LHC top WG

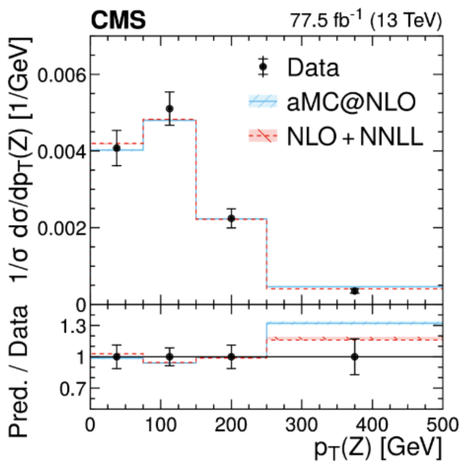
Measurements of inclusive and differential cross sections for top quark production in association with a Z boson in proton-proton collisions at $\sqrt{s}$ = 13 TeV

Beatriz Ribeiro Lopes, on behalf of the CMS collaboration

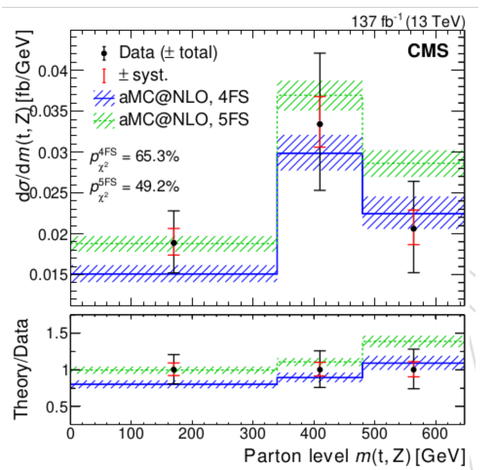
Introduction

- Top-boson processes offer insight into QCD and EW sectors
- Differential measurements of **tZq** and **tt̄Z** with Run 2 by both ATLAS and CMS
- Evidence for **tWZ** reported by CMS
- Simultaneous measurement:
  - less dependent on signal modelling assumptions,
  - consistently treat correlations between systematic uncertainties
  - ✦ enhance sensitivity to deviations from SM that affect all processes (e.g. anomalous **tZ**, **tbW** couplings)

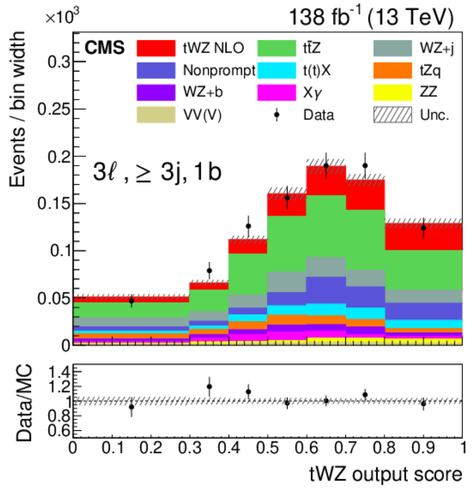
JHEP03(2020)056

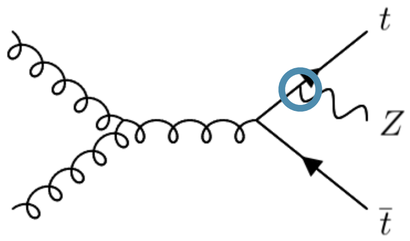


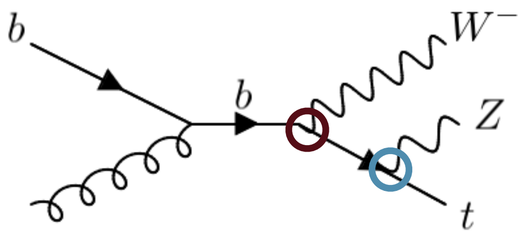
JHEP02(2022)107

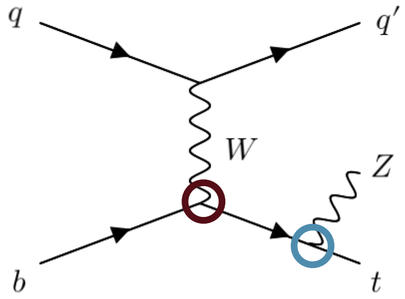


Phys. Lett. B 855 (2024) 138815



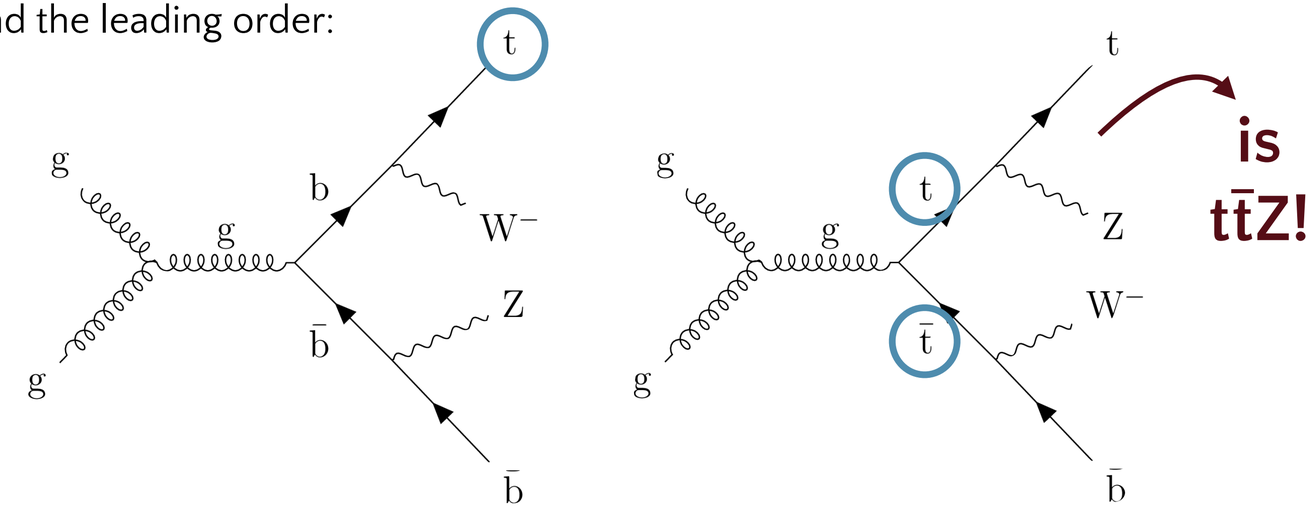






Modelling of tWZ

- Overlaps with $t\bar{t}Z$ and $t\bar{t}$ within the SM beyond the leading order:



- Amplitude split into resonant and non-resonant part $\mathcal{A}_{pp\to tWZ} = \mathcal{A}^{\text{non-resonant}}_{pp\to tWZ} + \mathcal{A}^{\text{resonant}}_{pp\to tWZ}$

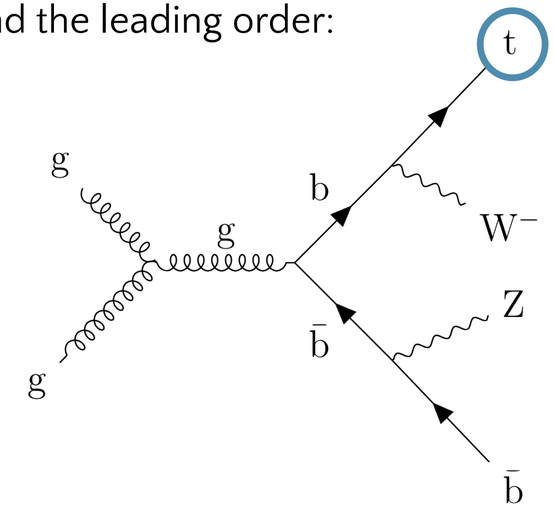
$$|\mathcal{A}_{pp\to tWZ}|^2 = |\mathcal{A}^{\text{non-resonant}}_{pp\to tWZ}|^2 + |\mathcal{A}^{\text{resonant}}_{pp\to tWZ}|^2 + 2\mathcal{R}(\mathcal{A}^{\text{non-resonant}}_{pp\to tWZ}\mathcal{A}^{\text{resonant}\,\dagger}_{pp\to tWZ})$$

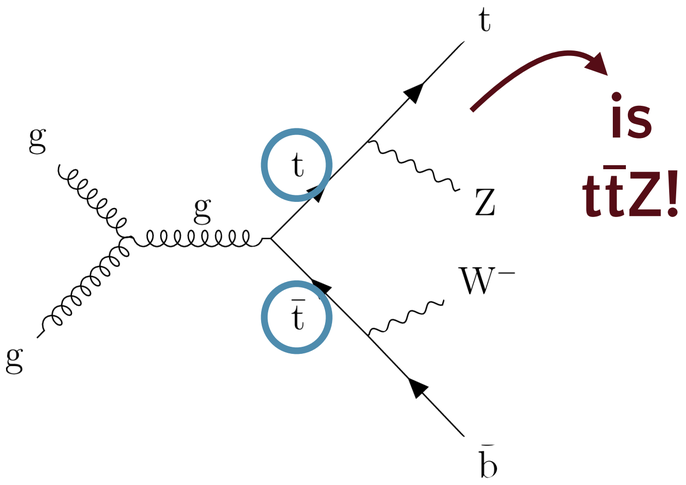
- **DR1** removes $\mathcal{A}^{\text{resonant}}_{pp\to tWZ}$ in $\mathcal{A}$, **DR2** removes $|\mathcal{A}^{\text{resonant}}_{pp\to tWZ}|^2$ in $\mathcal{A}^2$, leaving interference term, **DS** adds a subtraction term

- **DR1 used as nominal**, DR2 for uncertainty (DS lies in between the two)

Modelling of tWZ

- Overlaps with $t\bar{t}Z$ and $t\bar{t}$ within the SM beyond the leading order:





is $t\bar{t}Z$!

