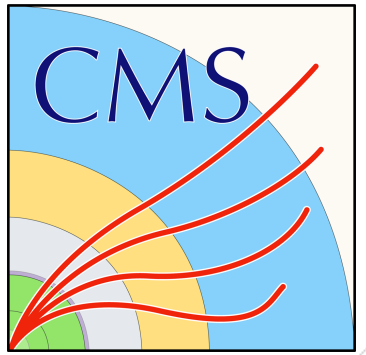


Inclusive and differential measurement of top quark cross sections in association with a Z boson

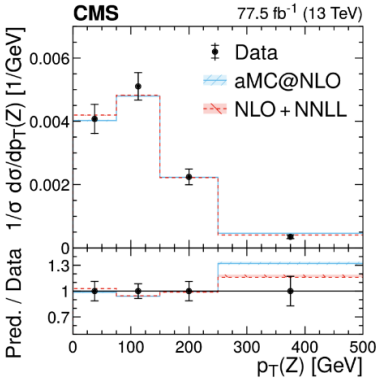
F. Colombina on behalf of the CMS Collaboration

LHC top WG

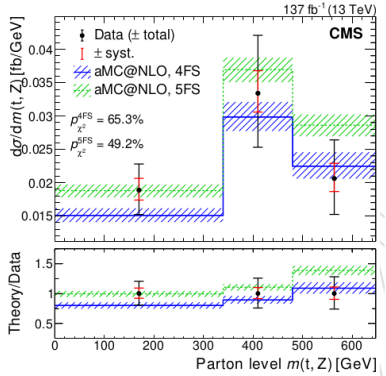
Overview and motivation

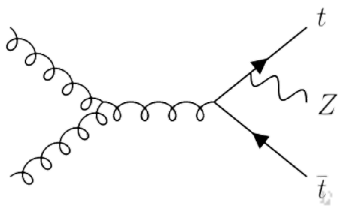
- Differential measurements of **tZq** and **ttZ** with Run-2
  - both ATLAS and CMS
- Evidence for **tWZ** reported by CMS
- Simultaneous measurement:
  - less dependent on signal modeling assumptions
  - enhance sensitivity to deviation from SM across signals

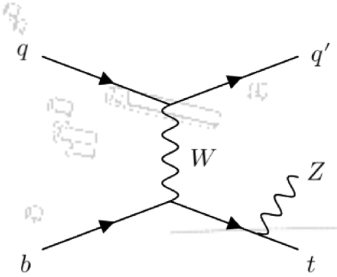
JHEP03(2020)056

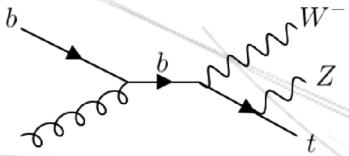


JHEP02(2022)107



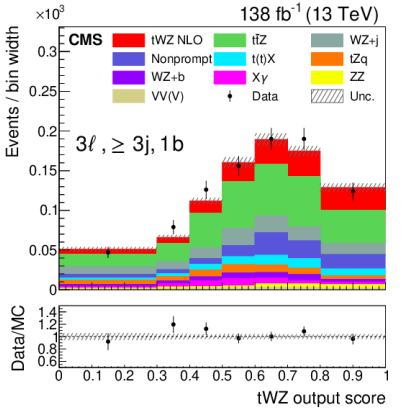






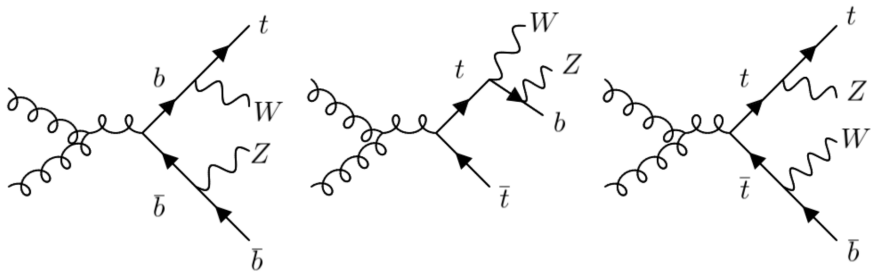
t-Z and W-b-t couplings

2312.11668



tWZ modeling

- tWZ modeling at NLO: intermediate top becomes resonant, overlap with $t\bar{t}Z$ and $t\bar{t}$
  - amplitude $\mathcal{A}$ divided into $\mathcal{A}^{(\text{res})}$ and $\mathcal{A}^{(\text{non-res})}$
  - DR1, removes $\mathcal{A}^{(\text{res})}$ in $\mathcal{A}$
  - DR2, removes $|\mathcal{A}^{(\text{res})}|^2$ in $|\mathcal{A}|^2$
  - DS, subtraction term
- **DR1** for nominal, **DR2** for uncertainty
- DS lies between DR1 and DR2



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

Event selection

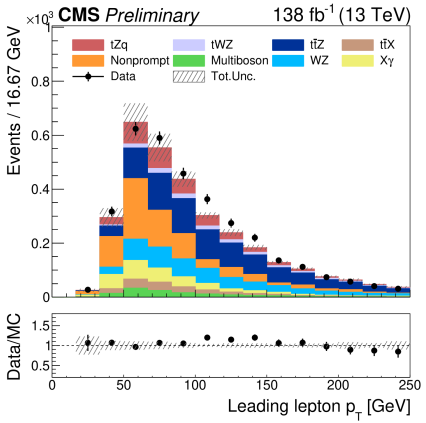
- Select $t\bar{t}Z$, tWZ and tZq in the same region

