Recent Top+Boson Measurements at CMS: t(t)+Z

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(on behalf of the CMS Collaboration)

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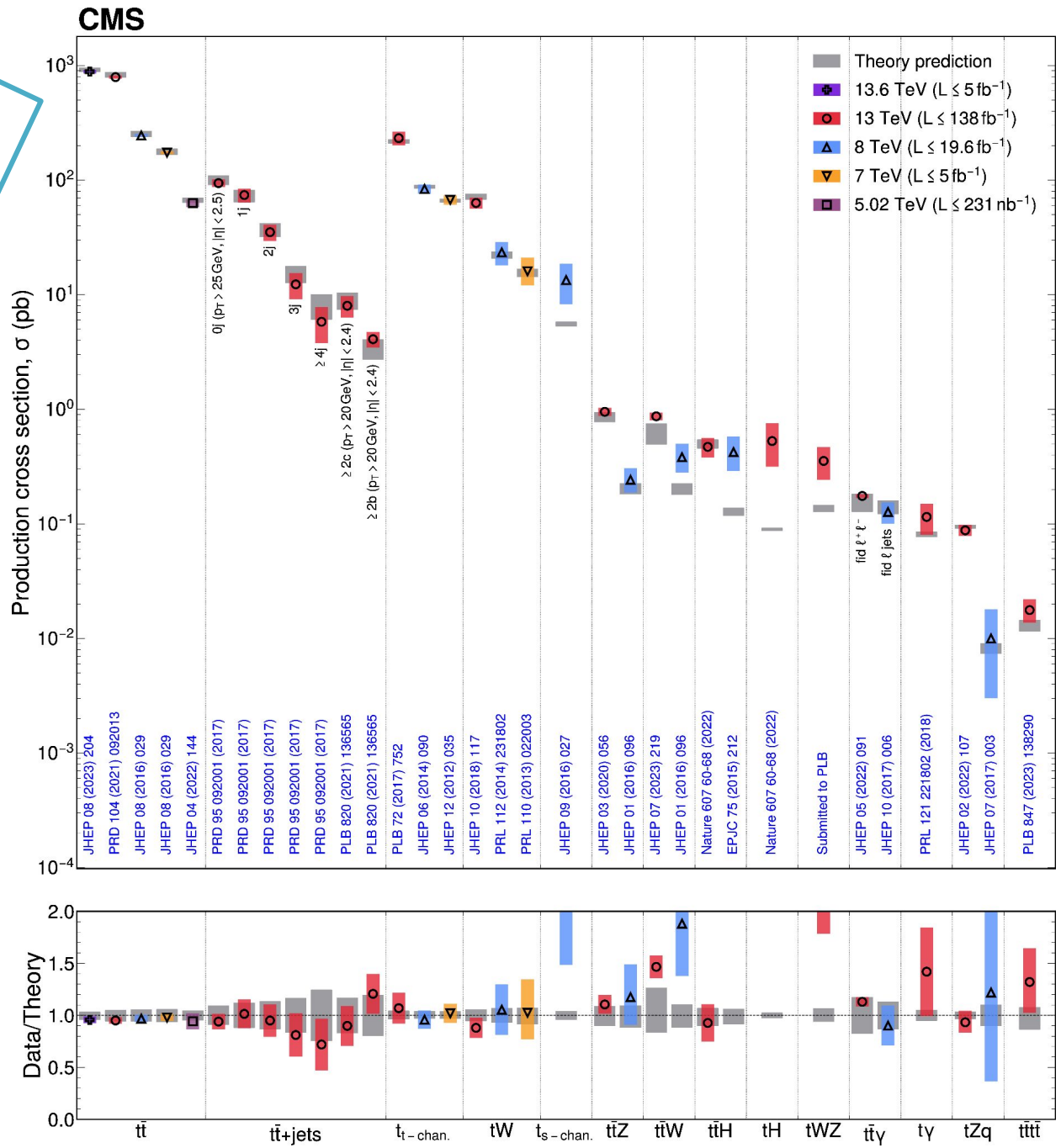
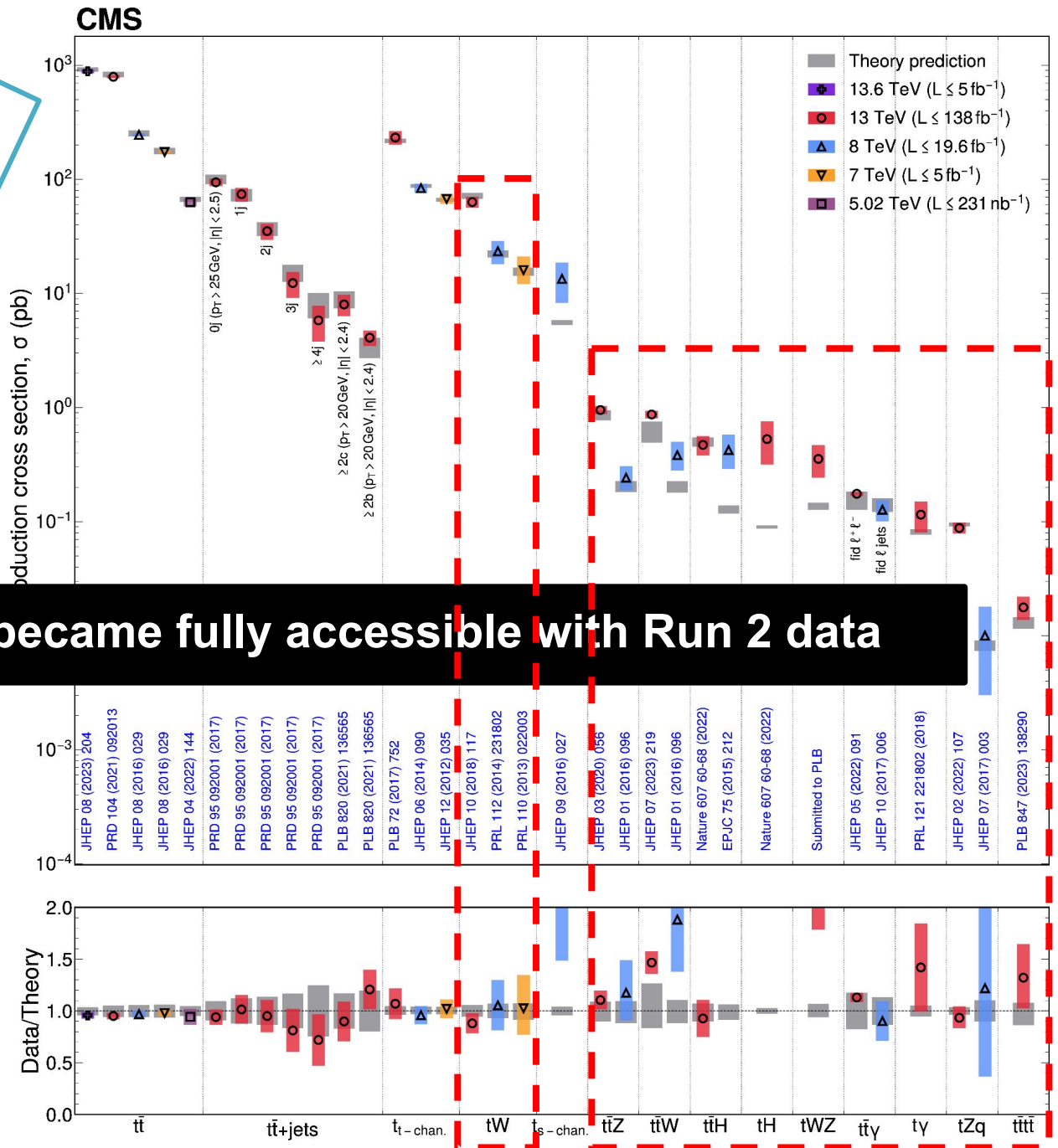
Top Quark Production

arXiv:2405.18661 - Stairway to discovery: a report on the CMS programme of cross section measurements from millibarns to femtobarns