- Amplitude split into resonant and non-resonant part $\mathcal{A}_{pp\to tWZ} = \mathcal{A}^{\text{non-resonant}}_{pp\to tWZ} + \mathcal{A}^{\text{resonant}}_{pp\to tWZ}$

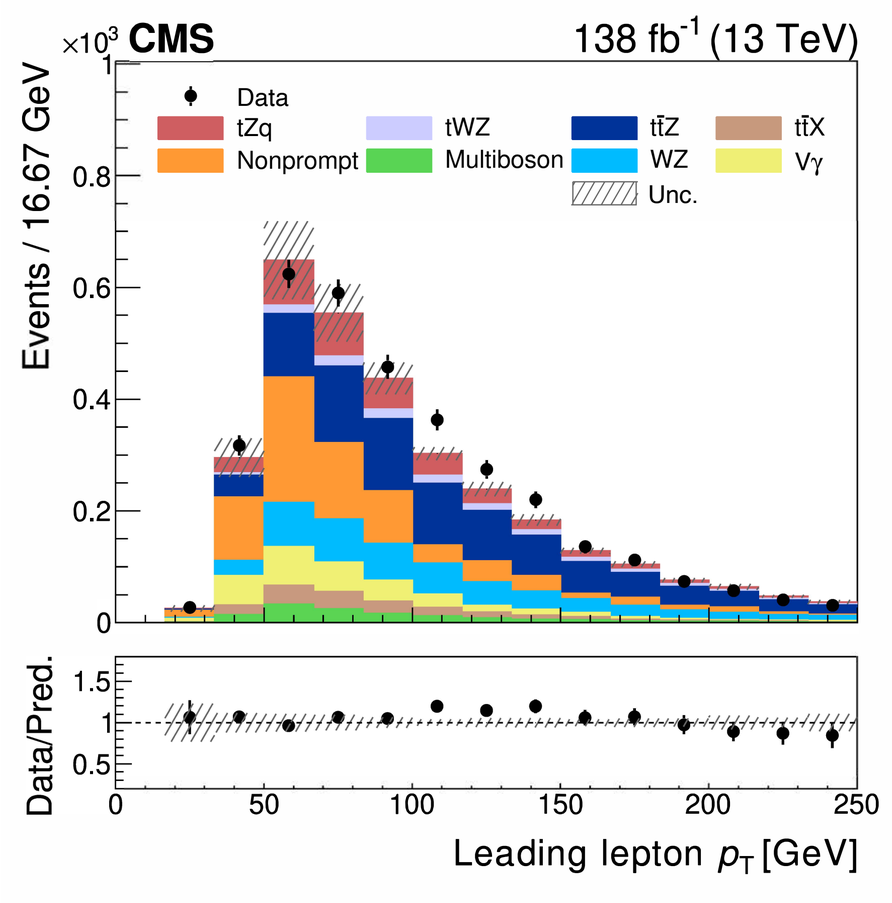
$$|\mathcal{A}_{pp\to tWZ}|^2 = |\mathcal{A}^{\text{non-resonant}}_{pp\to tWZ}|^2 + |\mathcal{A}^{\text{resonant}}_{pp\to tWZ}|^2 + 2\mathcal{R}(\mathcal{A}_{p}$$

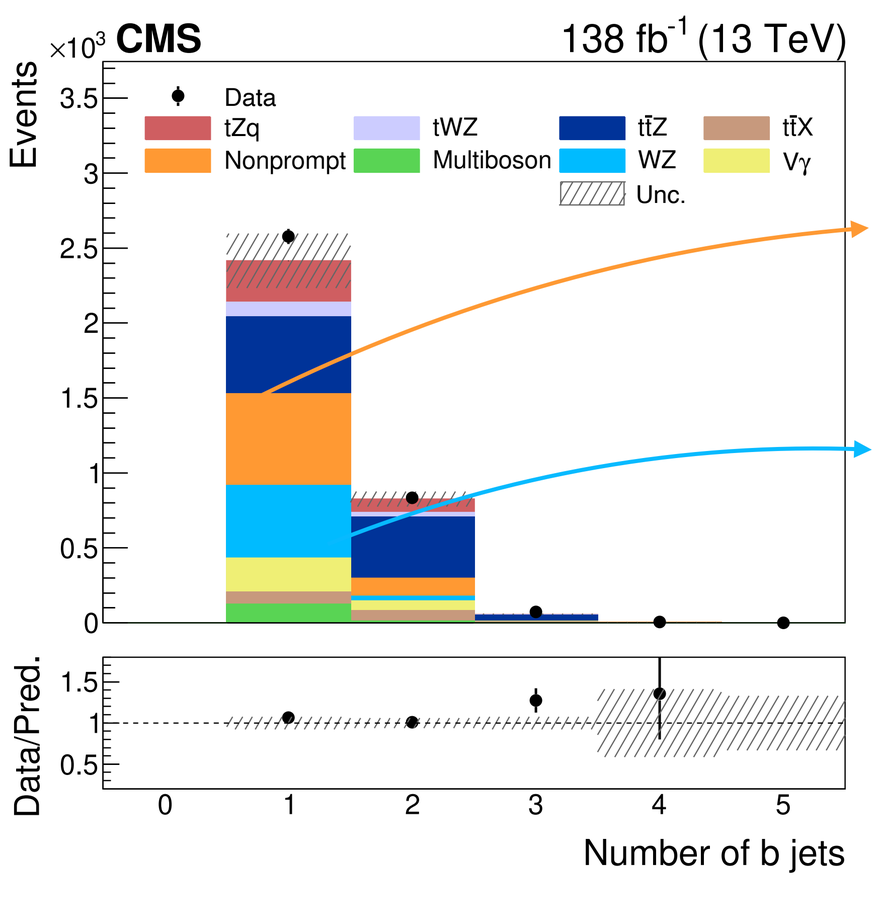
$t\bar{t}Z$ and tWZ are treated as one signal

- **DR1** removes $\mathcal{A}^{\text{resonant}}_{pp\to tWZ}$ in $\mathcal{A}$, **DR2** removes $|\mathcal{A}^{\text{resonant}}_{pp\to tWZ}|^2$ in $\mathcal{A}^2$, leaving inte.
- **DR1 used as nominal**, DR2 for uncertainty (DS lies in between the two)

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

- Single signal region with **exactly three leptons** (e or μ), **≥2 jets**, **≥1 b-tagged jet**
- One opposite sign lepton pair with invariant mass consistent with Z boson
- Jets with $|\eta| < 5$, if b-tagged required to be central





Nonprompt lepton contribution estimated from data

WZ and other smaller backgrounds from simulation

Nonprompt lepton estimation

Measurement region (MR)

- QCD multijet samples
- Exactly 1 “fakeable”* lepton
- >= 1 jet well-separated from lepton

Application region (AR)

- Same selection as SR, but with “fakeable” leptons

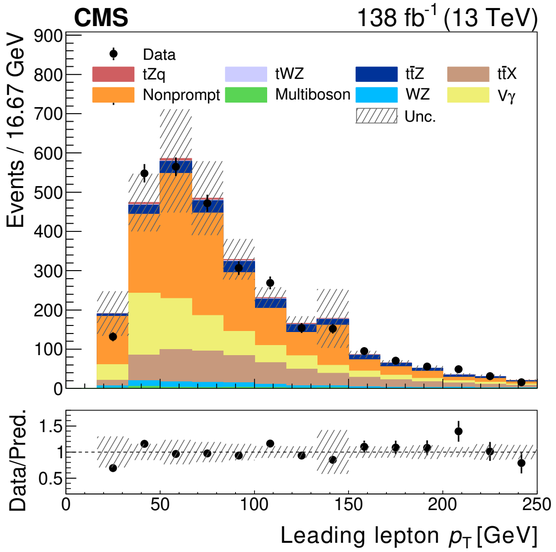
Compute per lepton:

$$\text{"fake" factor } f_i = \frac{N_{\text{tight}}}{N_{\text{tight}} + N_{\text{fakeable}}}$$

per event:

$$\text{weight} = (-1)^{n^{**}-1} \prod_{i=1}^{3} \frac{f_i}{1 - f_i}$$

Apply to

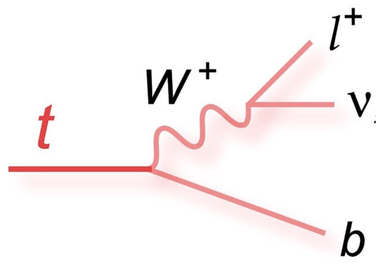


- Contribution in SR = (Reweighted data in AR – prompt contribution from simulation)
- Estimation validated in off Z-peak region
- Statistical uncertainties on f_i propagated from MR & additional per-bin uncertainty for residual nonclosure

*fakeable: leptons with loose quality criteria
**n: # of fakeable leptons not passing the tight ID

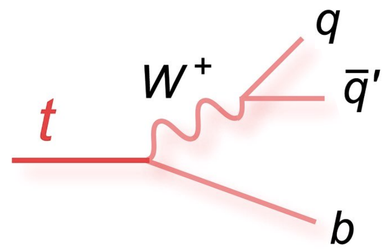
Top quark reconstruction

- Top quark reconstruction algorithm considers three cases:
  - **2 jets, 1 b tag:** leptonic top is reconstructed from $\ell + \nu + b$



  - **3 jets, ≥1 b tag:** leptonic and hadronic top candidates are reconstructed separately, lowest χ^2 kept

$$\chi^2_{t,lep} = \left(\frac{m_{l\nu b} - m_t}{\sigma_{t,lep}}\right)^2 \qquad \chi^2_{t,had} = \left(\frac{m_{jjb} - m_t}{\sigma_{t,had}}\right)^2$$

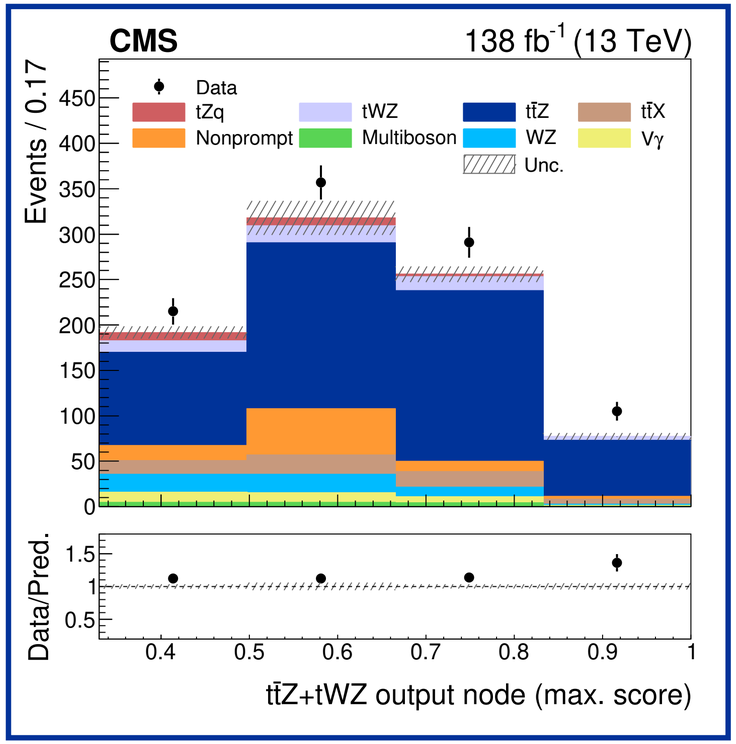


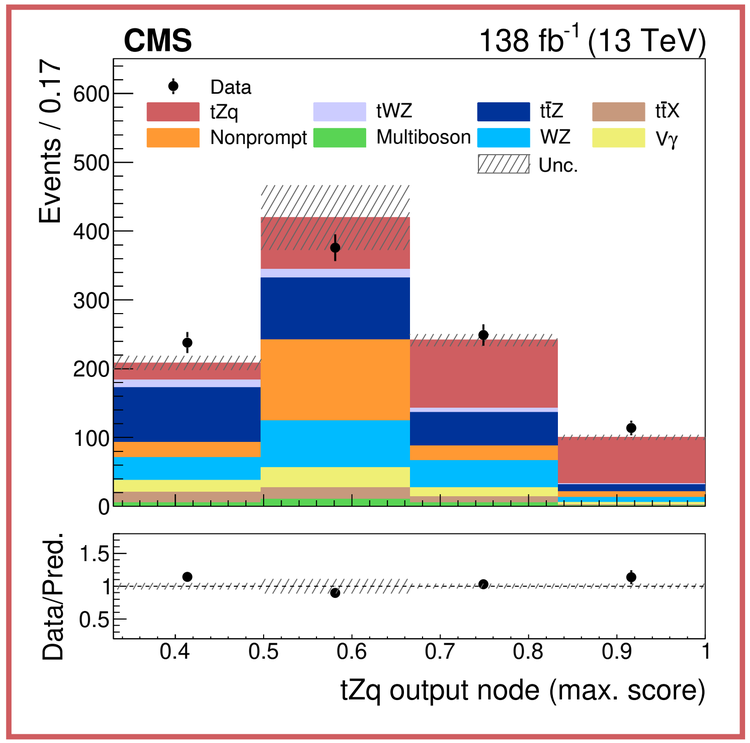
  - **≥4 jets, ≥1 b tag:** both hadronic and leptonic top are reconstructed

