and assigned to events in CR enriched in nonprompt leptons
  - 30% uncertainty assigned from validation test

# Neural networks in the tWZ analysis

- Resolved: 3 leptons, 2j, ≥ 1b **Binary NN**
  3 leptons, ≥ 3j, ≥ 1b **Multiclass NN**
  ~~4 leptons, ≥ 1b~~

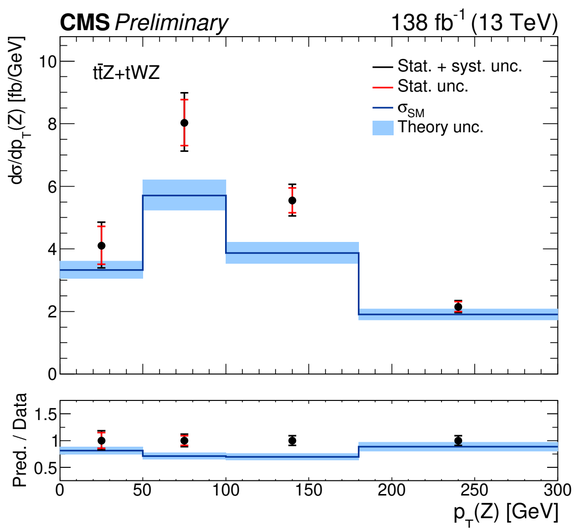
Binary classifier DNN discriminating tWZ vs backgrounds.
**Inputs**: nbjet, jet pT and eta, observables combining jet and lepton kinematics

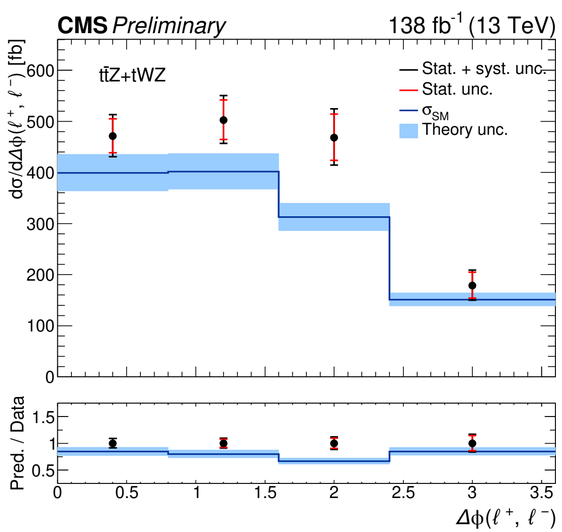
Fully connected DNN with tWZ, ttZ and background output nodes. **Inputs**: nbjet, jet pT and eta, observables combining jet and lepton kinematics, reconstructed top quark kinematics

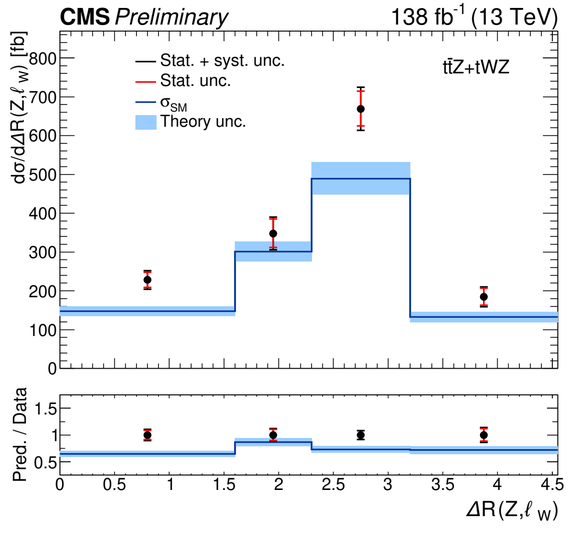
- Boosted: ~~hadronic top decay (fat jet)~~
  Leptonic top decay (lep. top tagger)