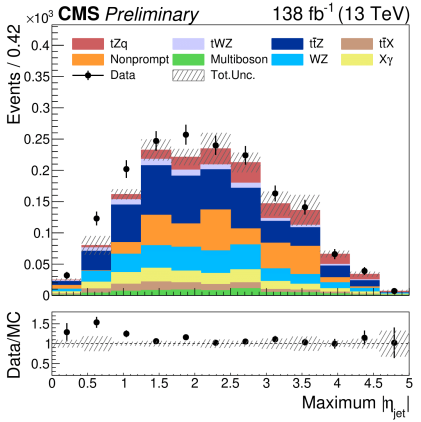
Object selection

- Isolated jets with $p_T > 25$ GeV, **$|\eta| < 5$**
  - if b-tagged, required to be central

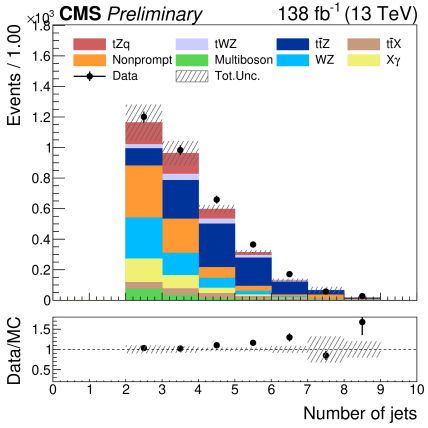
Event selection

- Exactly three leptons ($e^{\pm}$ or $\mu^{\pm}$)
  - $p_T > 25, 15, 10$ GeV
- One lepton pair with:
  - opposite sign, same flavor
  - $|m_{\ell\ell} - Z| < 20$ GeV
- **$N_j \geq 2$**, $N_b \geq 1$