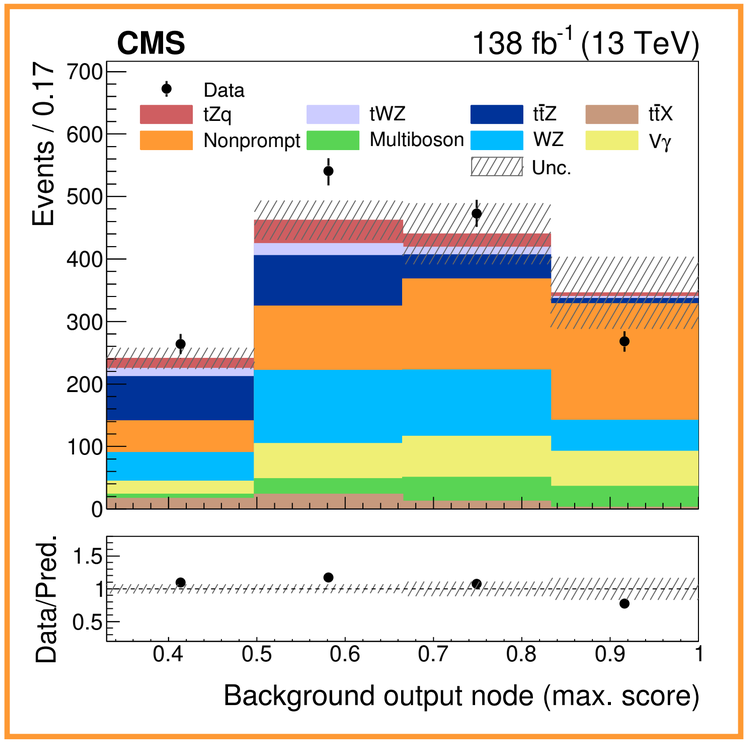
$$\chi^2_t = \left(\frac{m_{l\nu b} - m_t}{\sigma_{t,lep}}\right)^2 + \left(\frac{m_{jjb} - m_t}{\sigma_{t,had}}\right)^2$$

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)
  - Input variables: kinematic properties; output of top quark reconstruction; number of jets, bjets







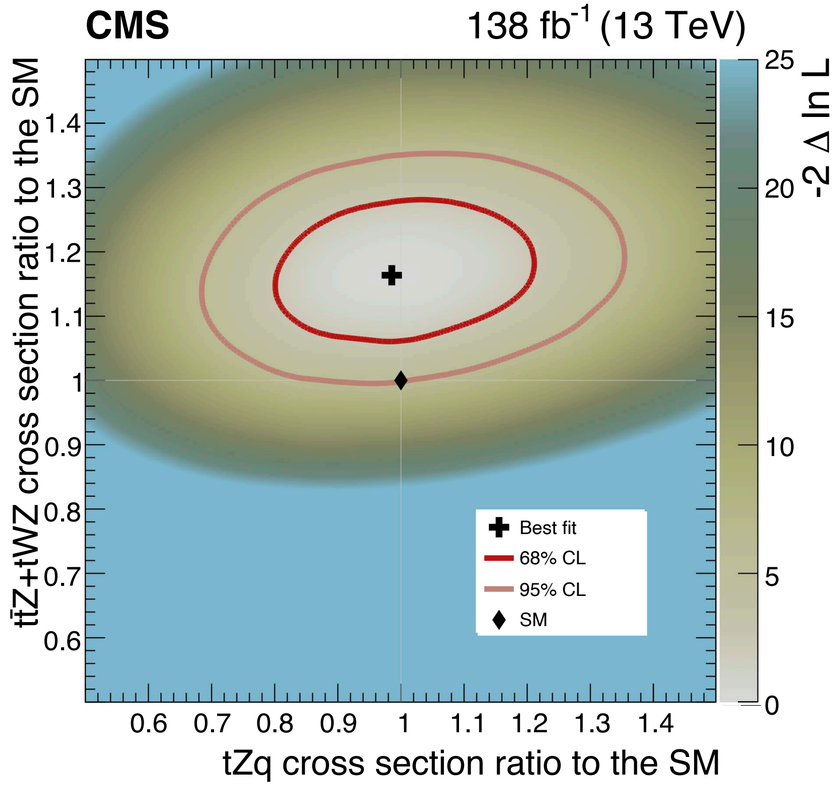
Inclusive measurement

- Simultaneous fit to 3 max-score output nodes in SR and number of jets / b jets in two extra regions ($t\bar{t}Z$ and WZ enriched)
- Profiled likelihood-ratio scan for $\sigma_{t\bar{t}Z+tWZ}$ and σ_{tZq}
- Limited by statistics, main syst. uncertainties on background modelling and b tagging
- Inclusive cross sections measured to be:

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

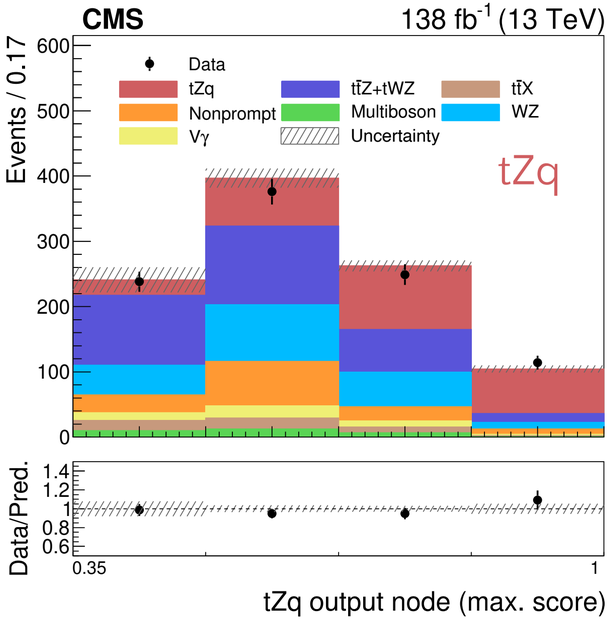
$$\sigma_{tZq} = 0.81 \pm 0.10 \text{ pb}$$

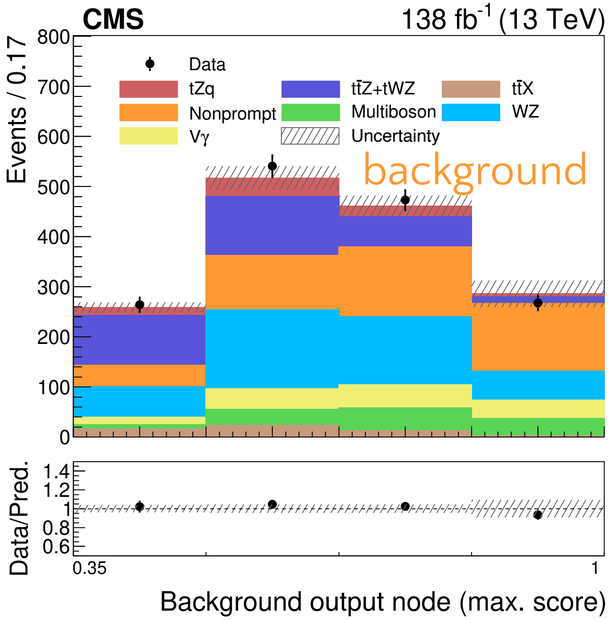
- Fixing the $t\bar{t}Z$ (tWZ) and tZq processes to the SM prediction yields a tWZ ($t\bar{t}Z$) cross section consistent with previous measurements

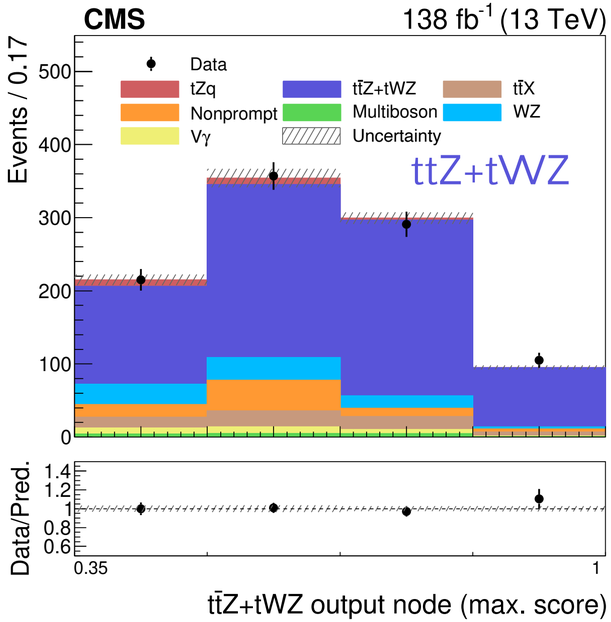


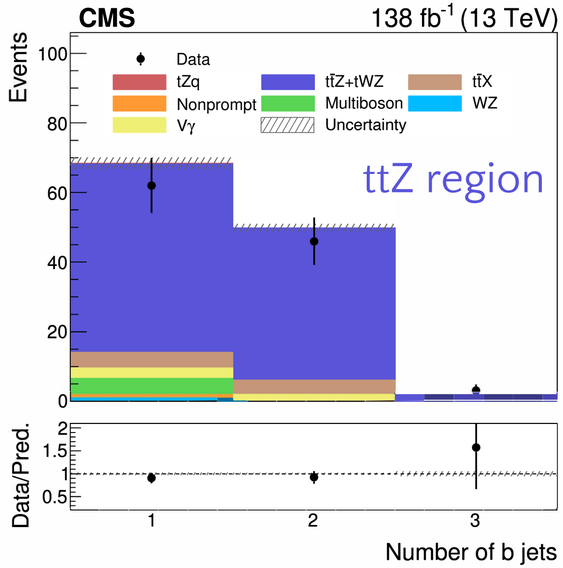
consistent with SM for **tZq**, slight excess for **$t\bar{t}$Z+tWZ**