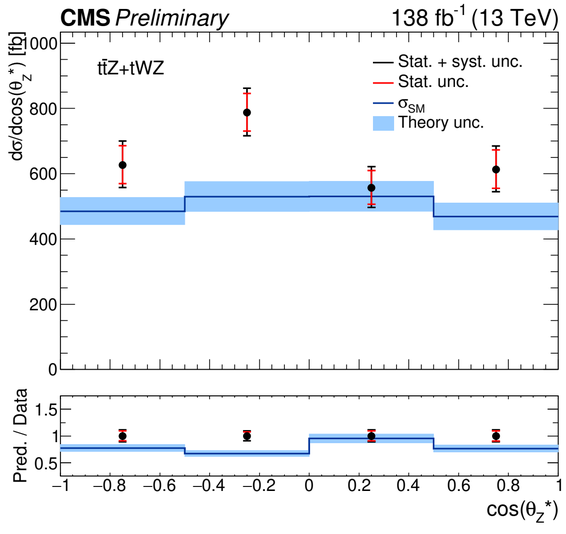
Fully connected DNN to tag lepton from the high pT top quark.
**Inputs**: third lepton and b jet kinematics

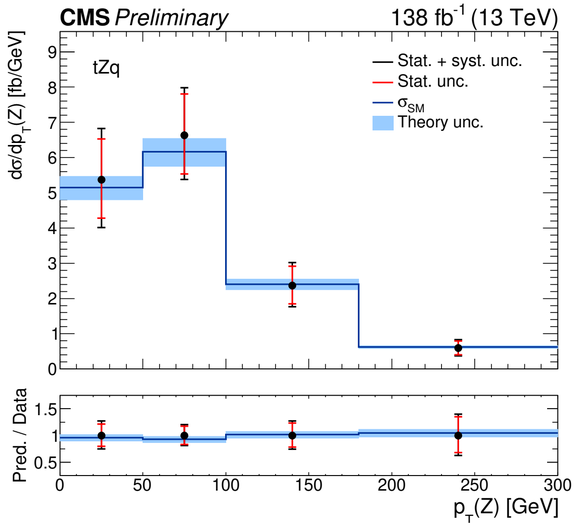
# ttZ, tWZ and tZq - other differential distributions