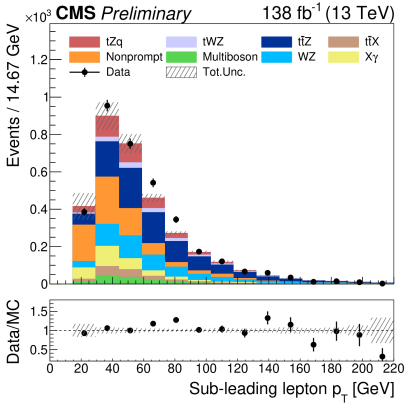


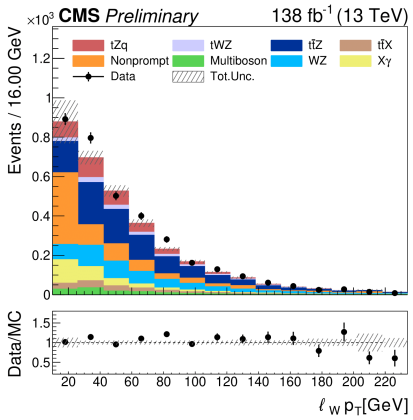


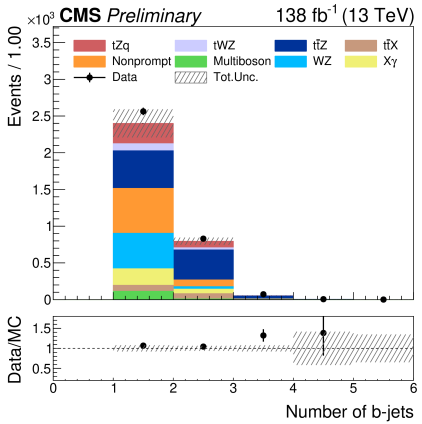
Main backgrounds:
nonprompt, WZ

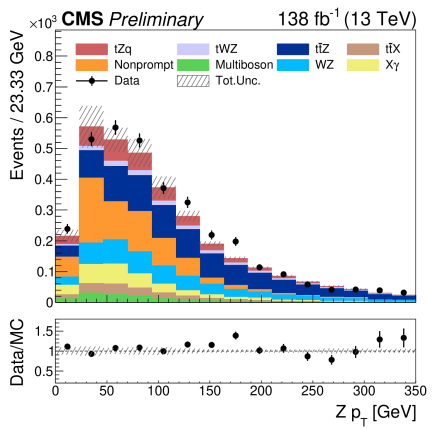


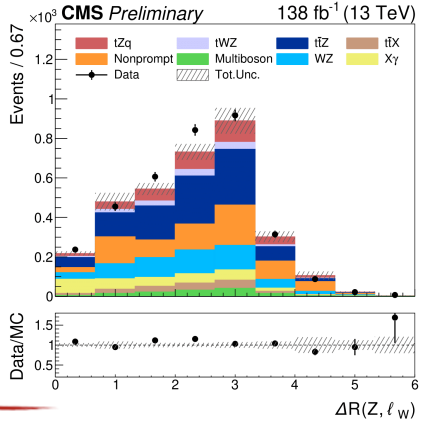
Event selection

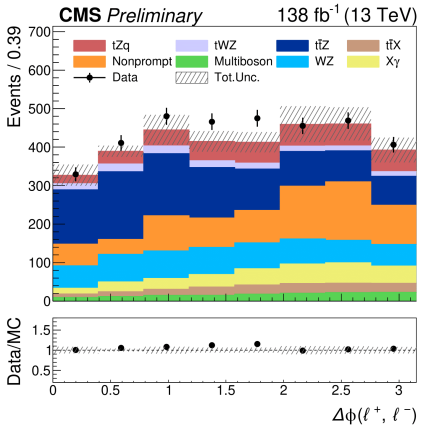


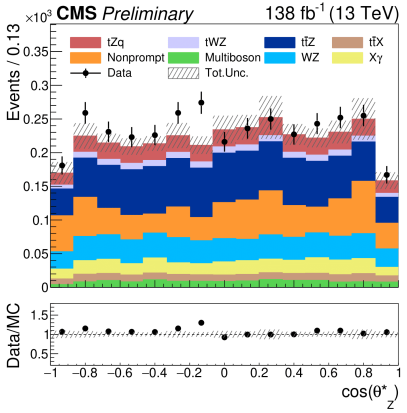












LHC top WG

Fake factor (FF) method

- Measurement region
  - QCD multijet samples
  - exactly one fakeable lepton
  - at least one jet with $\Delta R_{\ell j} > 0.7$
  - per-lepton FF:

$$f_i = \frac{N_{tight}}{N_{tight} + N_{fakeable}}$$

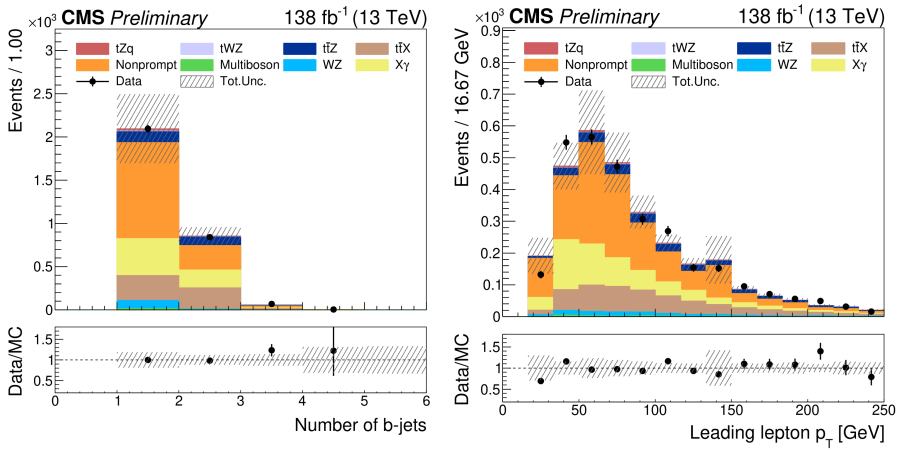
evaluated for tWZ CMS analysis

- Application region (AR): same selection as SR, but fakeable leptons
- Leptons divided into prompt and nonprompt
- Weight in this region:

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

n: fakeable leptons not tight

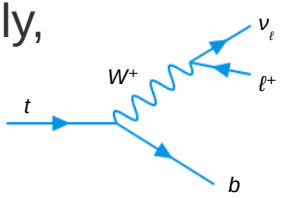
- Contribution in SR: estimated from data in the AR, removing events with only prompt leptons
- Off-Z-peak region to check the estimation



Top quark reconstruction

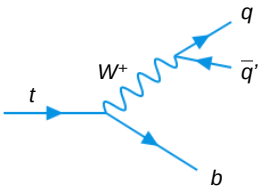
- Three different cases are considered:
  - 2 jets, 1 b-tag: only leptonic top is reconstructed
  - 3 jets, ≥ 1 b-tag: both hadronic and leptonic top reconstructed separately, lowest χ^2 is kept

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



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

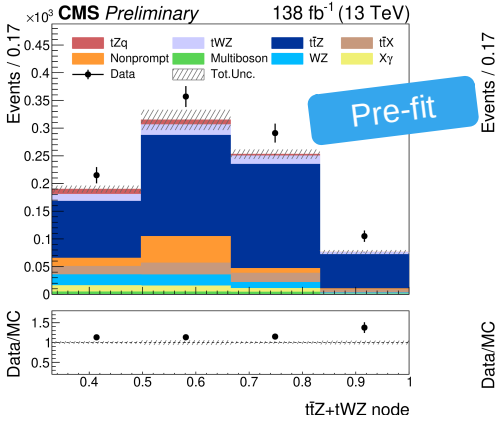
$$\chi_t^{\ 2} = \left(\frac{m_{l\nu b} - m_t}{\sigma_{t,lep}}\right)^2 + \left(\frac{m_{bjj} - m_t}{\sigma_{t,had}}\right)^2$$