Top Quark + Boson Production

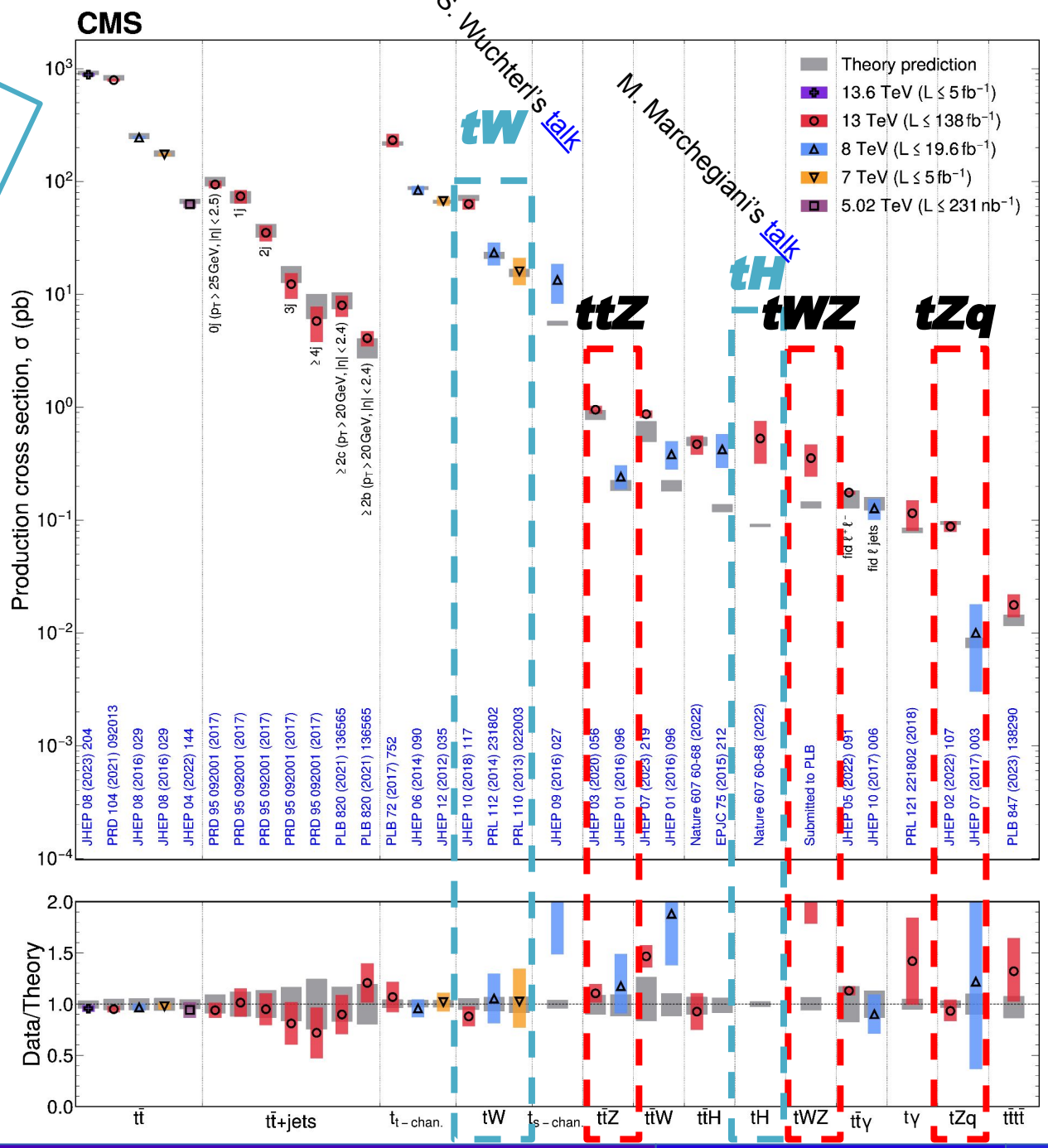


t(t)+V production modes became fully accessible with Run 2 data

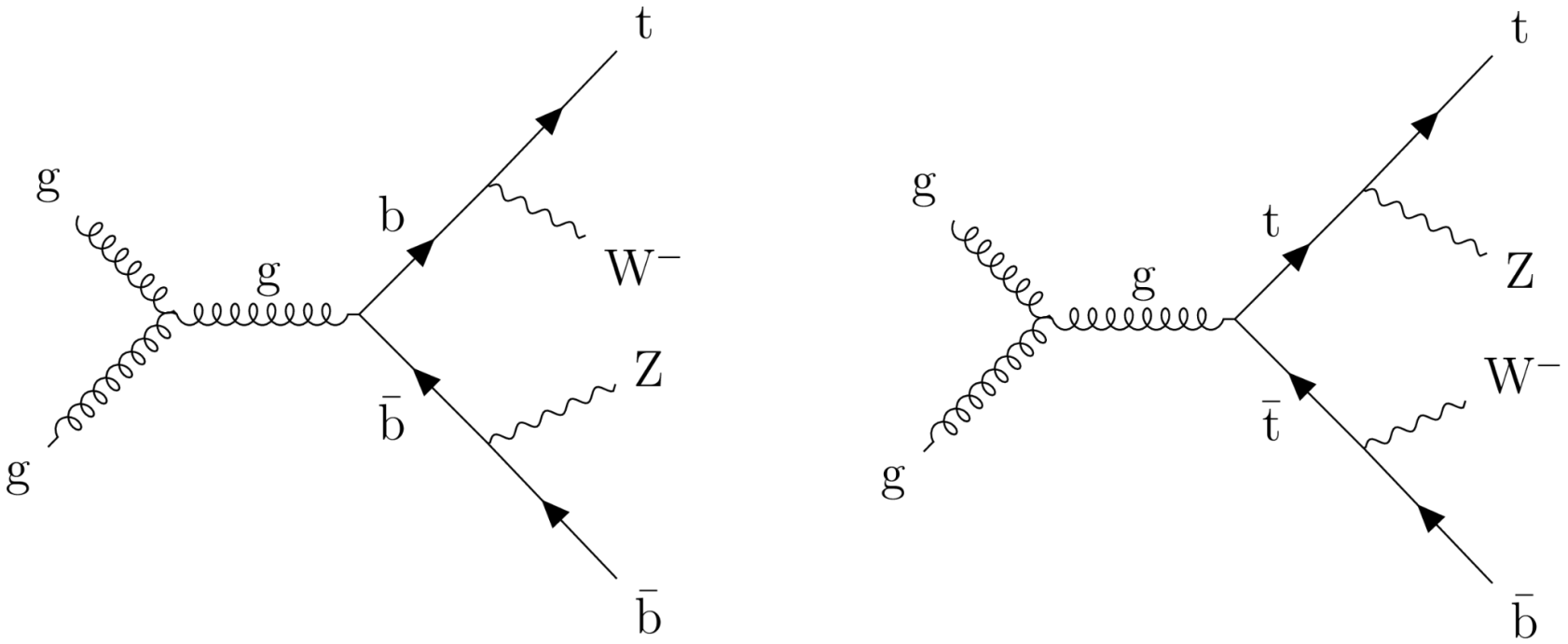
arXiv:2405.18661 - S… to discovery: a report on the CMS programme of … section measurements from millibar… femtobarns

This talk: t(t) + Z Boson Production

arXiv:2405.18661 - Stairway to discovery: a report on the CMS programme of cross section measurements from millibarns to femtobarns



tWZ Production



- Sensitive to the top quark **electroweak couplings**
- Allows for investigation of **interference** effects within the SM (e.g. **with ttZ**)
- Shows increased **sensitivity** for some **SMEFT** operators
- Challenges:
  - Signal simulation: interference with ttZ
  - Discrimination from the overwhelming ttZ background

tWZ - arXiv:2312.11668 (submitted to PLB)