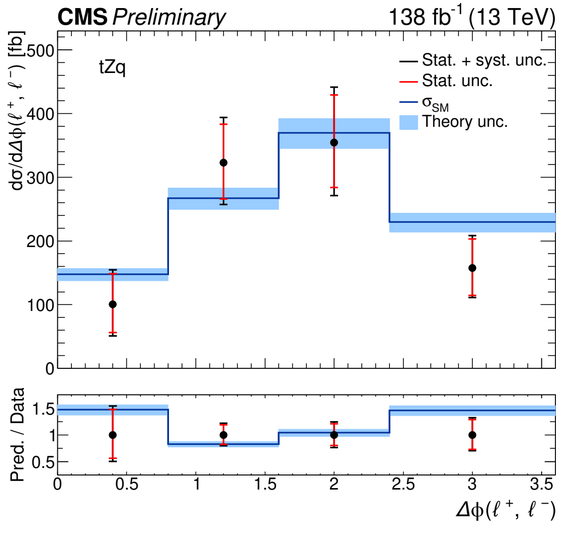


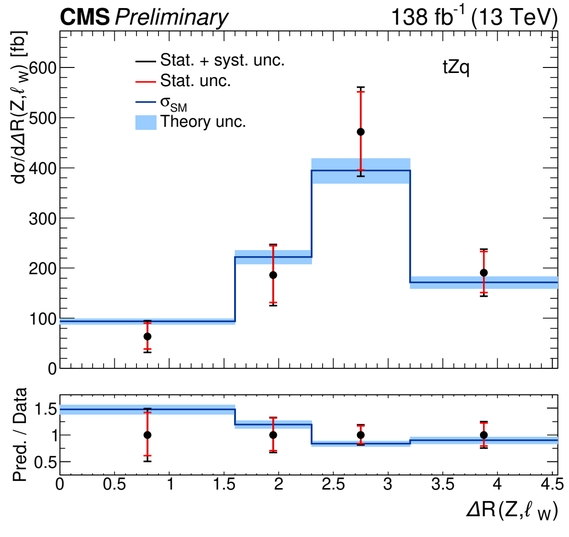



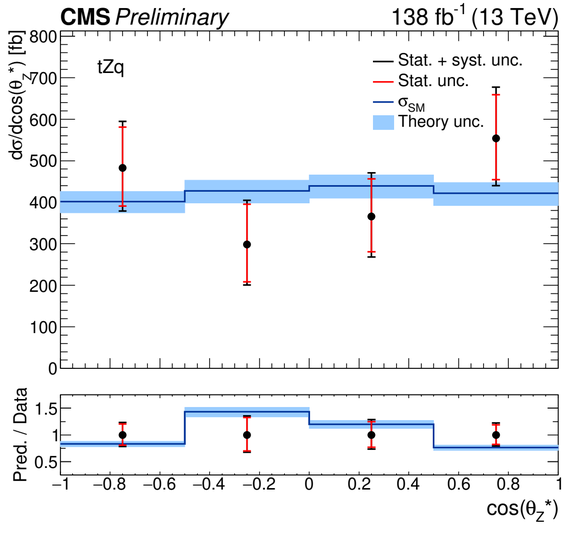



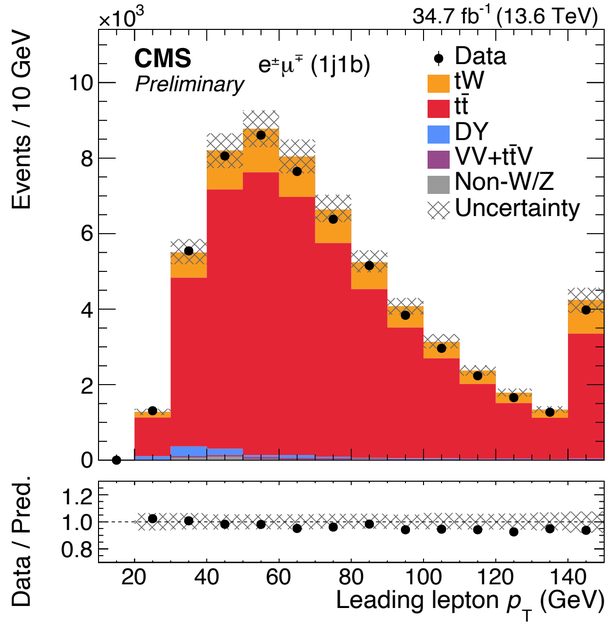



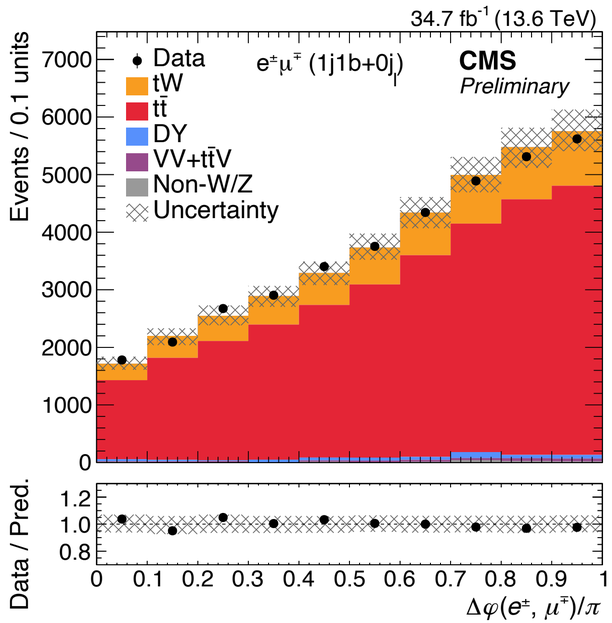



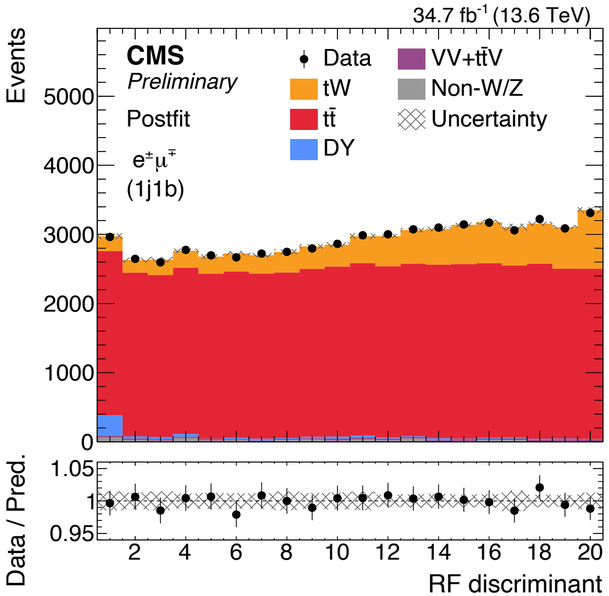
# ttZ, tWZ and tZq - systematic uncertainties