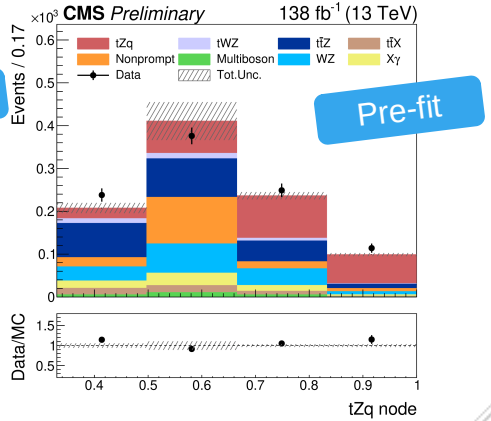


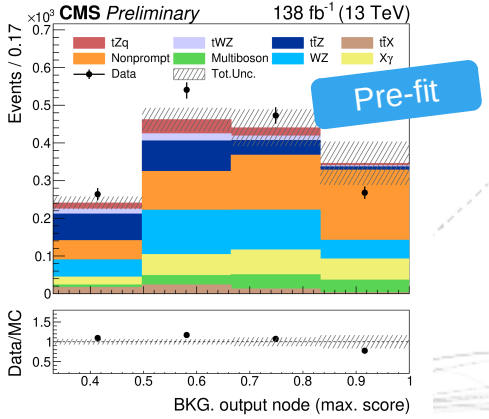
when reconstruction is not possible, unphysical value given to the related variables

Signal-background discrimination

- Multiclass classifier with 3 output nodes:
  - tZq
  - $t\bar{t}Z$+tWZ
  - backgrounds
- k-fold cross-validation approach (k=2)
- Inputs:
  - kinematic properties
  - top reconstruction
- Good discrimination achieved (AUC ~87%)
- Checked correlation among inputs and unfolding observables to avoid biases
- Max-score splitting for fit categories

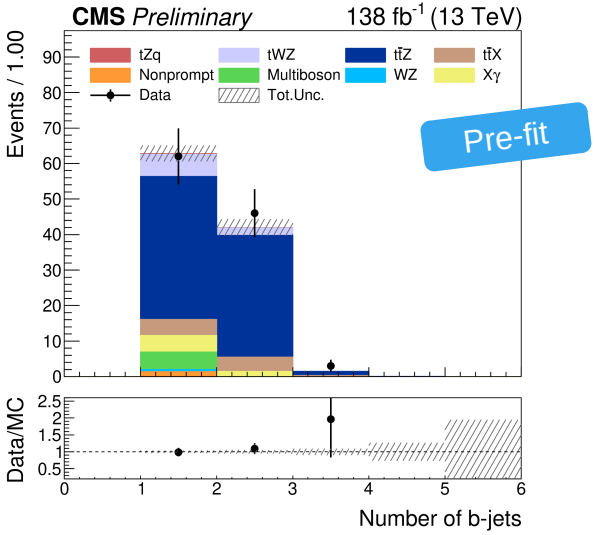


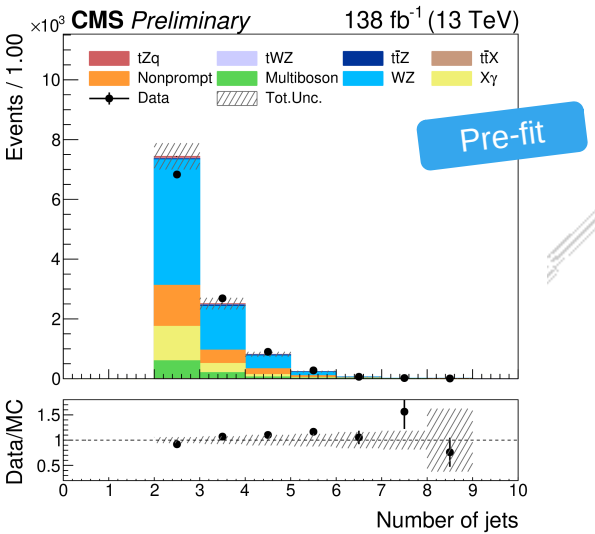




Inclusive measurement

- Two additional regions included in the fit for the inclusive measurement:
  - four lepton region → pure in $t\bar{t}Z$
  - zero b-jet region → CR for WZ
- Both regions are rather pure, no classifier necessary
  - four lepton → b-jet multiplicity
  - zero b-jet → jet multiplicity
- For the SR, the three output nodes are included in the fit