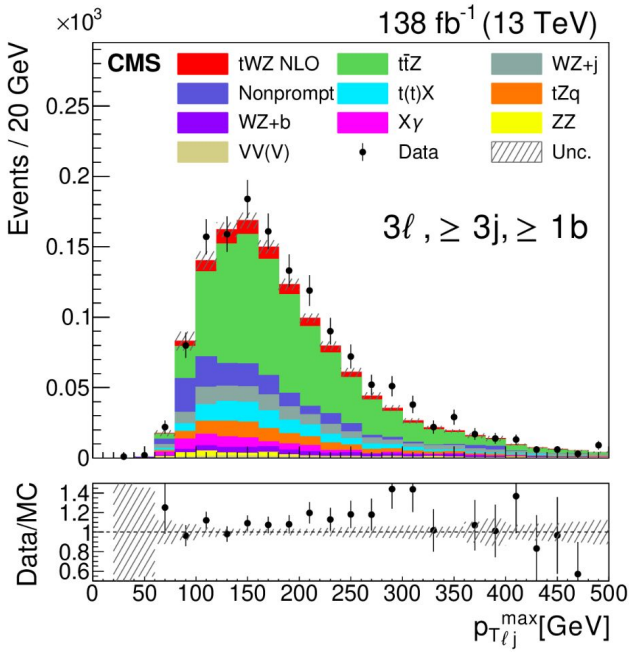
- Measurement performed in **final states with three or four leptons**
  - Z boson is reconstructed via its decays to electron or muon pairs
  - W boson decays either to leptons or hadrons

- Analysis is performed in **two regions** of the phase space
  - Top quark is almost at rest: sensitive to the SM tWZ production
  - Top quark with p_T>270 GeV: enhanced sensitivity for new phenomena (SMEFT)

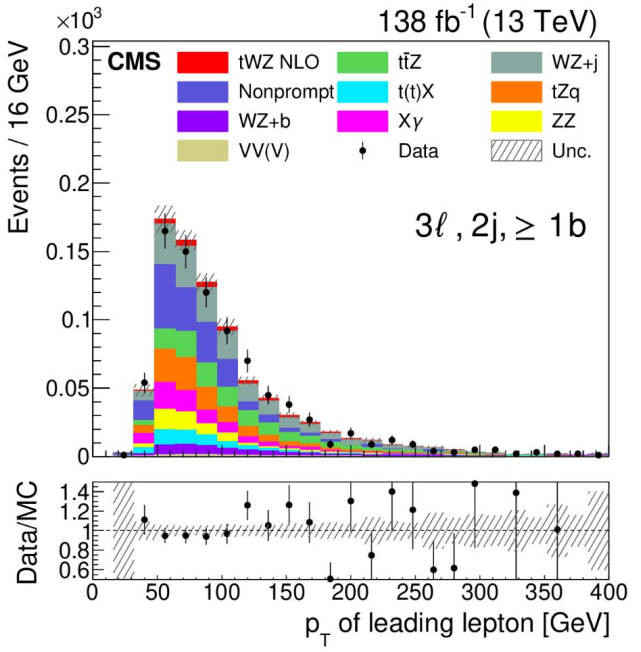
- Signal (SR) and control regions (CR) based on the number of leptons and (b-tag) jets
  - **Binned maximum likelihood fit of 7 distributions**

tWZ - arXiv:2312.11668 (submitted to PLB)

- SR in low energy
  - **3 leptons**
    - **2j, ≥ 1b**: binary classifier for **tWZ** vs Others
    - **≥3j, ≥1b**: Multiclass classifier for **tWZ** (1b) vs. **ttZ** (≥2b) vs Others
  - **4 leptons, ≥1b**: b-tagged jet multiplicity

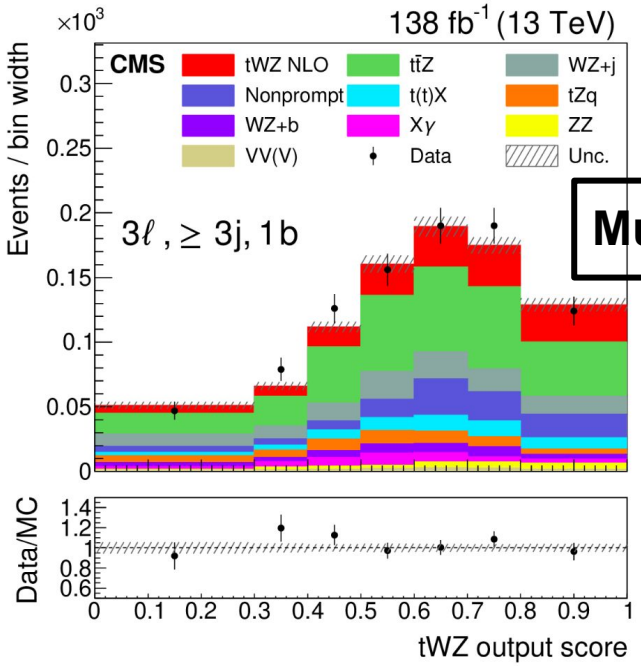


- SR in high energy: event yields
  - Leptonic top tagger (leptonic decays) or Fat jets (hadronic decays)

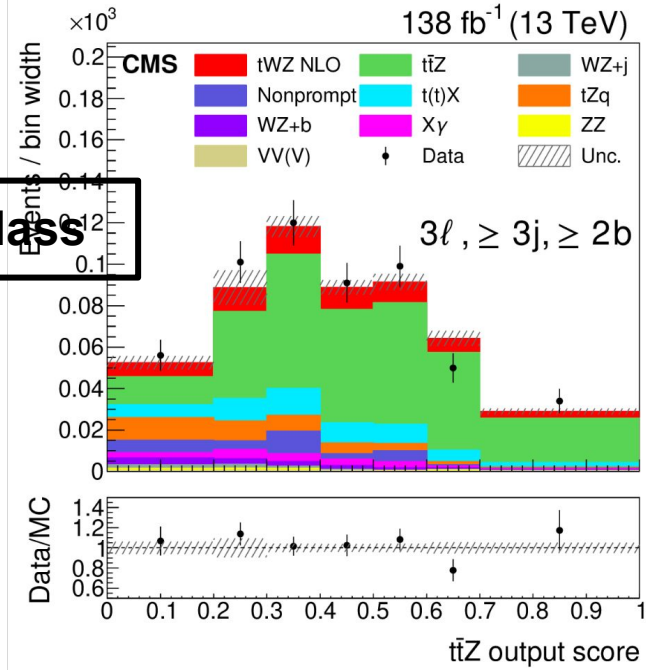


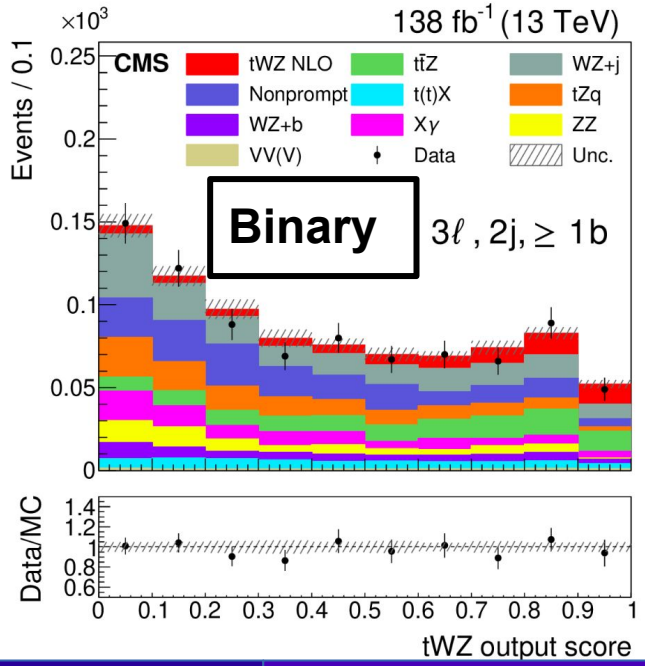
- CR for diboson backgrounds: event yields
  - 4 leptons (ZZ)
  - 3 leptons, 0b (WZ)

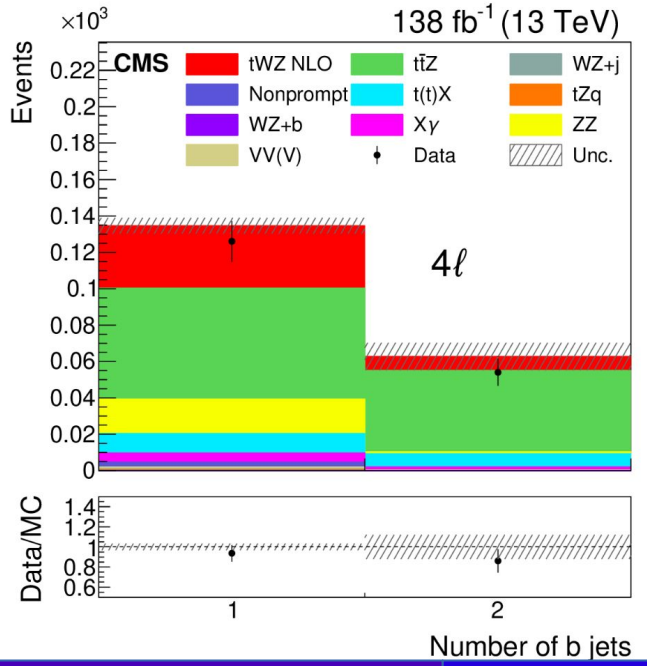
tWZ - arXiv:2312.11668 (submitted to PLB)