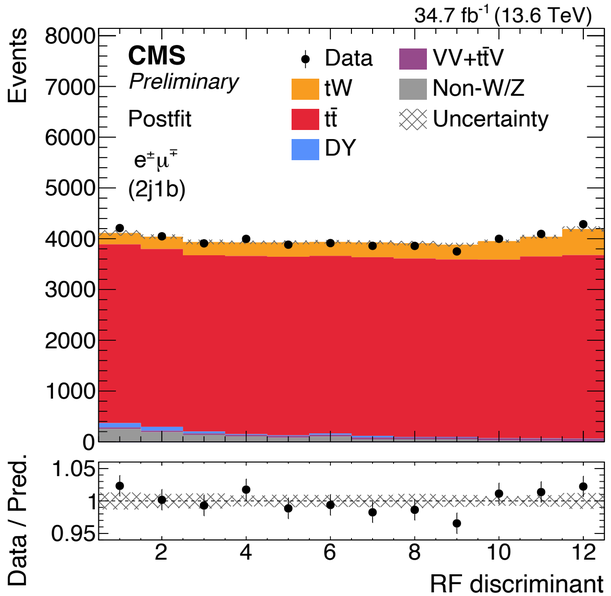
| Source | $\sigma(t\bar{t}Z + tWZ)$ | $\sigma(tZq)$ |
|---|---|---|
| Trigger | 2% | 2% |
| Trigger prefiring | <1% | 2% |
| Lepton identification efficiencies | 1% | 2% |
| b tagging | 1% | 2% |
| Jet energy scale | 1% | 3% |
| Jet energy resolution | <1% | 1% |
| Missing transverse momentum | <1% | 3% |
| Nonprompt background | 2% | 3% |
| Pileup | <1% | 1% |
| Luminosity | 2% | 2% |
| Statistical | 3.7% | 10% |
| Background modeling | 2% | 4% |
| Factorization scale | 1% | 1% |
| Renormalization scale | 1% | 2% |
| Parton shower | <1% | 2% |
| PDF and $\alpha_S$ | <1% | <1% |
| Underlying event and color reconnection | 1% | 2% |
| tWZ modeling | <1% | <1% |
| MC statistical | <1% | 1% |
| Total | 6% | 13% |