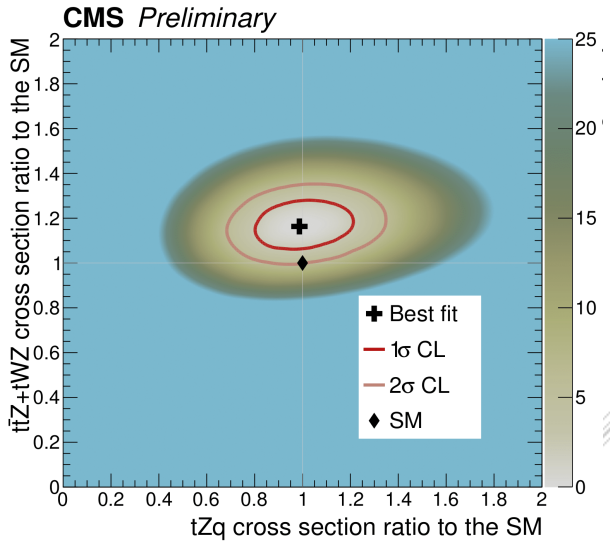




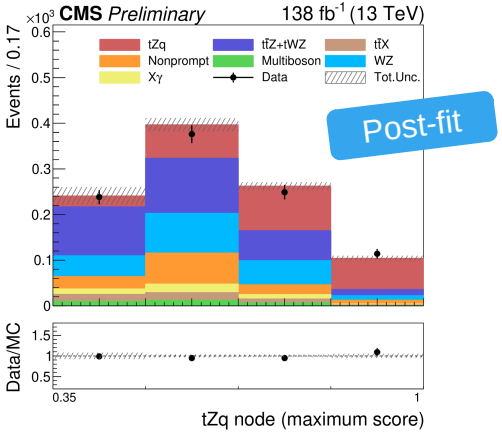
Inclusive measurement

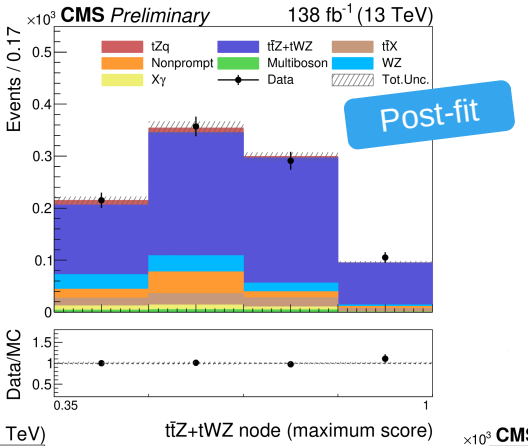
- Profile likelihood-ratio scan for σ_{tZq} and $\sigma_{t\bar{t}Z+tWZ}$
- Statistically limited
  - main syst: background modeling, (b-)jets
- Good agreement with SM for tZq, small excess for $t\bar{t}Z+tWZ$
- Consistent with previous CMS measurements
- When separating $t\bar{t}Z$ and tWZ
  - $\sigma_{t\bar{t}Z} = 0.99 \pm 0.07$ pb
  - $\sigma_{t\bar{t}Z} = 0.88 \pm 0.16$ pb → tWZ freely floating

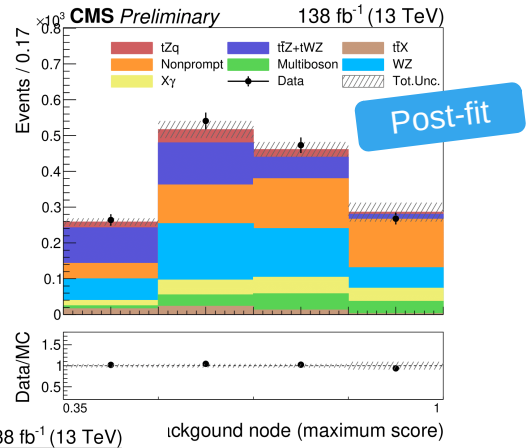
$$\sigma_{t\bar{t}Z+tWZ} = 1.14 \pm 0.07 \text{ pb}$$
$$\sigma_{tZq} = 0.81 \pm 0.10 \text{ pb}$$