Multiclass



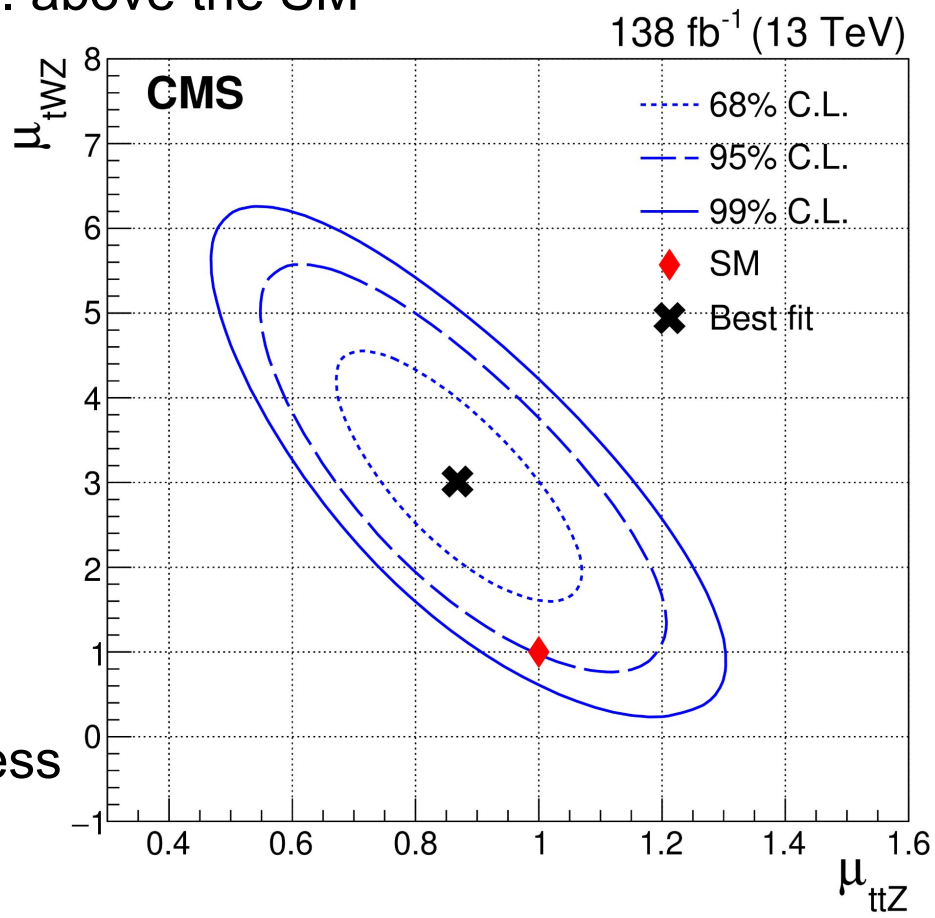




tWZ - arXiv:2312.11668 (submitted to PLB)

- Observed (expected) significance of 3.4σ (1.4σ) → **first evidence!**
  - σ_{tWZ} = 354 ± 54 (stat) ± 95 (syst) fb, two s.d. above the SM

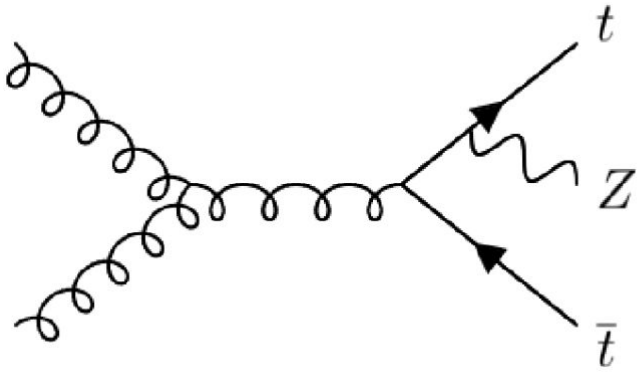
- Dominant systematic uncertainties
  - **ttZ normalization**: 18%
  - bkg normalization (other than ttZ): 12%
  - Experimental sources: 10%
  - Signal modeling: 5%

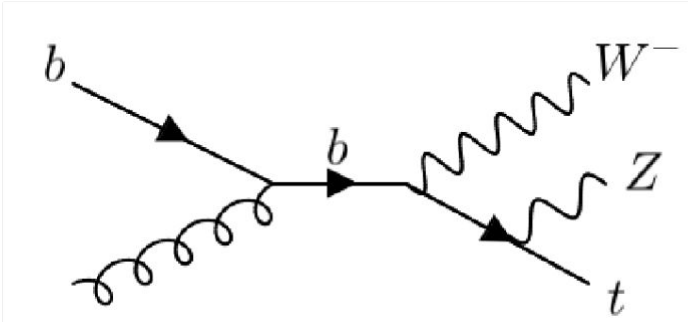


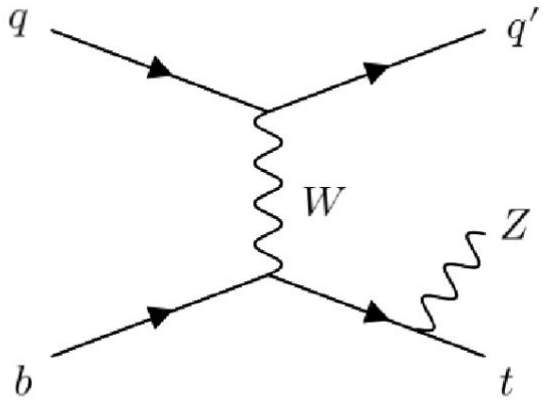
- **Anti-correlation** is observed with the ttZ process

- **Fixing the ttZ cross section** to the measured value, the statistical significance of the signal stays above **three s.d.**

ttZ, tWZ, and tZq - CMS-PAS-TOP-23-004







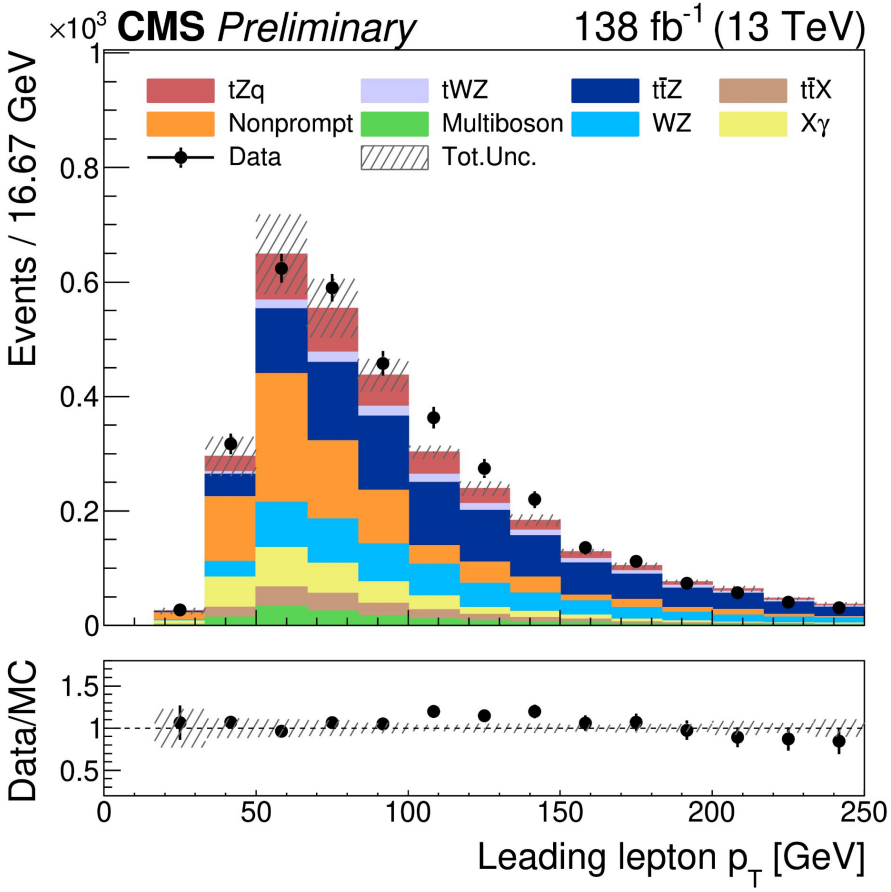
- tZq and ttZ already measured (also differentially)
- Evidence for tWZ production
- Strong interplay between ttZ and tWZ: similar experimental signature and significant interference beyond leading order
- tZq also important from the experimental point of view