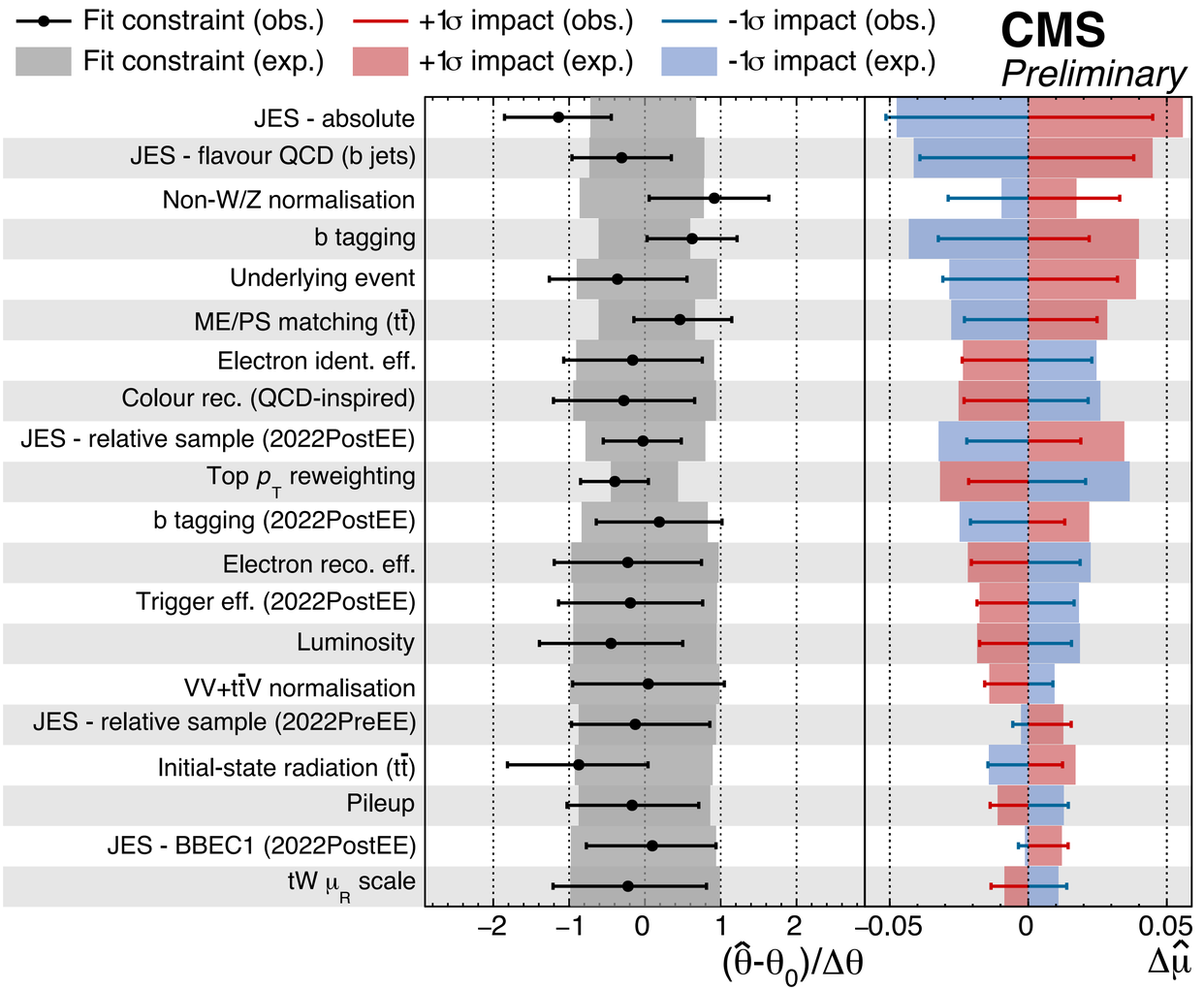
# tW at 13.6 TeV - more distributions and syst. Uncertainties