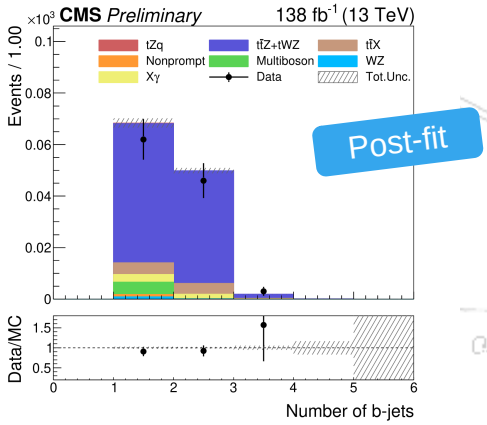


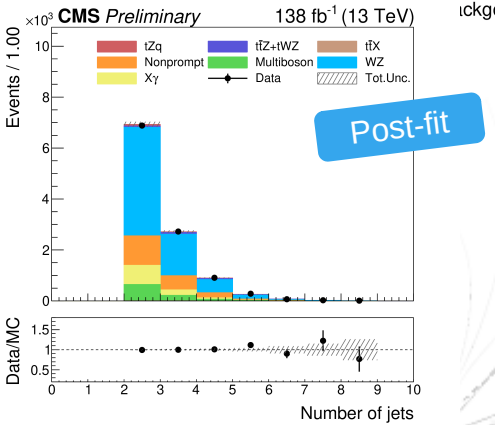
Inclusive measurement









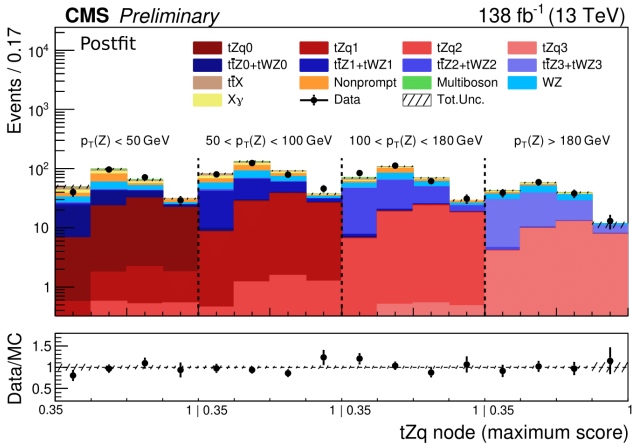


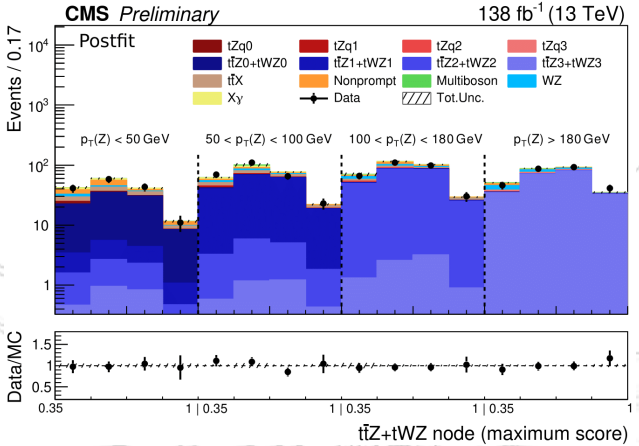
Differential measurement

- Cross sections measured as a function of five leptonic observables:
  - $p_T(Z)$
  - $p_T(\ell_W)$
  - $\Delta R(Z, \ell_W)$
  - $\Delta\phi(\ell, \ell')$
  - $\cos(\theta^*)$

$\theta(\ell^-,Z)$, boosted into Z boson rest frame

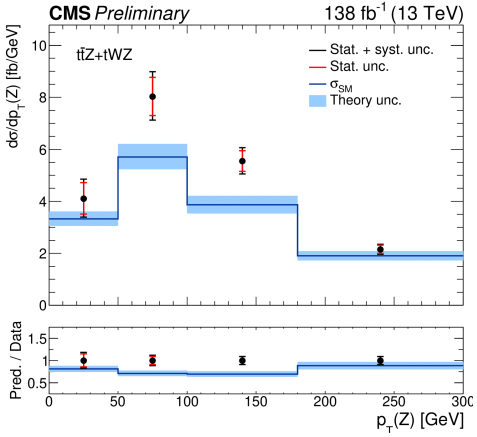
- Divide output notes into 4 bins
- Background output node still included in the fit as one bin

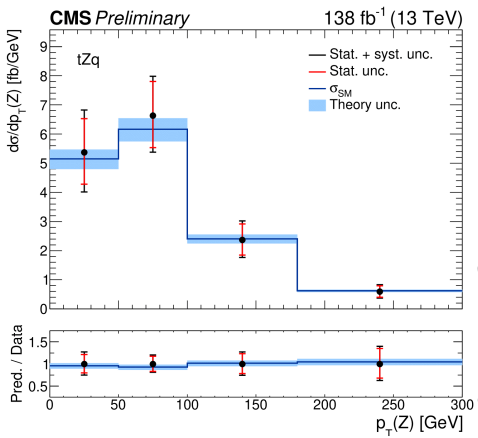


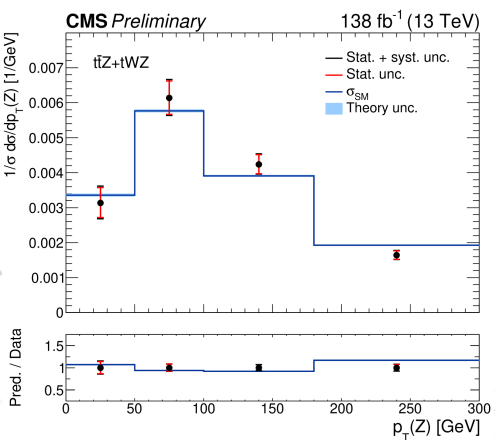


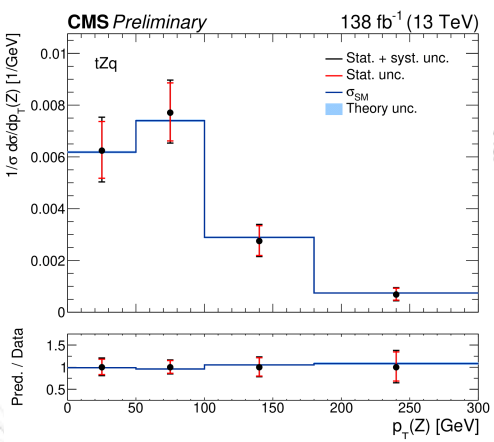
Unfolding

- Unfolding performed simultaneously for tZq and $t\bar{t}Z$+tWZ
- General trend as for the inclusive measurement:
  - small excess for $t\bar{t}Z$+tWZ
  - tZq in agreement with SM expectations