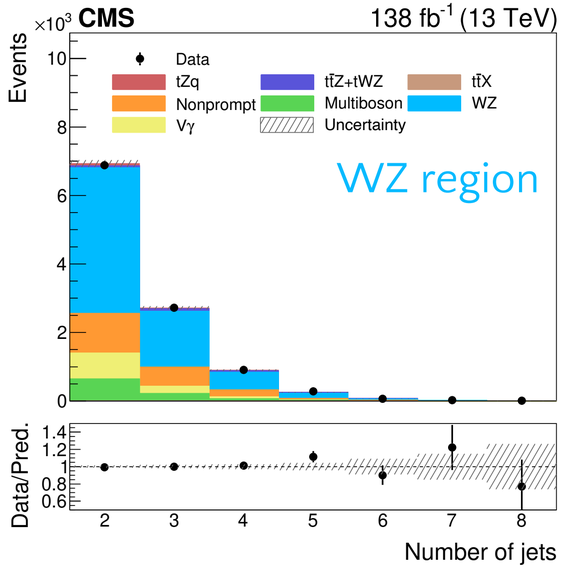
Inclusive measurement — post-fit distributions





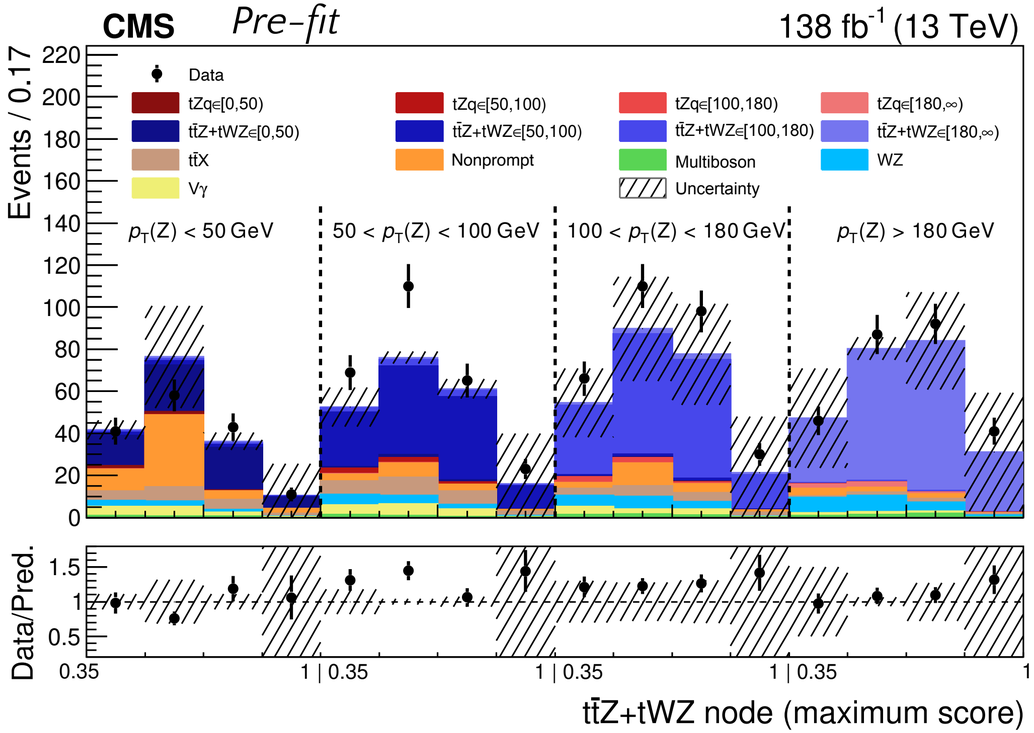


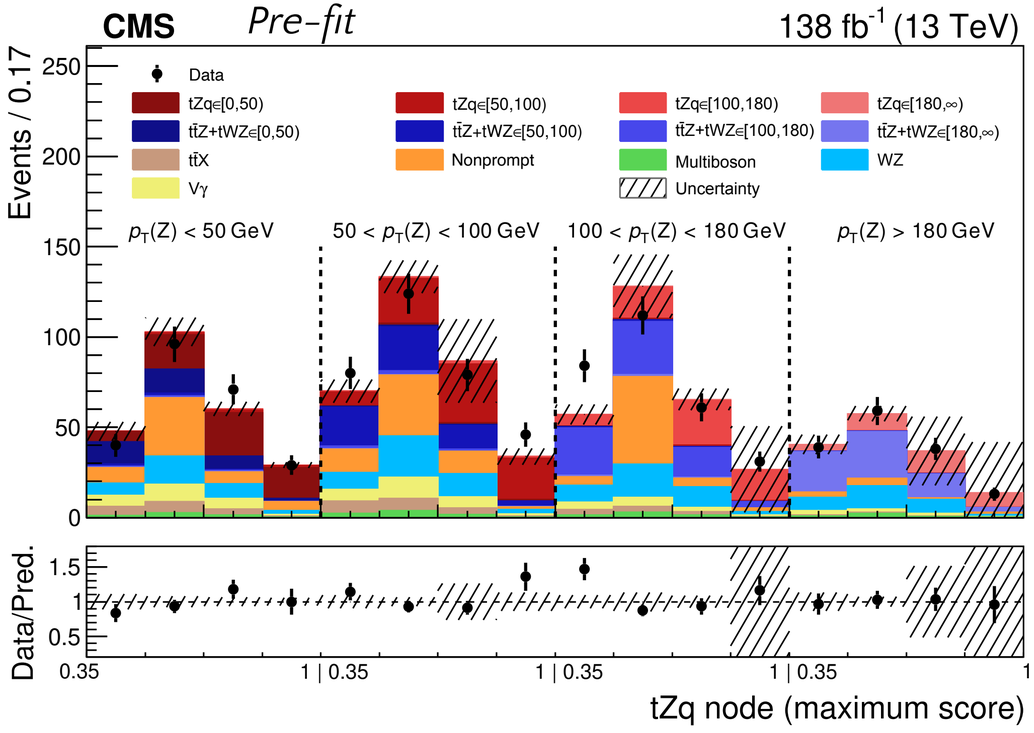




Differential measurements

- Cross sections measured as function of lepton and Z observables
- Maximum likelihood unfolding
- Templates split in generator-level bins of observable to measure for the tZq and ttZ+tWZ signals

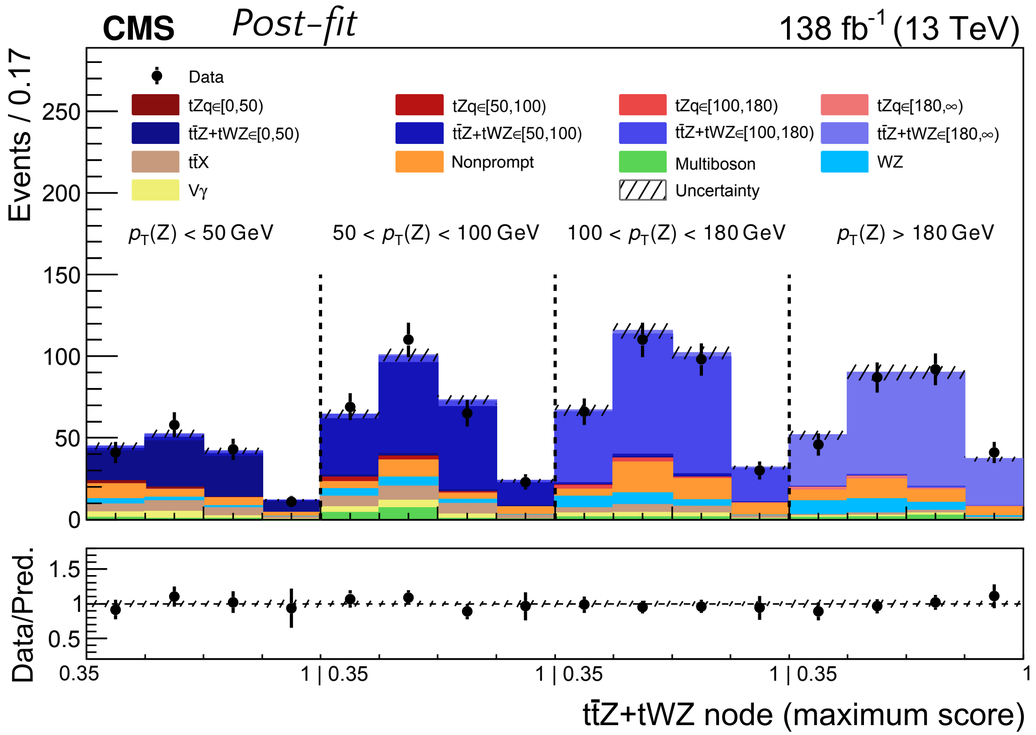


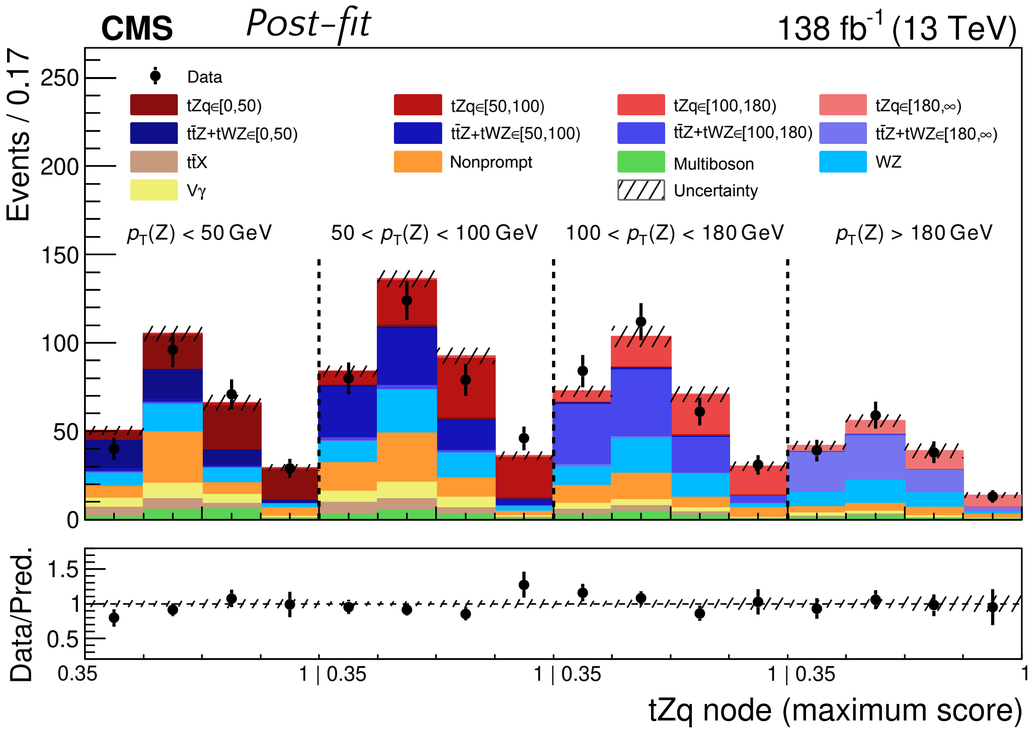


- Measurements compared to predictions from aMC@NLO

Differential measurements

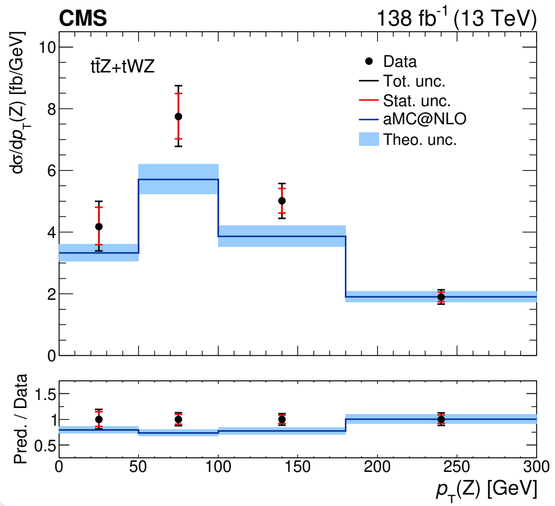
- Extract cross section modifiers from the fit and compute differential cross sections for both processes