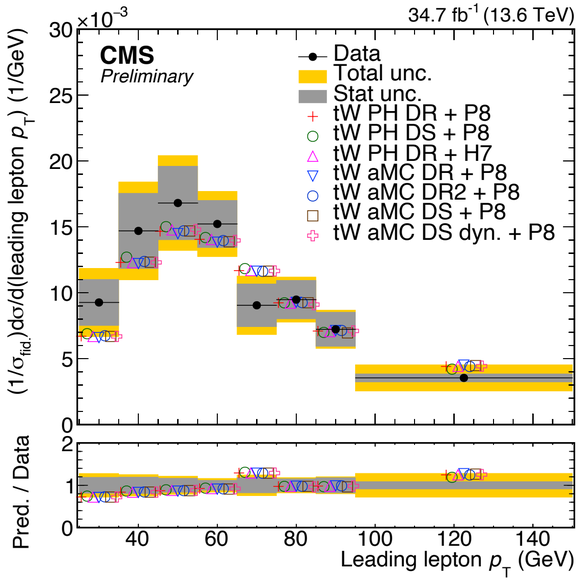



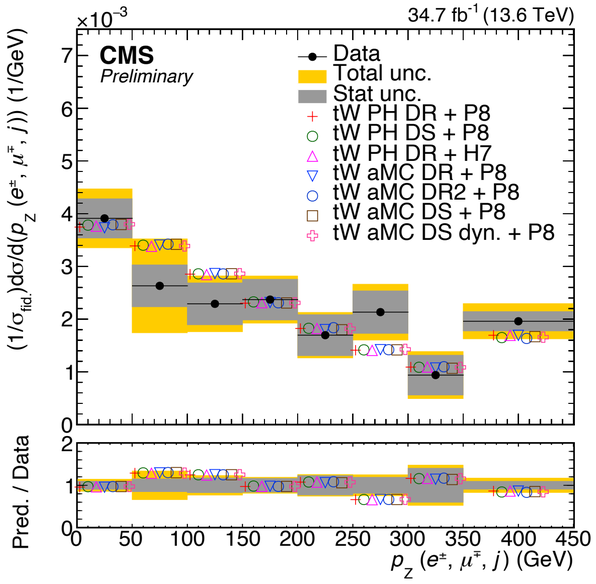



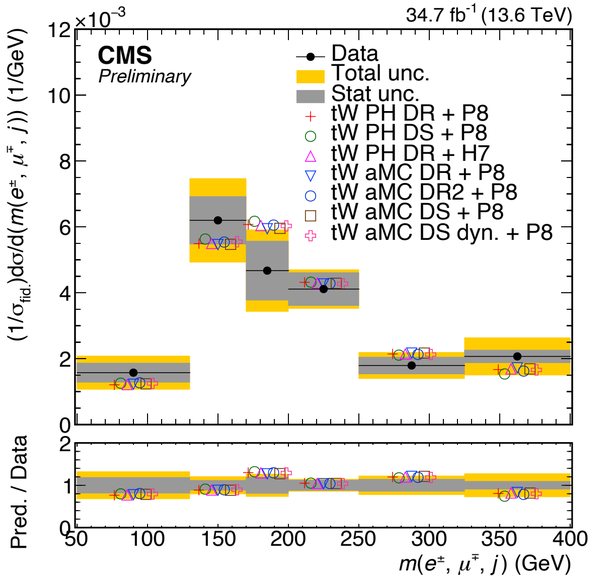



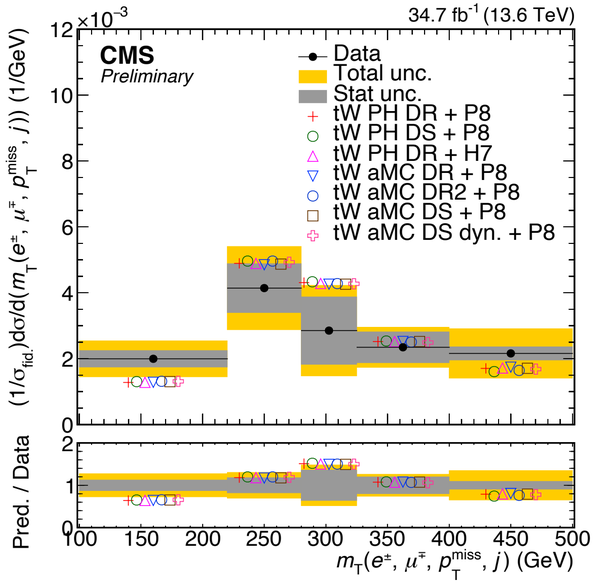



# tW at 13.6 TeV - more differential distributions

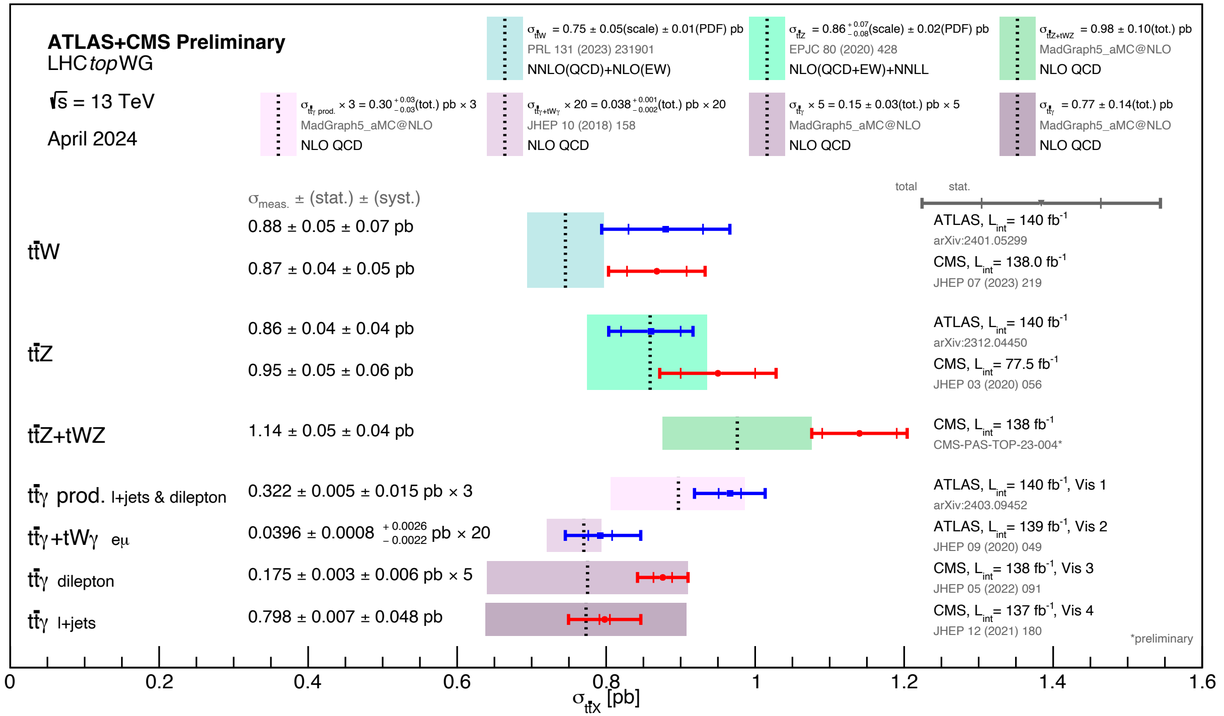


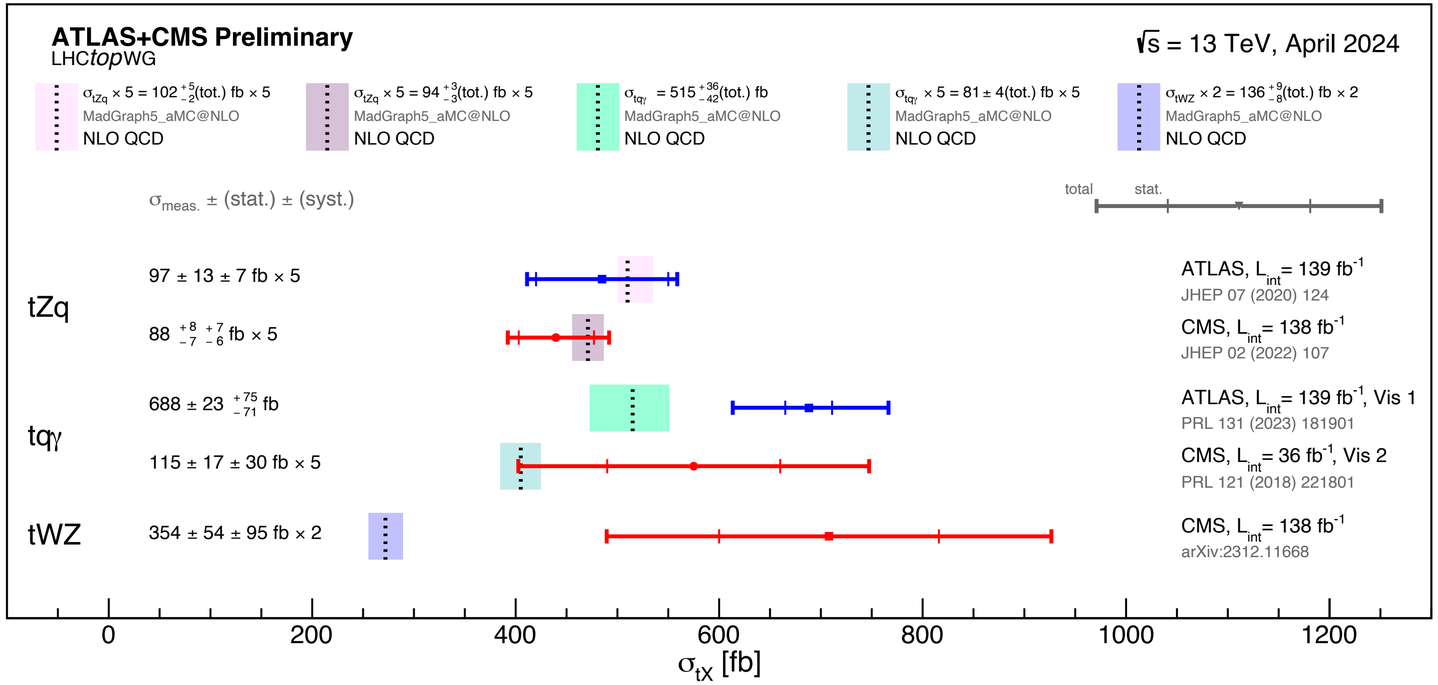



# Summary


ATLAS+CMS Preliminary
LHCtopWG
√s = 13 TeV
April 2024
σ_tW = 0.75 ± 0.05(scale) ± 0.01(PDF) pb
PRL 131 (2023) 231901
NNLO(QCD)+NLO(EW)
σ_tZ = 0.86 +0.07 −0.08 (scale) ± 0.02(PDF) pb
EPJC 80 (2020) 428
NLO(QCD+EW)+NNLL
σ_tZ+WZ = 0.98 ± 0.10(tot.) pb
MadGraph5_aMC@NLO
NLO QCD
σ_tt̄γ prod. × 3 = 0.30 +0.03 −0.03 (tot.) pb × 3
MadGraph5_aMC@NLO
NLO QCD
σ_tt̄γ+tWγ × 20 = 0.038 +0.001 −0.002 (tot.) pb × 20
JHEP 10 (2018) 158
NLO QCD
σ_tt̄γ × 5 = 0.15 ± 0.03(tot.) pb × 5
MadGraph5_aMC@NLO
NLO QCD