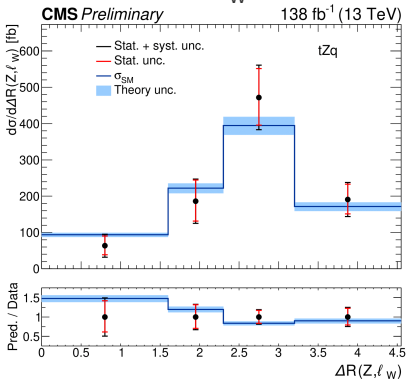




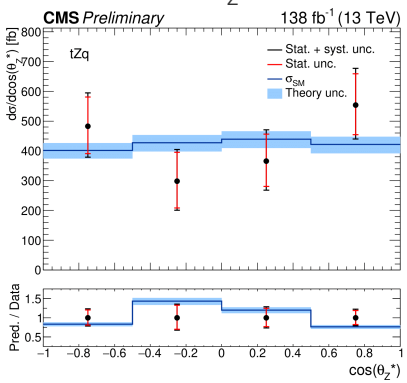


Unfolding

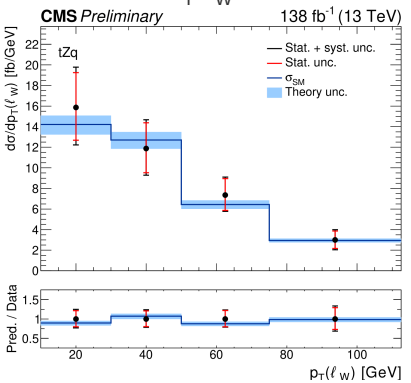
$\Delta R(Z,\ell_W)$



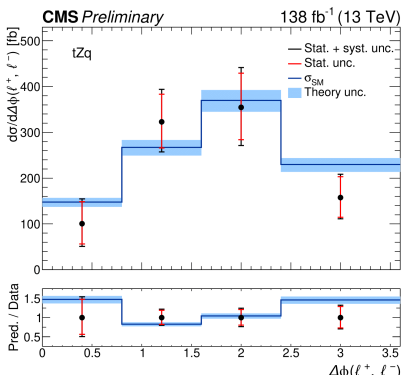
$\cos\theta_Z^*$

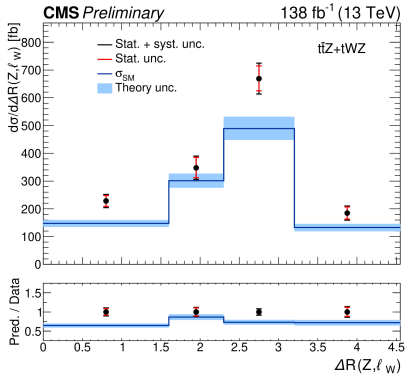


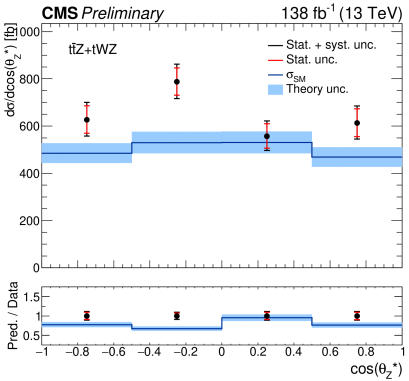
$p_T(\ell_W)$

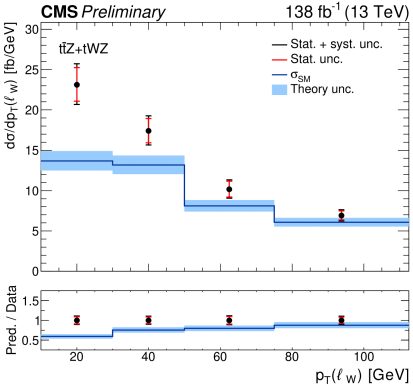


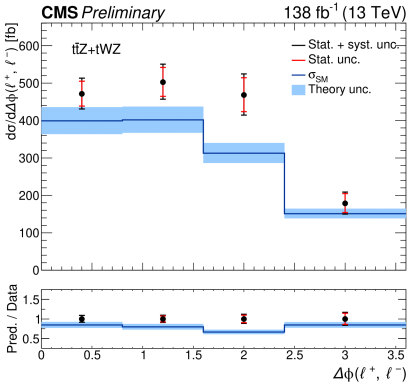
$\Delta\phi(\ell,\ell')$





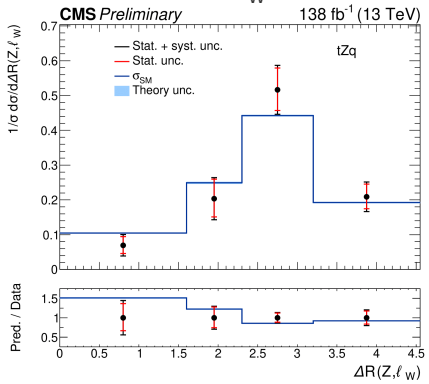




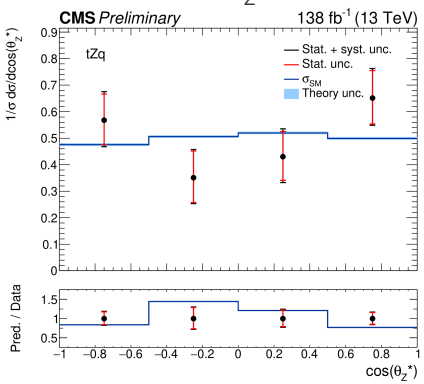


Unfolding

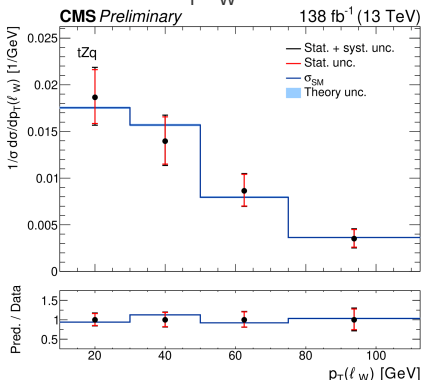
$\Delta R(Z,\ell_W)$



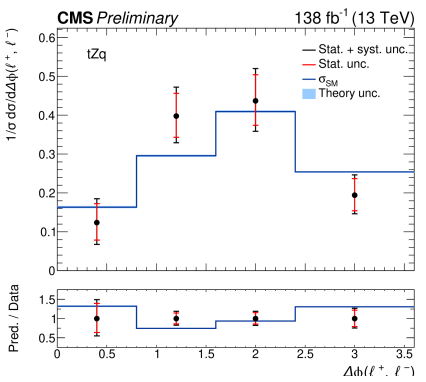
$\cos\theta_Z^*$