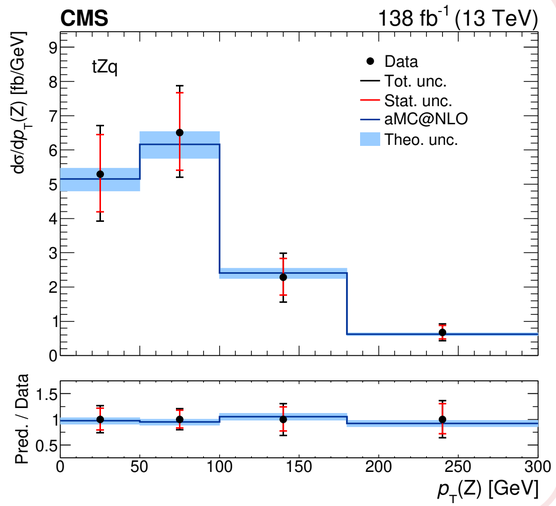


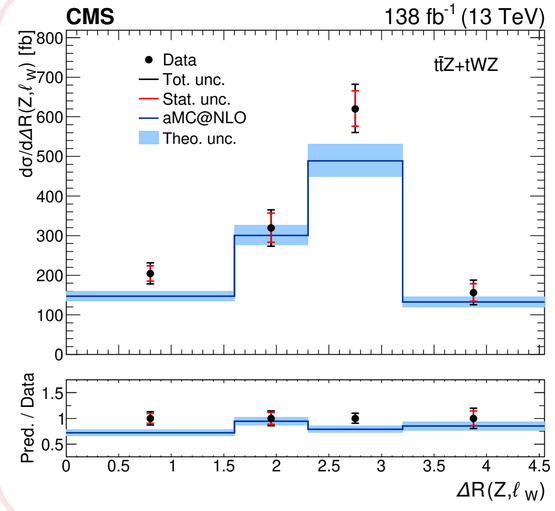


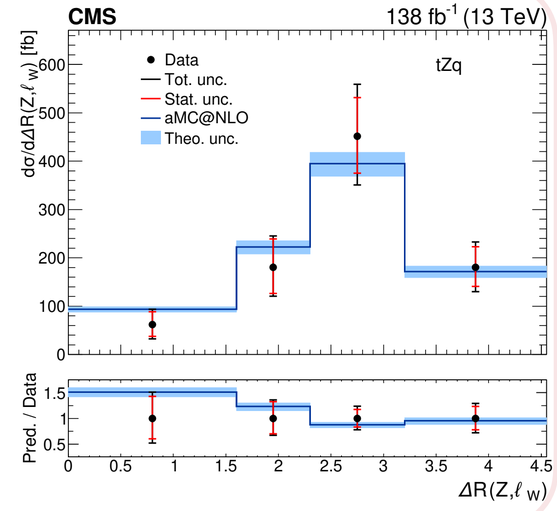
- Measurements compared to predictions from aMC@NLO

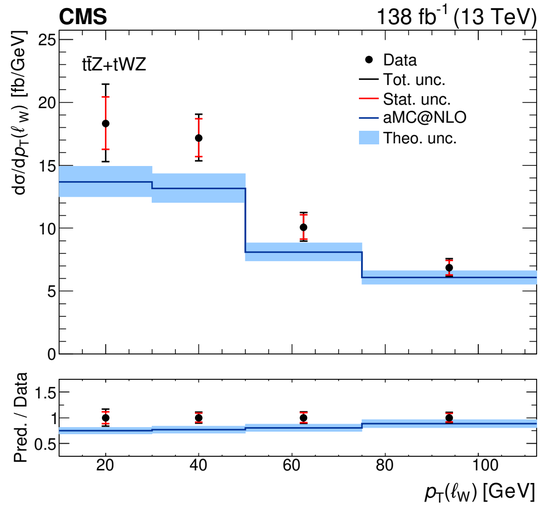
Absolute differential cross sections

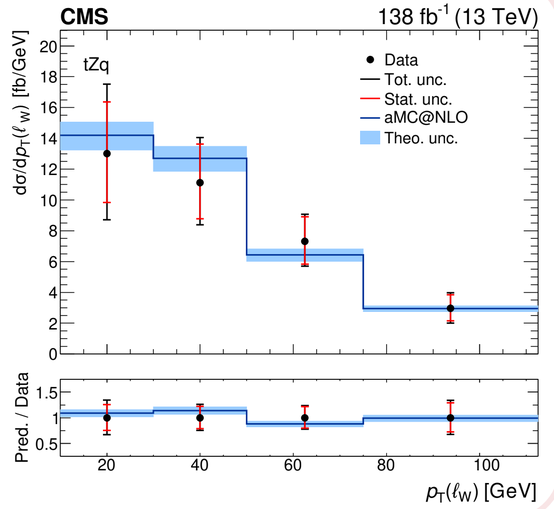


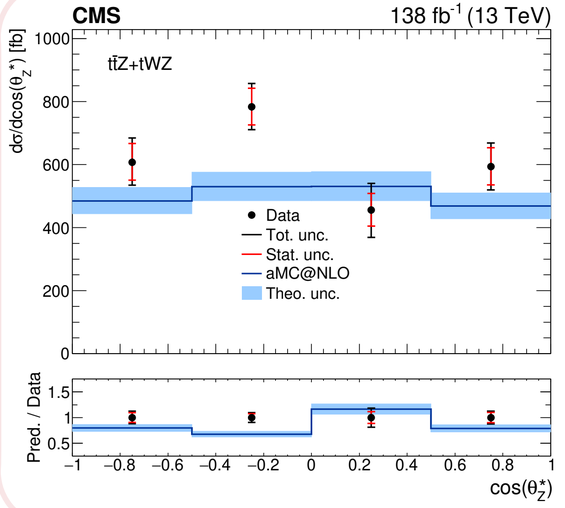


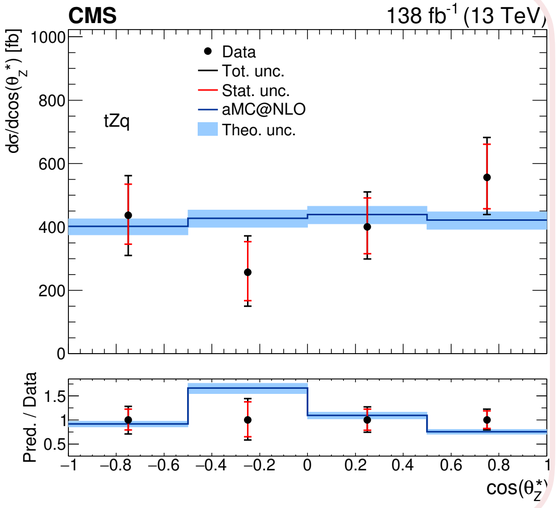






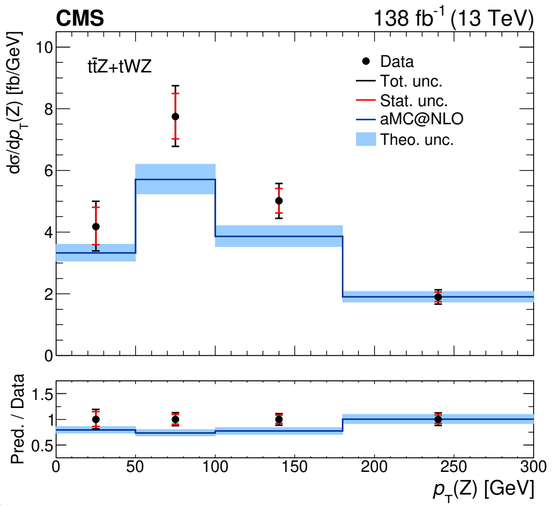


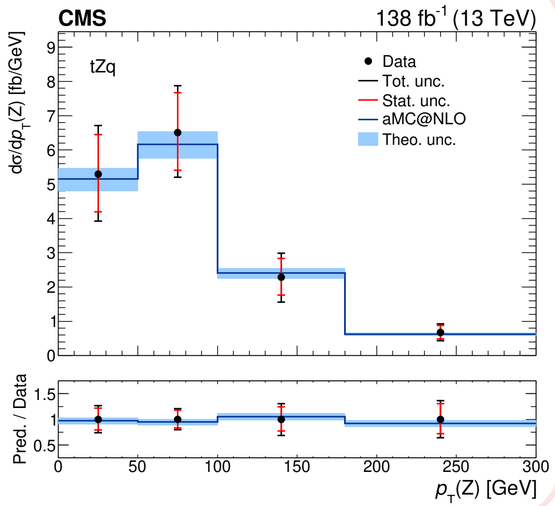


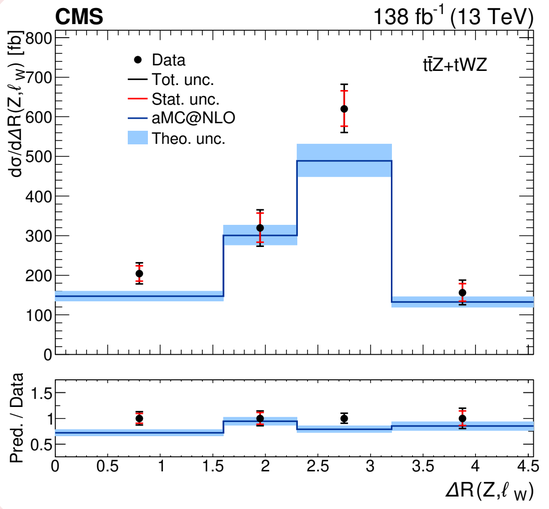


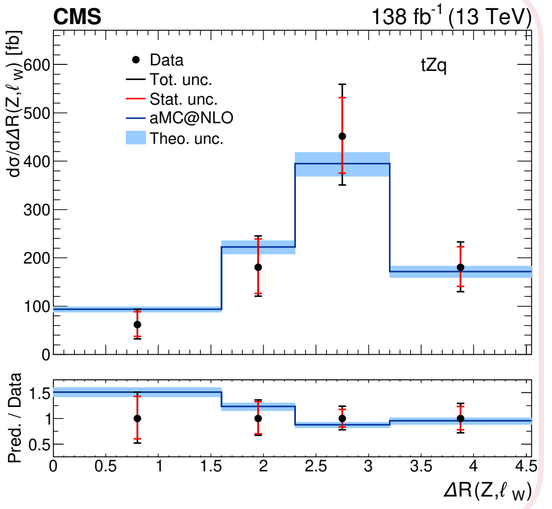
- Good agreement overall for tZq, slight excess for tt̄Z+tWZ