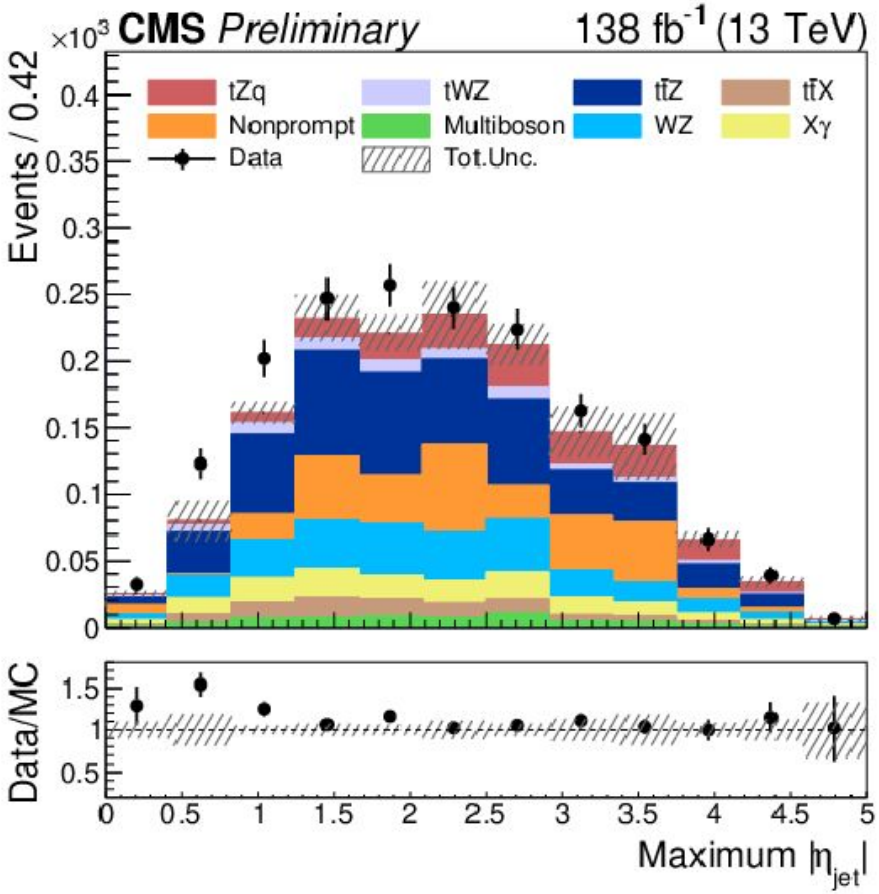
⇒ Goals: measure ttZ and tWZ processes together and reduce common systematic uncertainties, and simultaneously with tZq

ttZ + tWZ and tZq - CMS-PAS-TOP-23-004

- First simultaneous measurement of single and pair production of top quarks in association with a Z boson

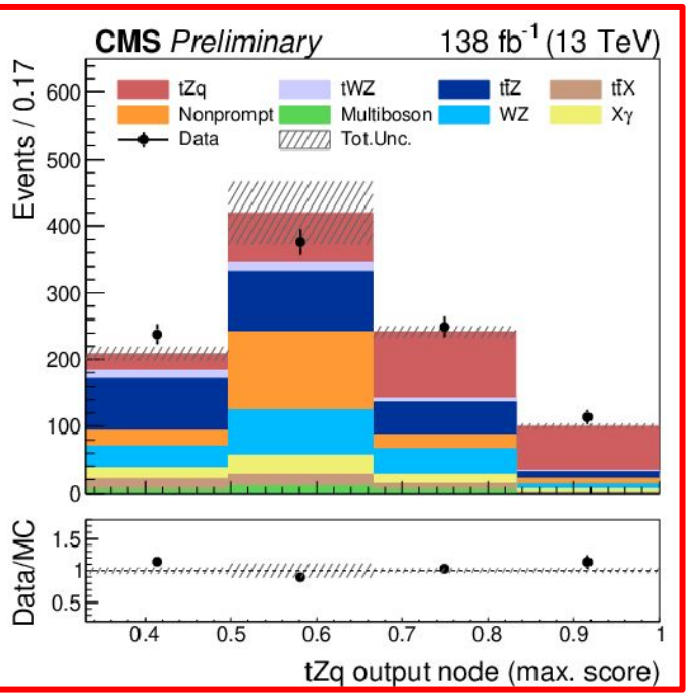
- Events with 3 leptons, ≥2 jets and ≥1 b-tagged jet are selected

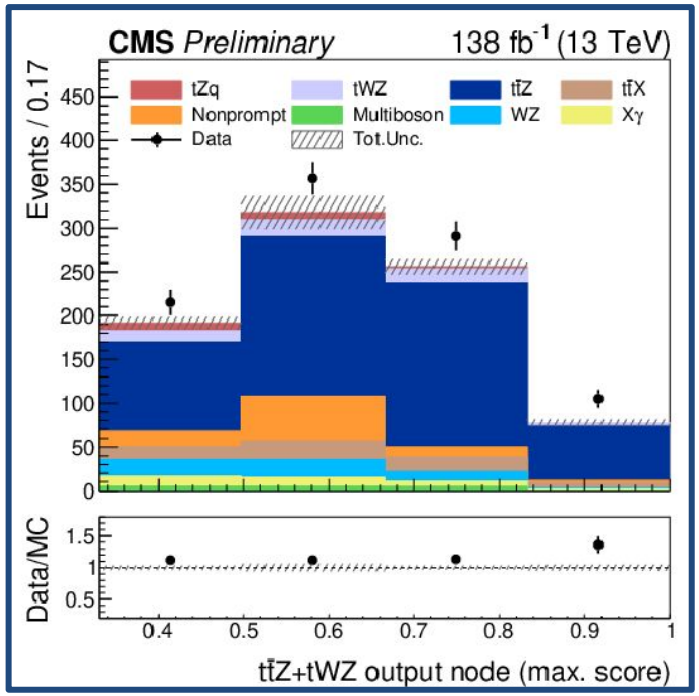


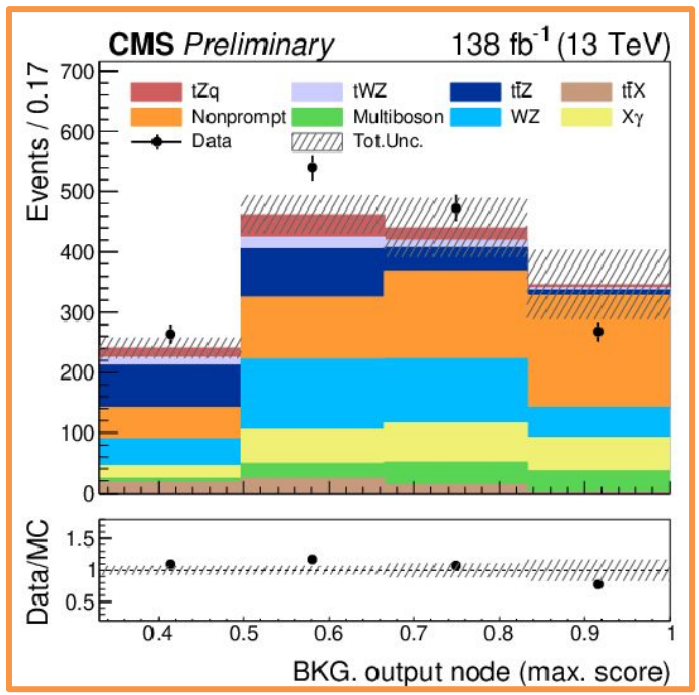


ttZ + tWZ and tZq - CMS-PAS-TOP-23-004

- The separation between the signals is achieved using a deep neural network classifier with three output nodes for the **tZq** process, the combined **ttZ** and **tWZ** processes, and **backgrounds**