σ_tt̄γ = 0.77 ± 0.14(tot.) pb
MadGraph5_aMC@NLO
NLO QCD
σ_meas. ± (stat.) ± (syst.)
total
stat.
tt̄W
0.88 ± 0.05 ± 0.07 pb
0.87 ± 0.04 ± 0.05 pb
ATLAS, L_int = 140 fb-1
arXiv:2401.05299
CMS, L_int = 138.0 fb-1
JHEP 07 (2023) 219
tt̄Z
0.86 ± 0.04 ± 0.04 pb
0.95 ± 0.05 ± 0.06 pb
ATLAS, L_int = 140 fb-1
arXiv:2312.04450
CMS, L_int = 77.5 fb-1
JHEP 03 (2020) 056
tt̄Z+tWZ
1.14 ± 0.05 ± 0.04 pb
CMS, L_int = 138 fb-1
CMS-PAS-TOP-23-004*
tt̄γ prod. l+jets & dilepton
0.322 ± 0.005 ± 0.015 pb × 3
ATLAS, L_int = 140 fb-1, Vis 1
arXiv:2403.09452
tt̄γ+tWγ eμ
0.0396 ± 0.0008 +0.0026 −0.0022 pb × 20
ATLAS, L_int = 139 fb-1, Vis 2
JHEP 09 (2020) 049
tt̄γ dilepton
0.175 ± 0.003 ± 0.006 pb × 5
CMS, L_int = 138 fb-1, Vis 3
JHEP 05 (2022) 091
tt̄γ l+jets
0.798 ± 0.007 ± 0.048 pb
CMS, L_int = 137 fb-1, Vis 4
JHEP 12 (2021) 180
*preliminary