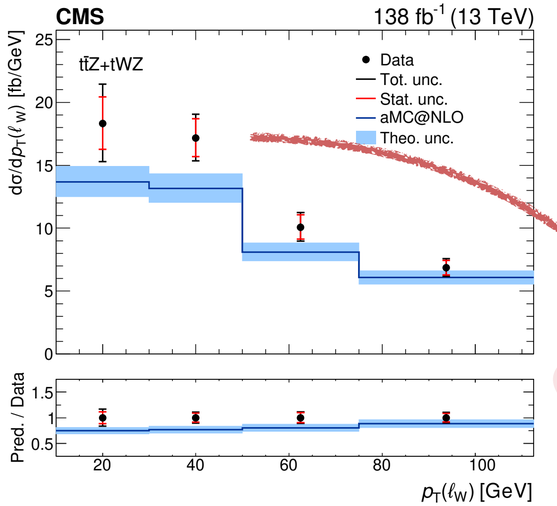
Absolute differential cross sections

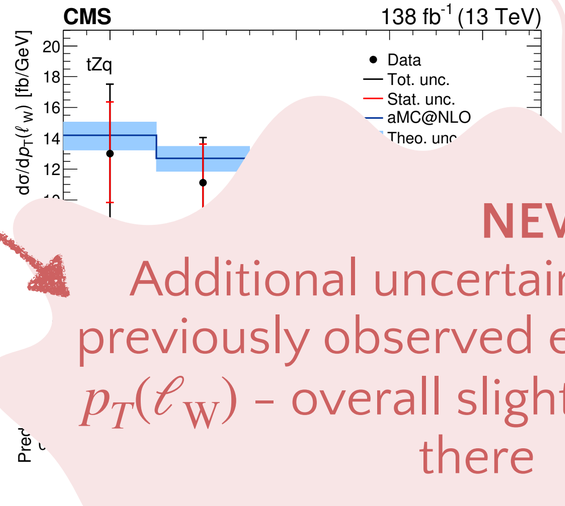


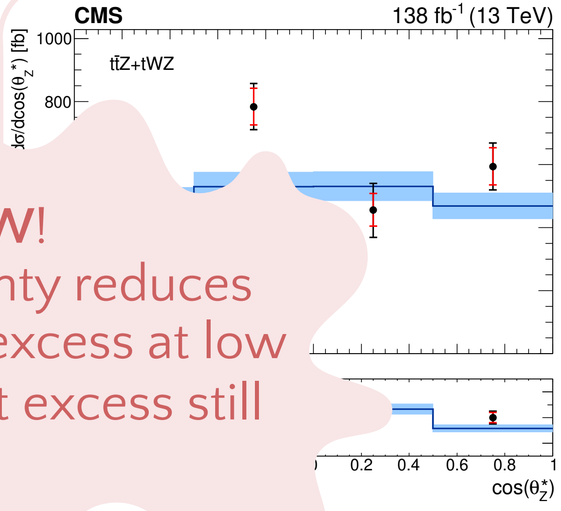


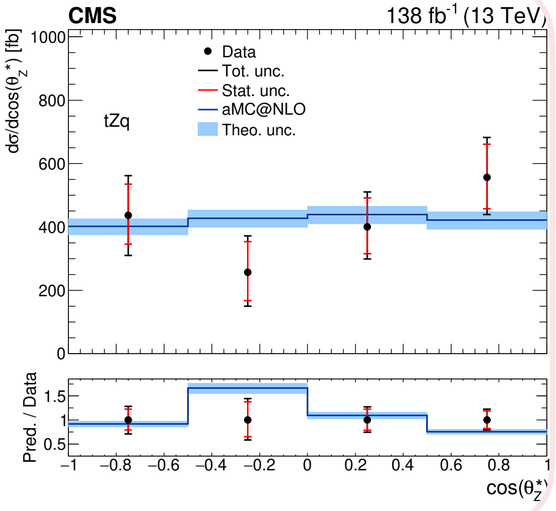










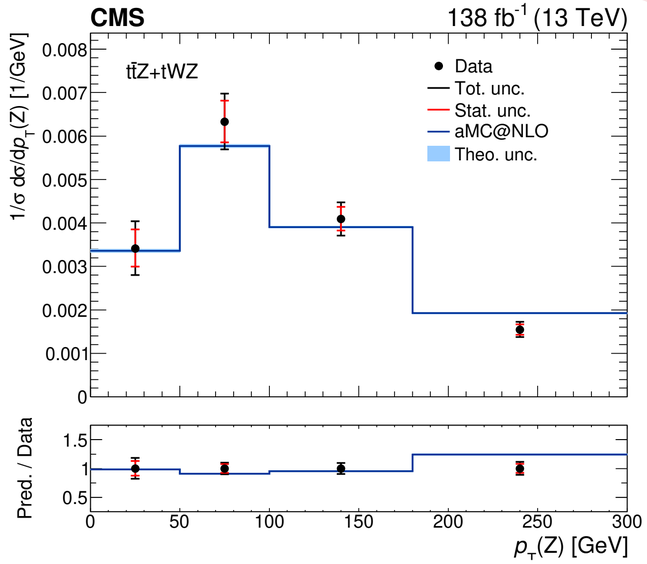


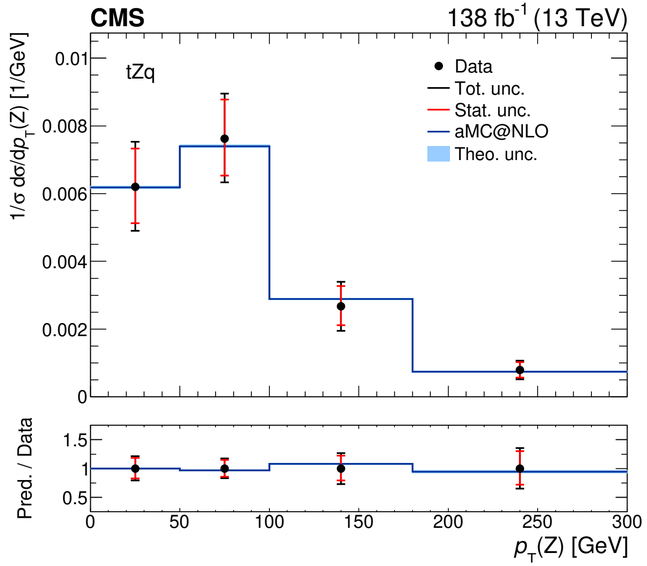
NEW!

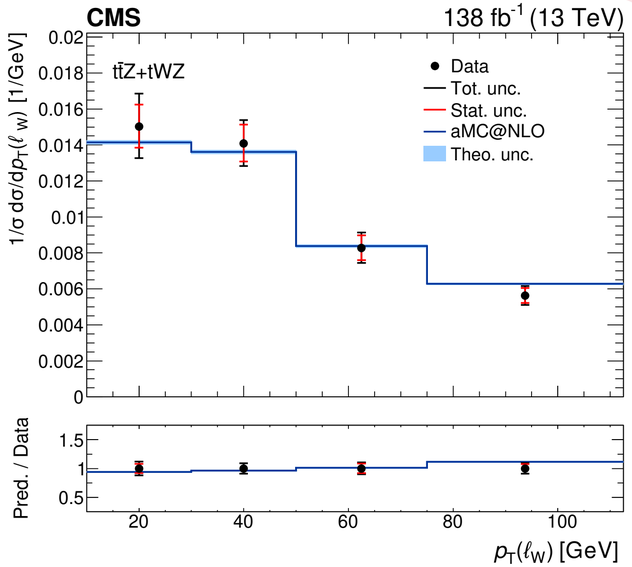
Additional uncertainty reduces previously observed excess at low $p_T(\ell_W)$ - overall slight excess still there

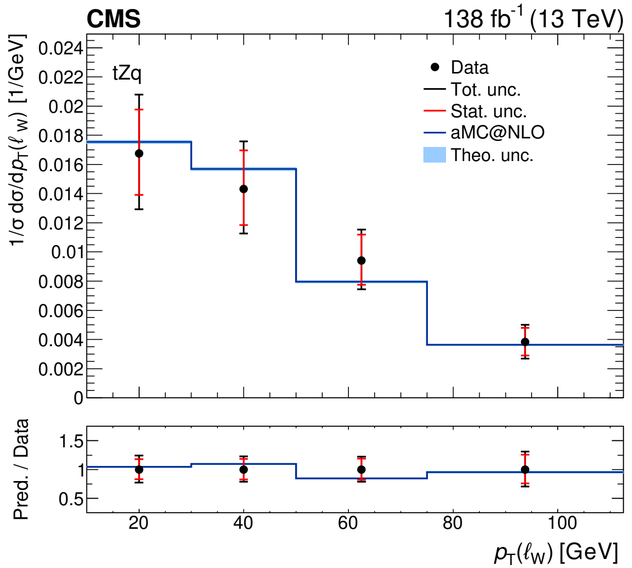
- Good agreement overall for tZq, slight excess for tt̄Z+tWZ