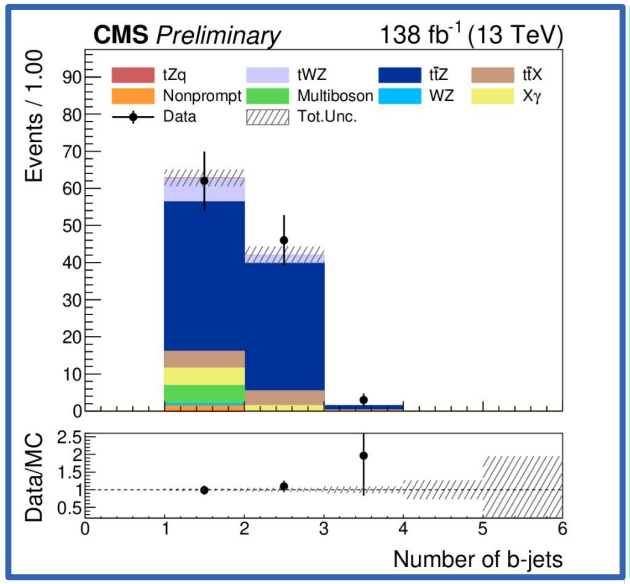


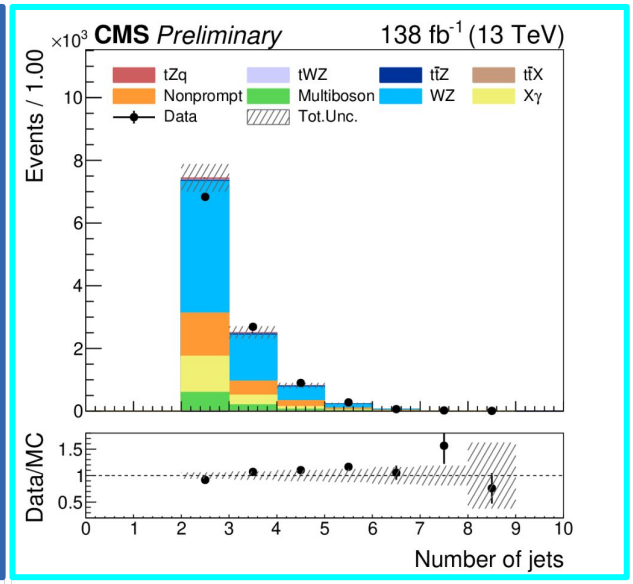




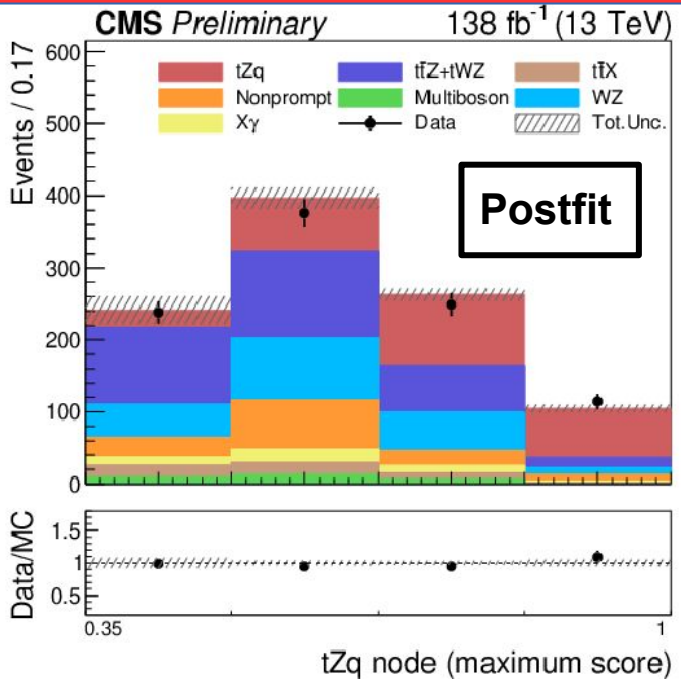
ttZ + tWZ and tZq Inclusive - CMS-PAS-TOP-23-004

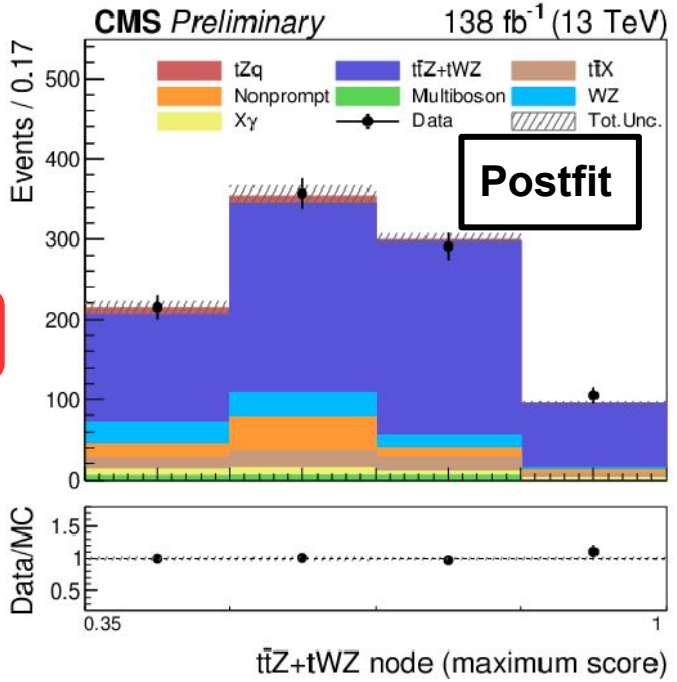
- For the inclusive cross sections, 2 CRs are used
  - 4 leptons (high purity in **ttZ**): b-tagged jet multiplicity
  - 0 b jets (enriched in **WZ**): jet multiplicity





- Profile likelihood-ratio scan
- The inclusive cross sections are measured to be
  σ(**ttZ**+**tWZ**)= 1.14 ± 0.07 pb and **σ(tZq)**= 0.81 ± 0.10 pb
  - Consistent with SM for tZq, small excess for ttZ+tWZ
- Statistically limited
  - Main syst: background modeling, (b-)jets