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
σ_tX [pb]


ATLAS+CMS Preliminary
LHCtopWG
√s = 13 TeV, April 2024
σ_tZq × 5 = 102 +5 −2 (tot.) fb × 5
MadGraph5_aMC@NLO
NLO QCD
σ_tZq × 5 = 94 +3 −3 (tot.) fb × 5
MadGraph5_aMC@NLO
NLO QCD
σ_tqγ = 515 +36 −42 (tot.) fb
MadGraph5_aMC@NLO
NLO QCD
σ_tqγ × 5 = 81 ± 4(tot.) fb × 5
MadGraph5_aMC@NLO
NLO QCD
σ_tWZ × 2 = 136 +9 −8 (tot.) fb × 2
MadGraph5_aMC@NLO
NLO QCD
σ_meas. ± (stat.) ± (syst.)
total
stat.
tZq
97 ± 13 ± 7 fb × 5
ATLAS, L_int = 139 fb-1
JHEP 07 (2020) 124
88 +8 −7 +7 −6 fb × 5
CMS, L_int = 138 fb-1
JHEP 02 (2022) 107
tqγ
688 ± 23 +75 −71 fb
ATLAS, L_int = 139 fb-1, Vis 1
PRL 131 (2023) 181901
115 ± 17 ± 30 fb × 5
CMS, L_int = 36 fb-1, Vis 2
PRL 121 (2018) 221801
tWZ
354 ± 54 ± 95 fb × 2
CMS, L_int = 138 fb-1
arXiv:2312.11668
0
200
400
600
800
1000
1200
σ_tX [fb]