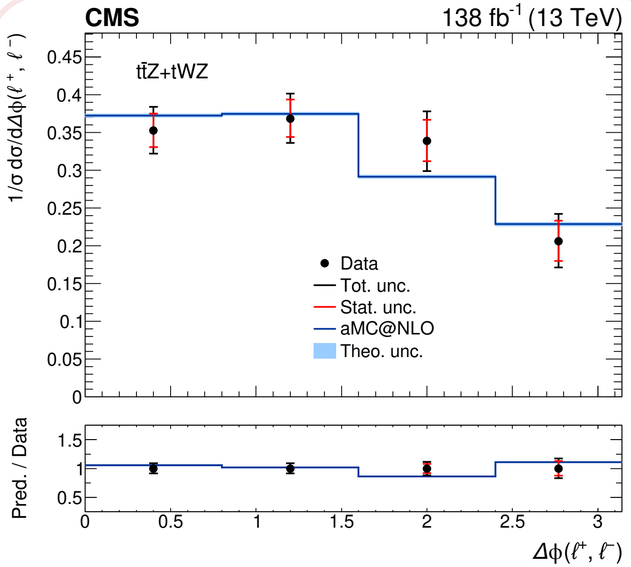
Normalized differential cross sections

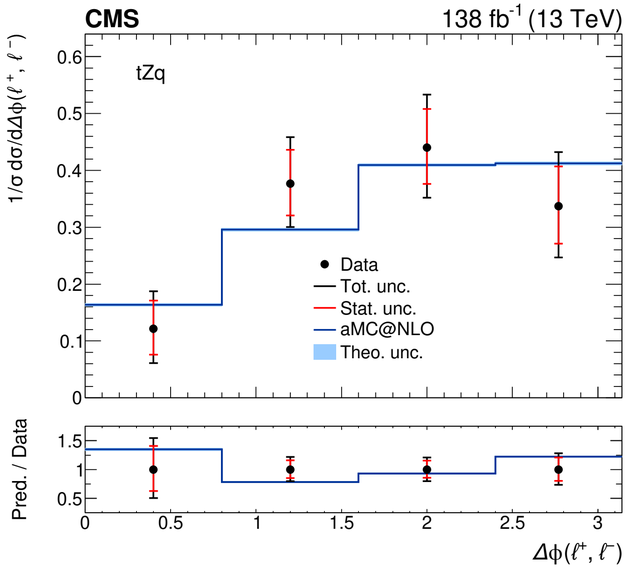




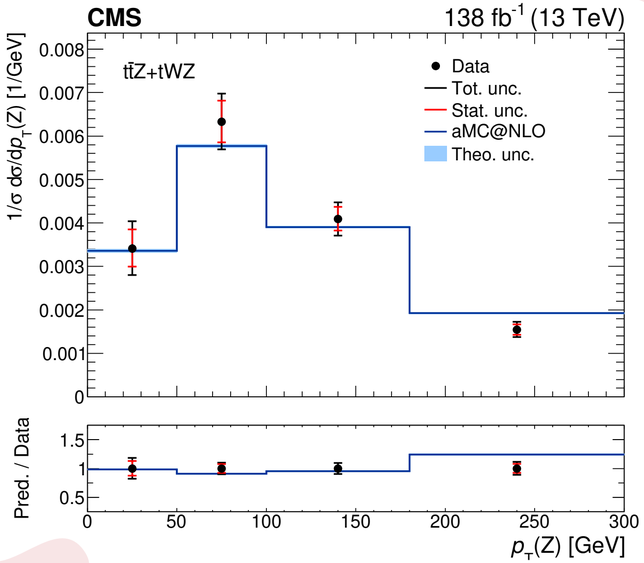


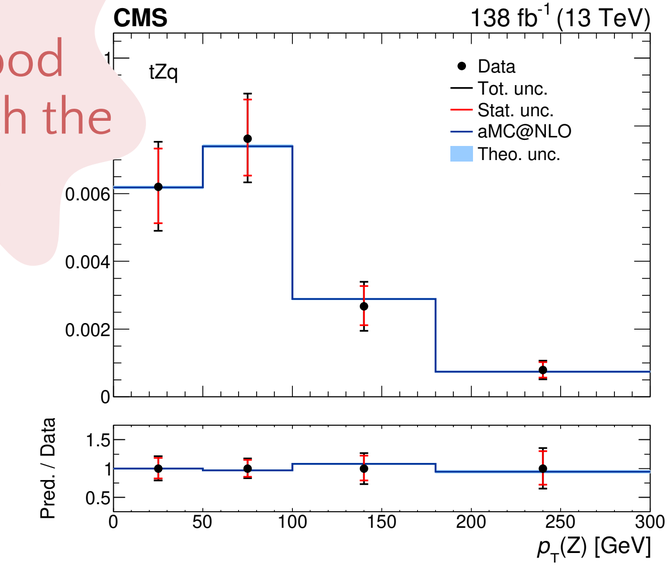


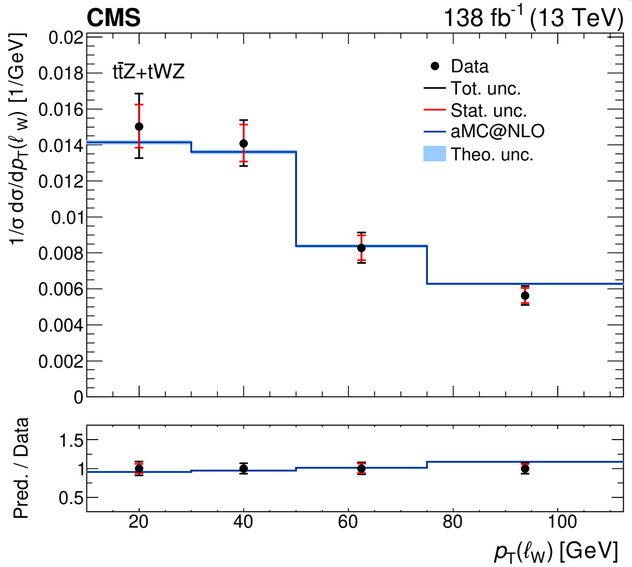


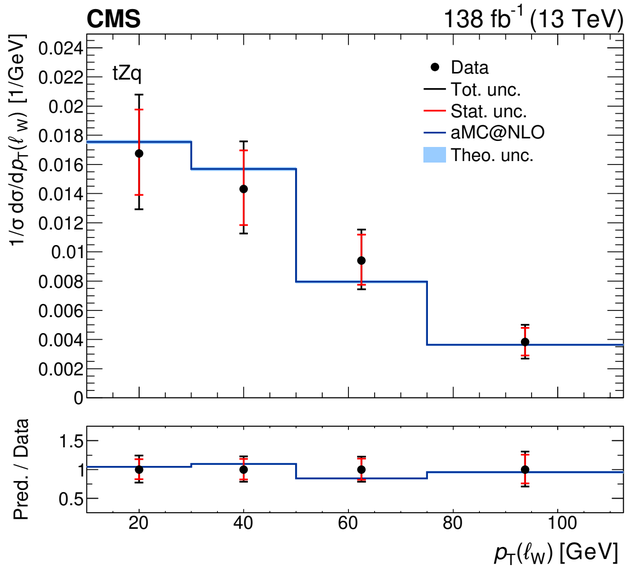


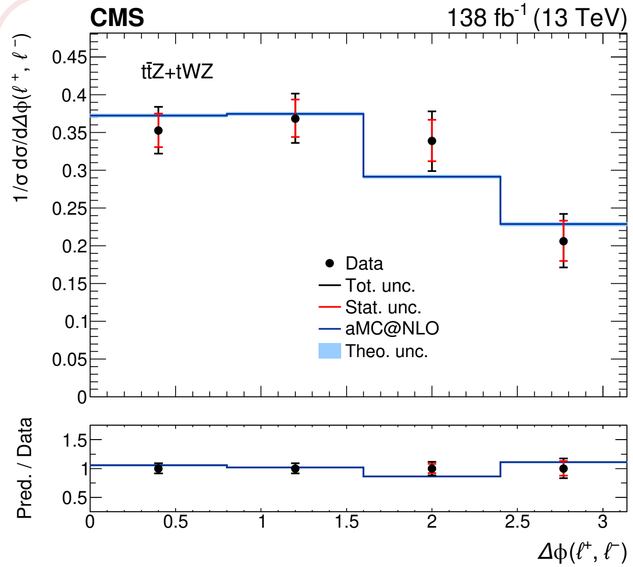
Normalized differential cross sections

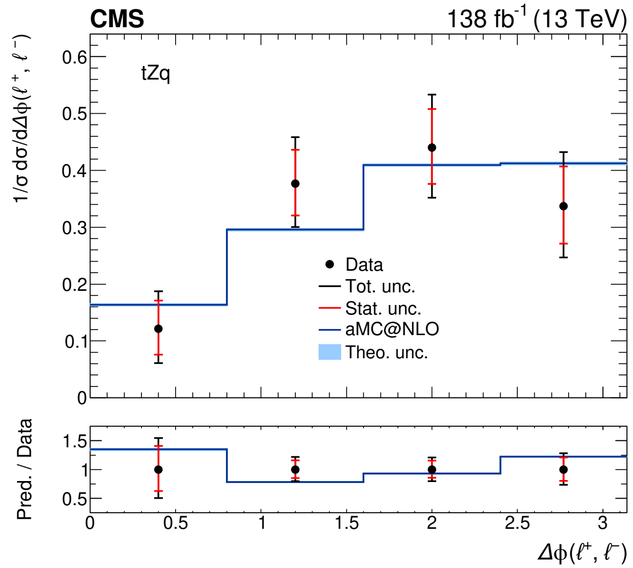












Shapes in good agreement with the predictions

B. R. Lopes

12.11.2024

LHC top WG

Summary

- First simultaneous measurements of **tZq** and **$t\bar{t}$Z+tWZ**, inclusive and differential
  - Now on arXiv and submitted to JHEP
- Correlations between processes studied for five kinematic variables
- Slight excess for $t\bar{t}$Z+tWZ, while tZq is in agreement with the SM predictions

Outlook

- Can be used for EFT interpretations
- Still limited by statistical uncertainties → Run 3 to bring improved precision!

Thank you!

LHC top WG

BACKUP SLIDES

B. R. Lopes

12.11.2024

Uncertainties on the nonprompt estimation

- Per bin nuisance: $\sigma_{nonprompt,i} = \sqrt{\sigma^2_{FR,i} + \sigma^2_{AR,i} + (30\%\,\text{of bin content})^2}$.