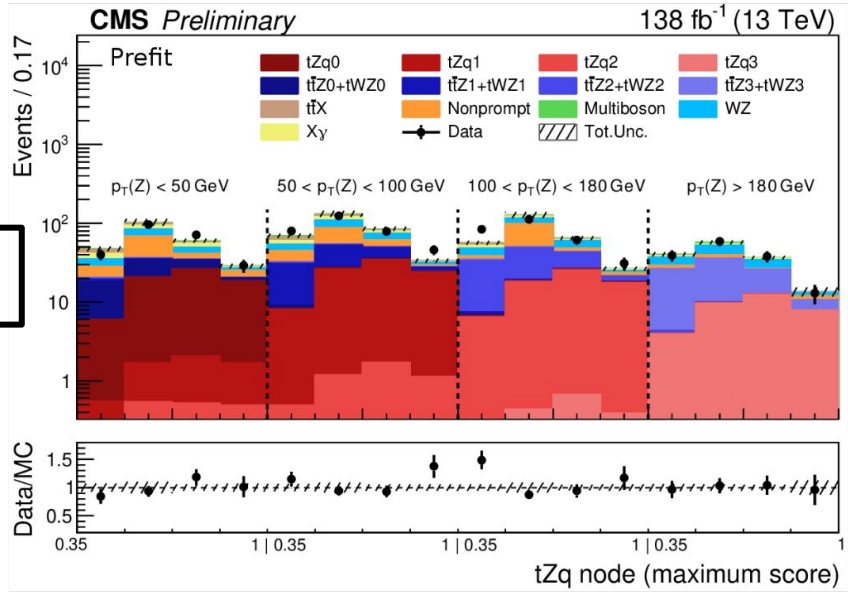


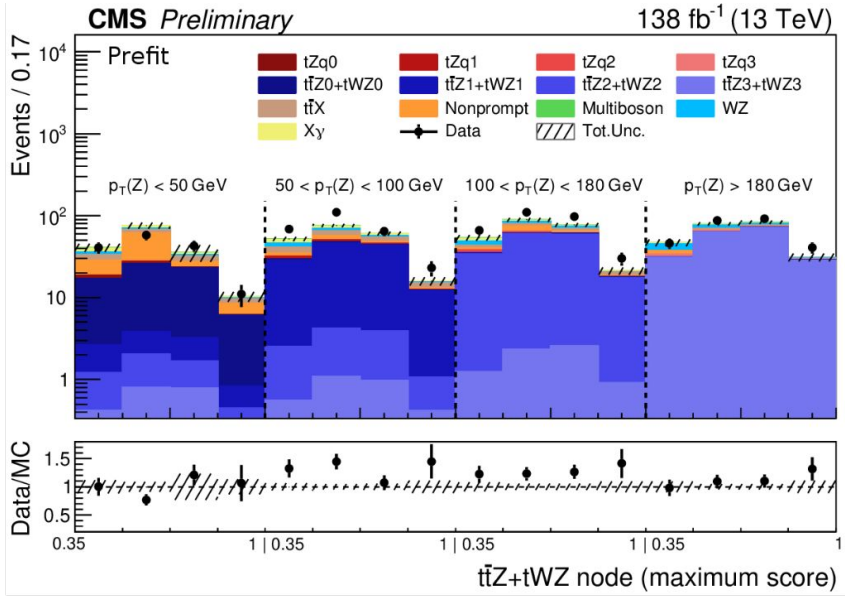


ttZ + tWZ and tZq Differential - CMS-PAS-TOP-23-004

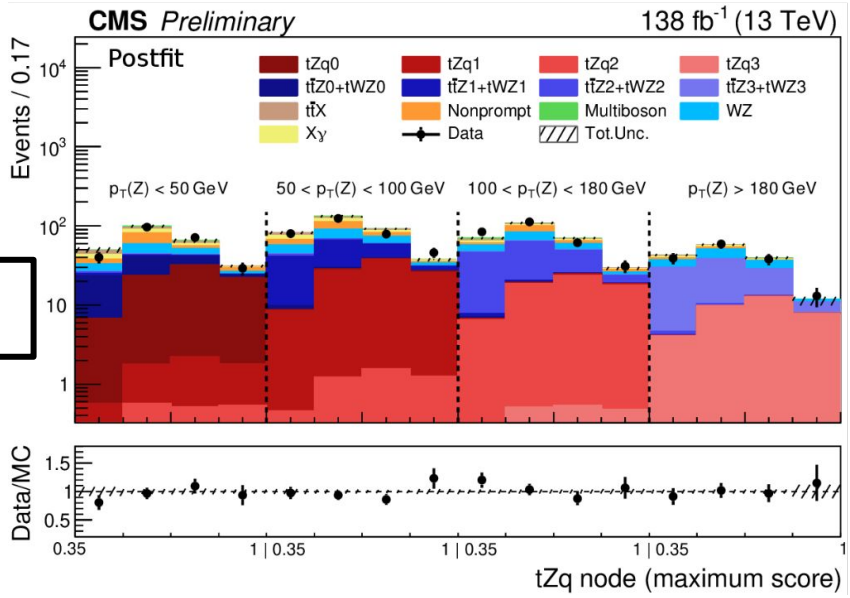
- The cross sections are measured differentially as functions of several observables
- Combined profile likelihood used for unfolding