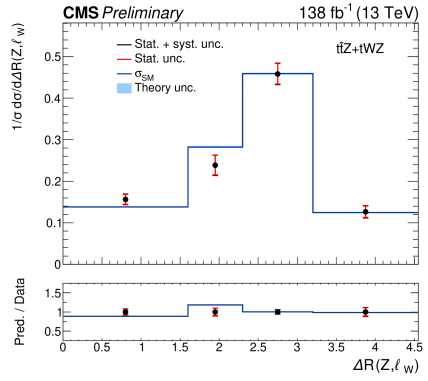


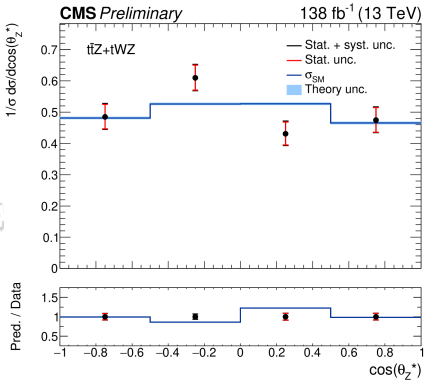
$p_T(\ell_W)$

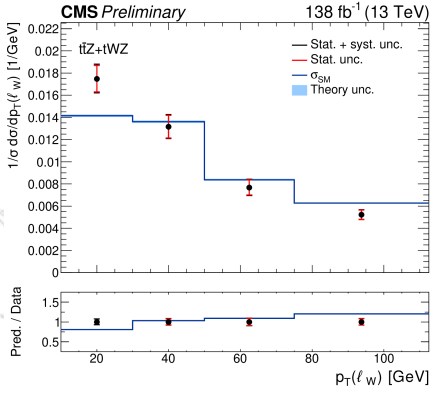


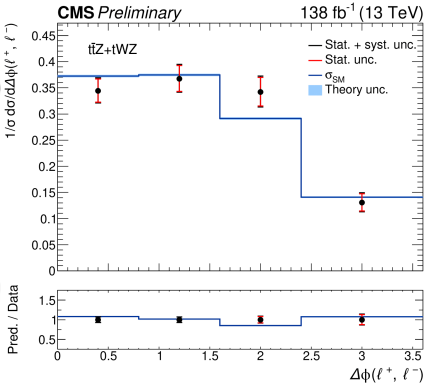
$\Delta\phi(\ell,\ell')$







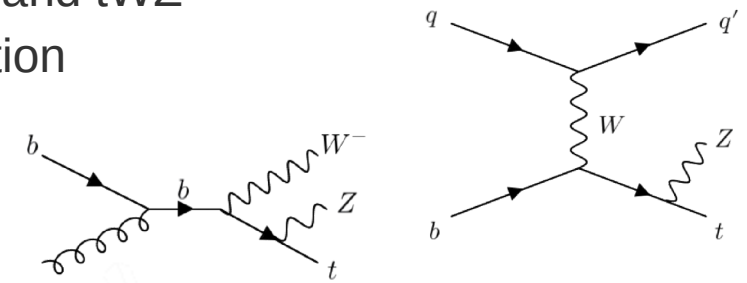


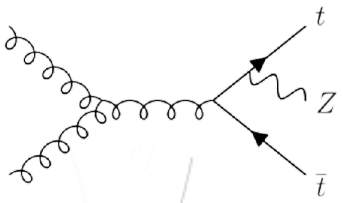


LHC top WG

Summary

- First simultaneous differential measurement of tZq, $t\bar{t}Z$ and tWZ
  - σ_{tZq} and $\sigma_{t\bar{t}Z+tWZ}$ and correlations measured as function of five variables
- Excess for $t\bar{t}Z$+tWZ, tZq in agreement with SM





Outlook

- Results can be used for theory and EFT interpretations
- Fiducial cross sections
- Run-3 to reduce statistical uncertainties

Thank you!