Statistical unc. in MR

Statistical unc. in AR

Systematic unc. to cover from residual mismodellings

- No difference in the behavior was observed as a function of lepton flavor
- Limited statistics in AR → some terms in FF application are = 0.
  - However, the uncertainties are not 0, but a one-sided uncertainty is set as the upper confidence interval of the Poisson statistics for 0 observed events, $1.8 \cdot \frac{f_i}{1 - f_i}$
  - This is more relevant at low lepton pT, where the fake rates are close to 1

Inclusive tWZ cross section

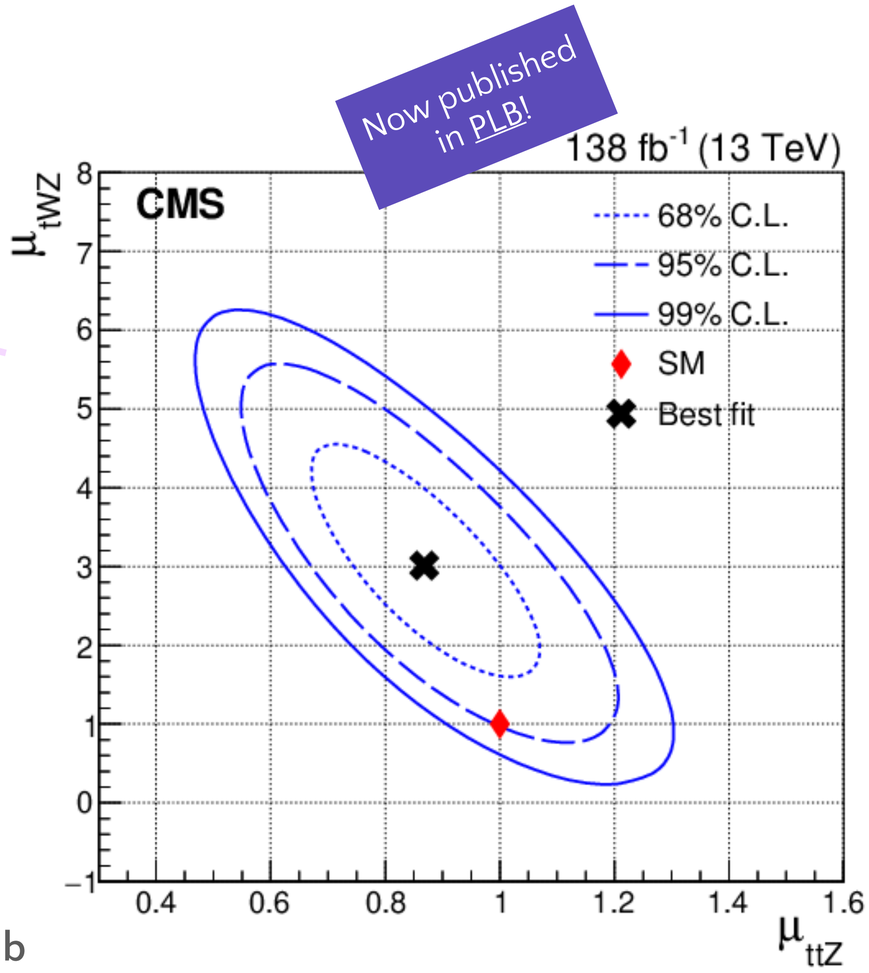
- Observed (expected) significance of 3.4σ (1.4σ) → **evidence!**

σ_{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**



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 $\beta \longrightarrow \delta + \gamma$

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

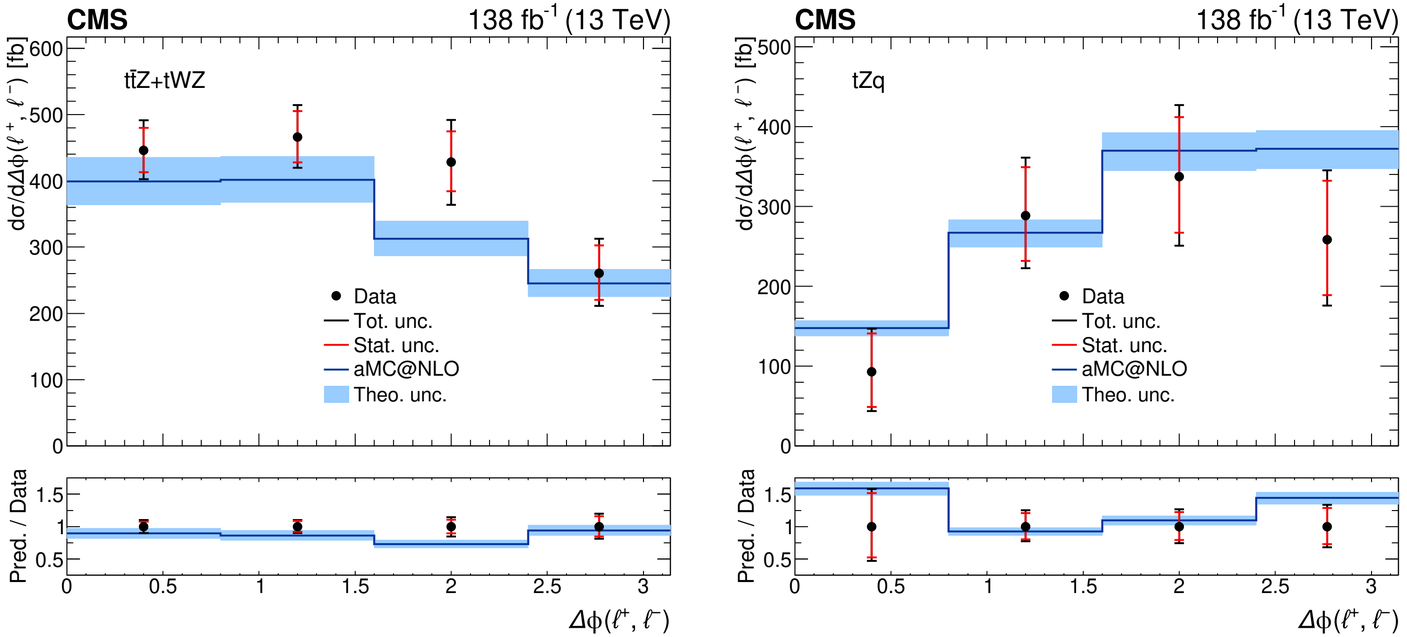
non-resonant, resonant

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

- 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

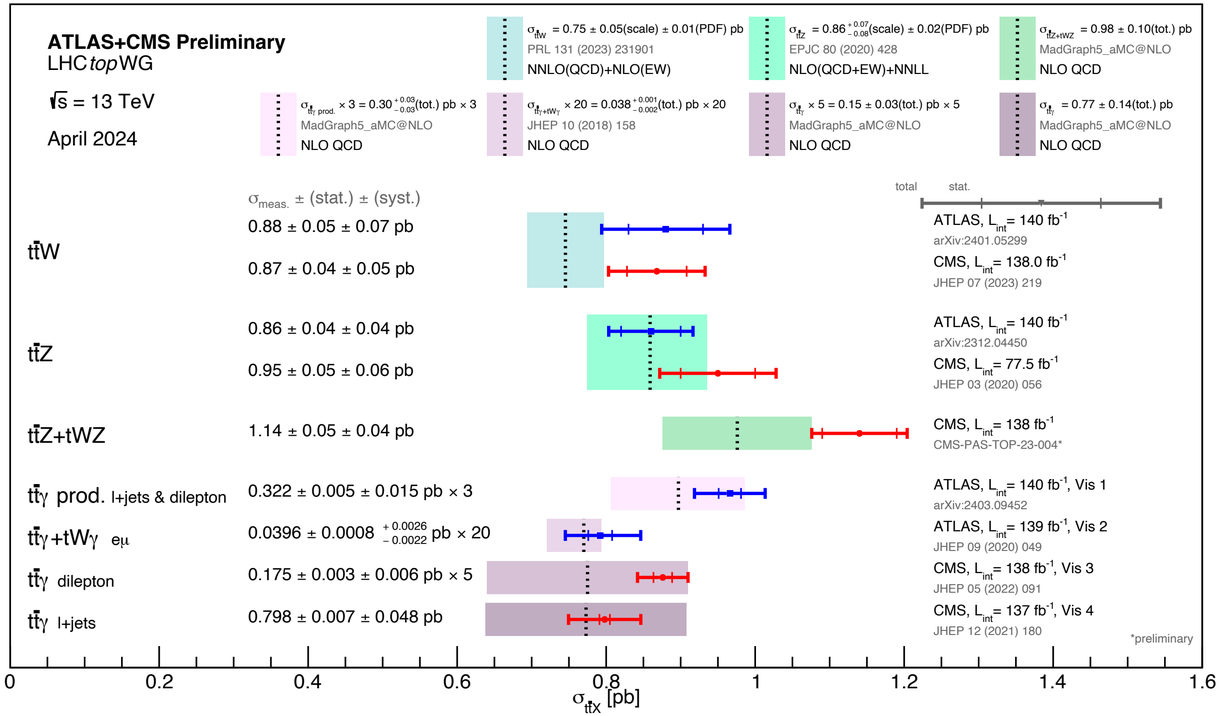
ttZ, tWZ and tZq – other differential distributions

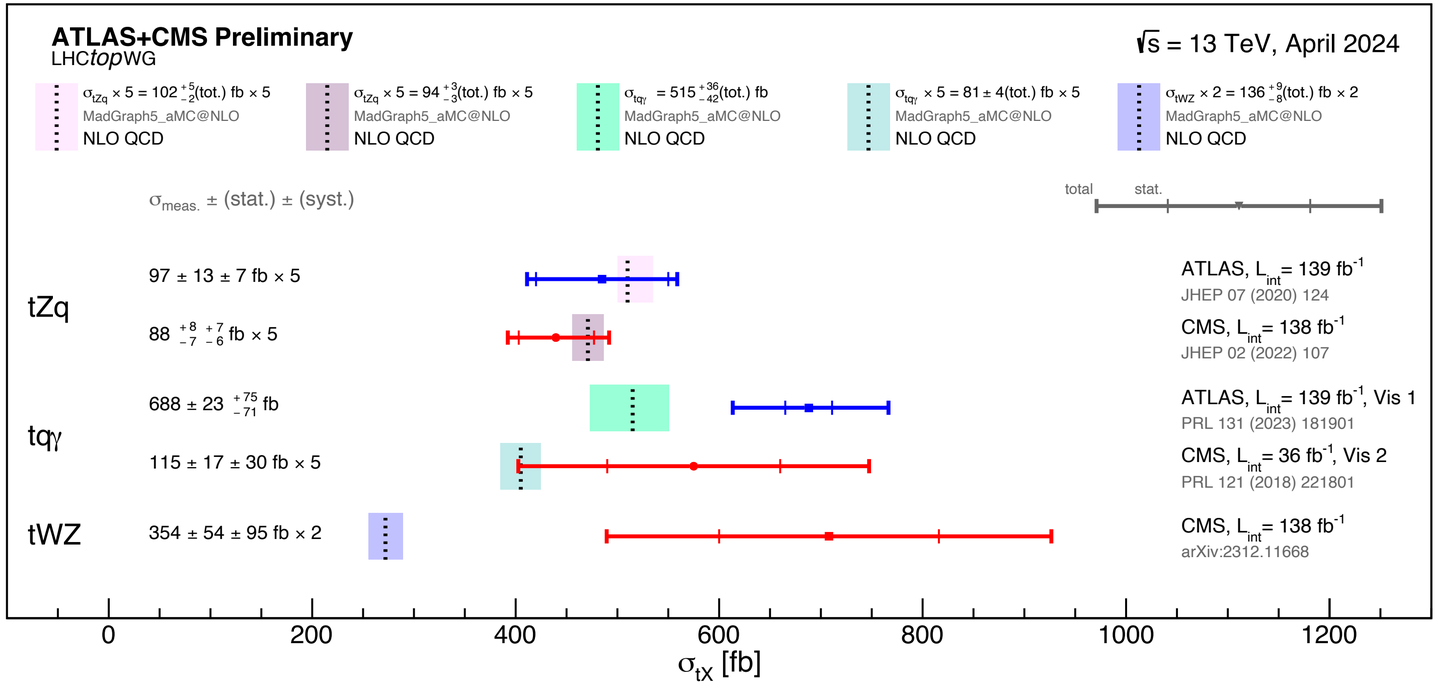


ttZ, tWZ and tZq – systematic uncertainties

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

Summary of t(t)X measurements





Electroweak and associated top quark production