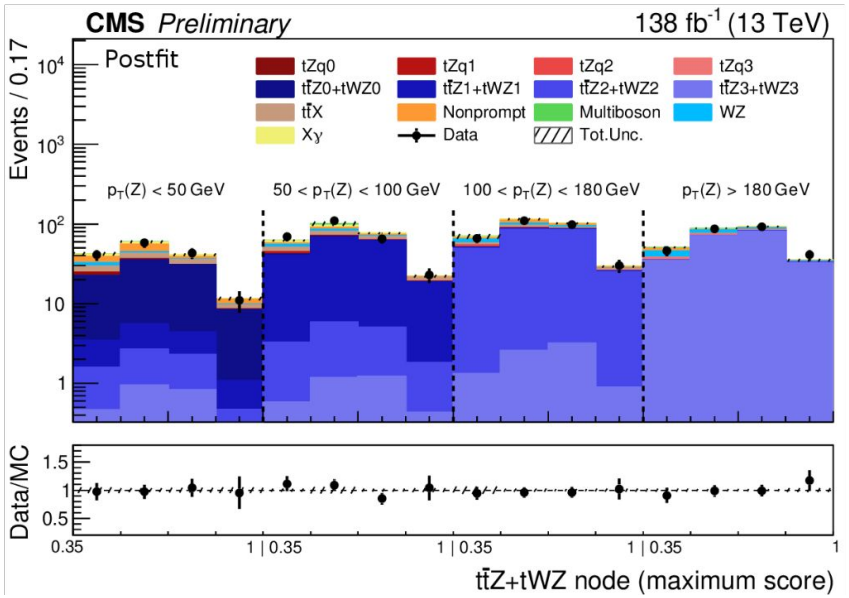
Prefit





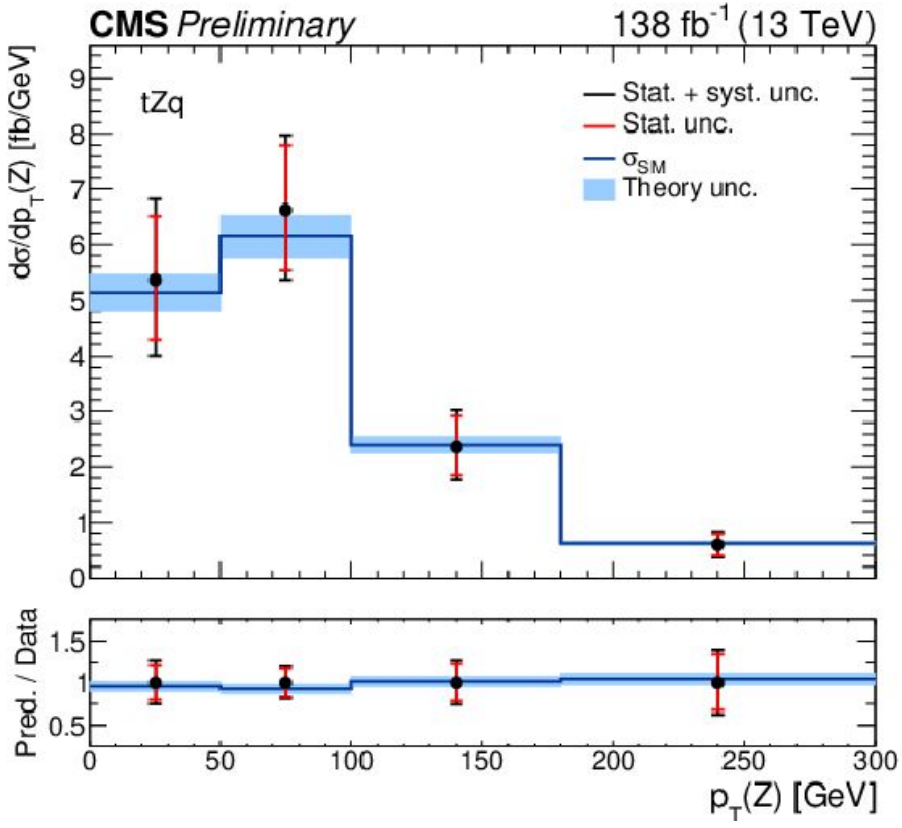
Postfit

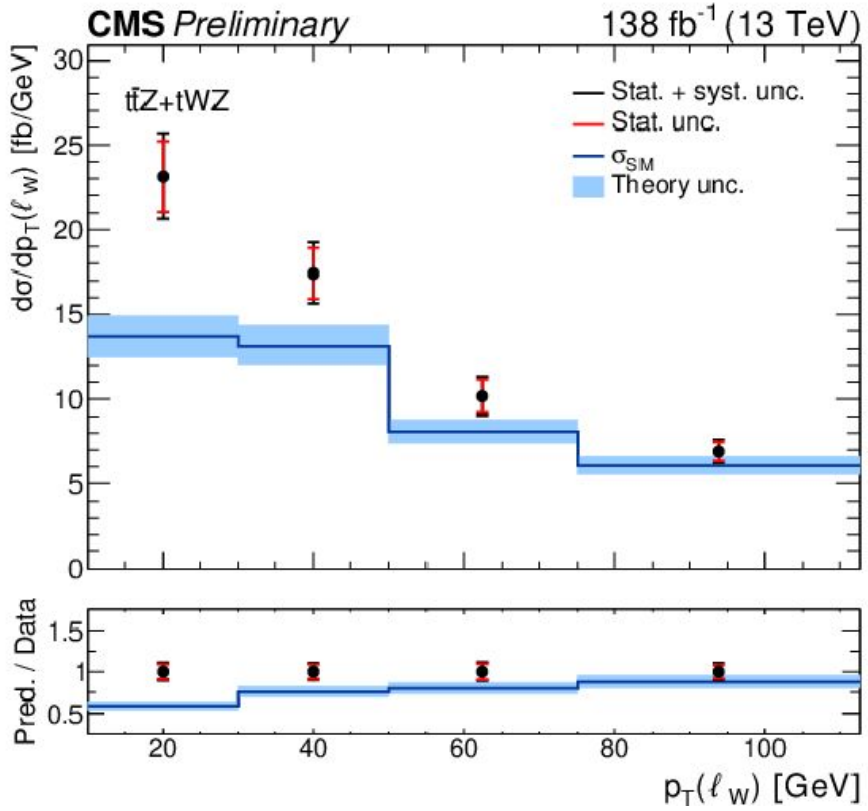




ttZ + tWZ and tZq Differential - CMS-PAS-TOP-23-004

- Unfolding performed simultaneously for tZq and ttZ+tWZ

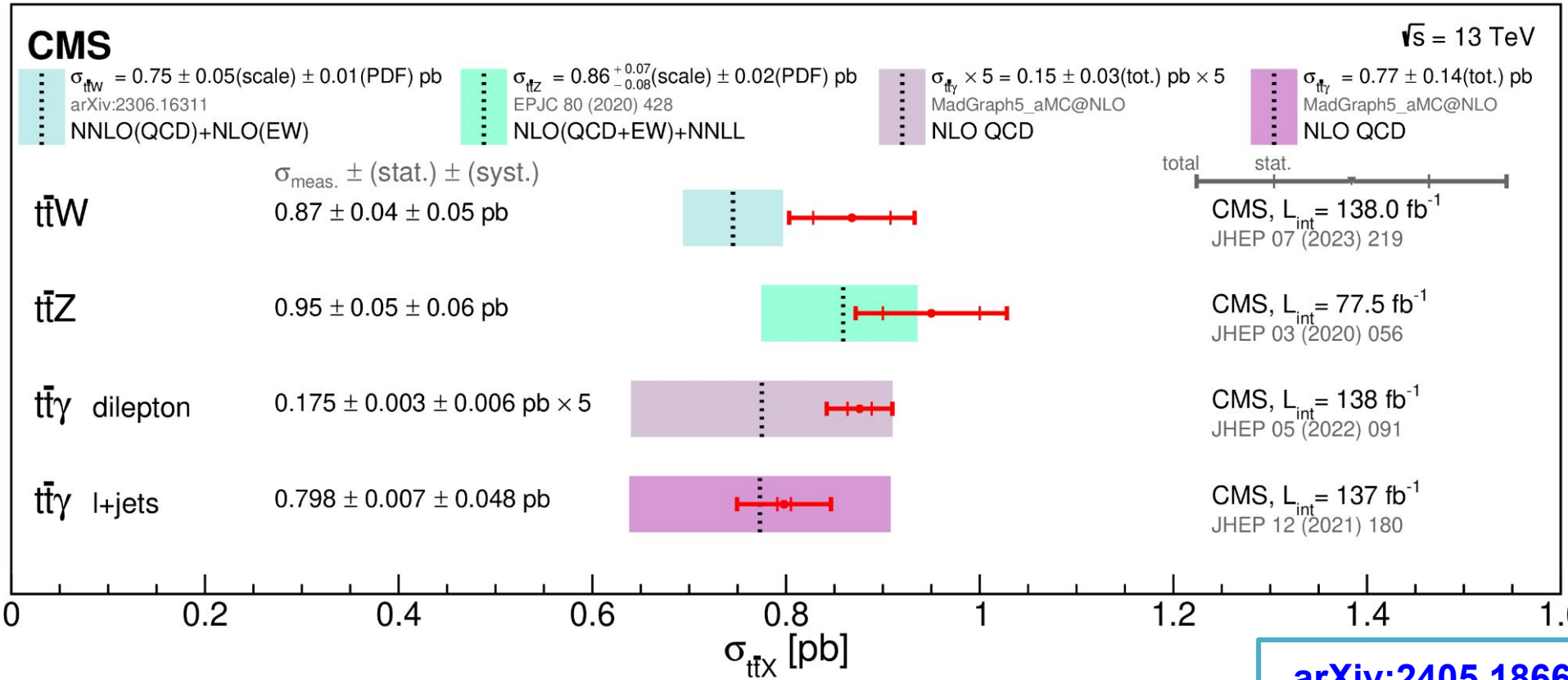




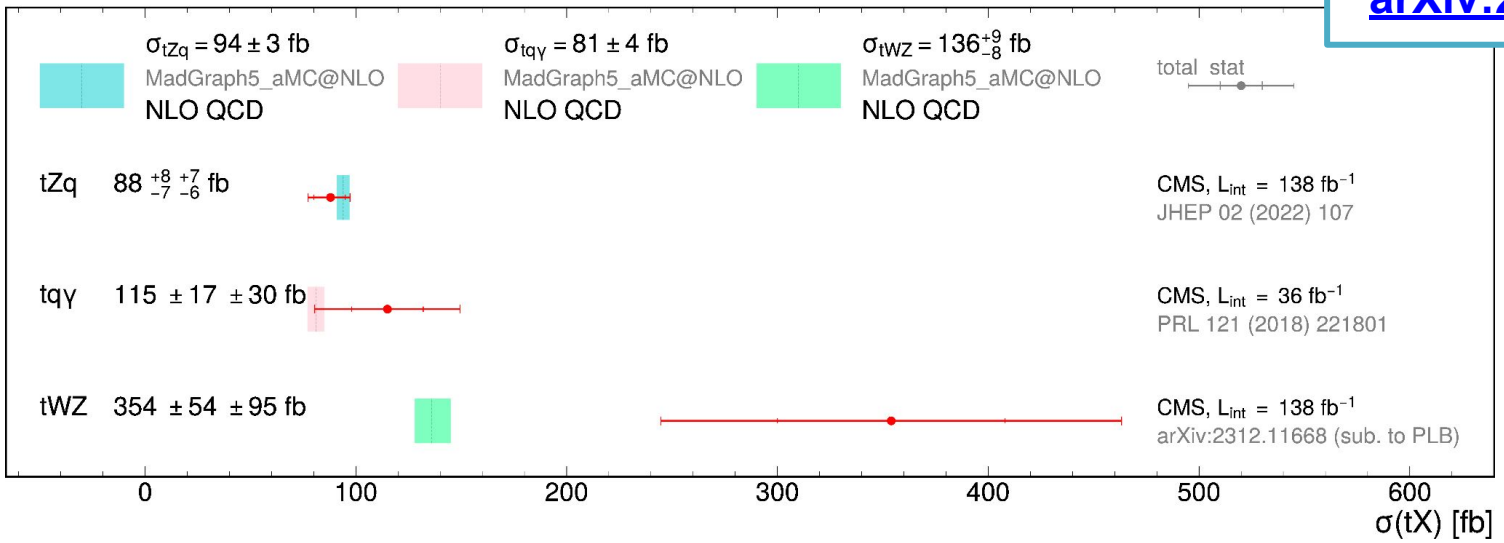
- Generally good agreement is found for the tZq process

- For ttZ+tWZ, a clear trend is observed as a function of the p_T of the lepton from the top quark, significant excess of the data over expectation at low values of p_T

Other t(t)+X

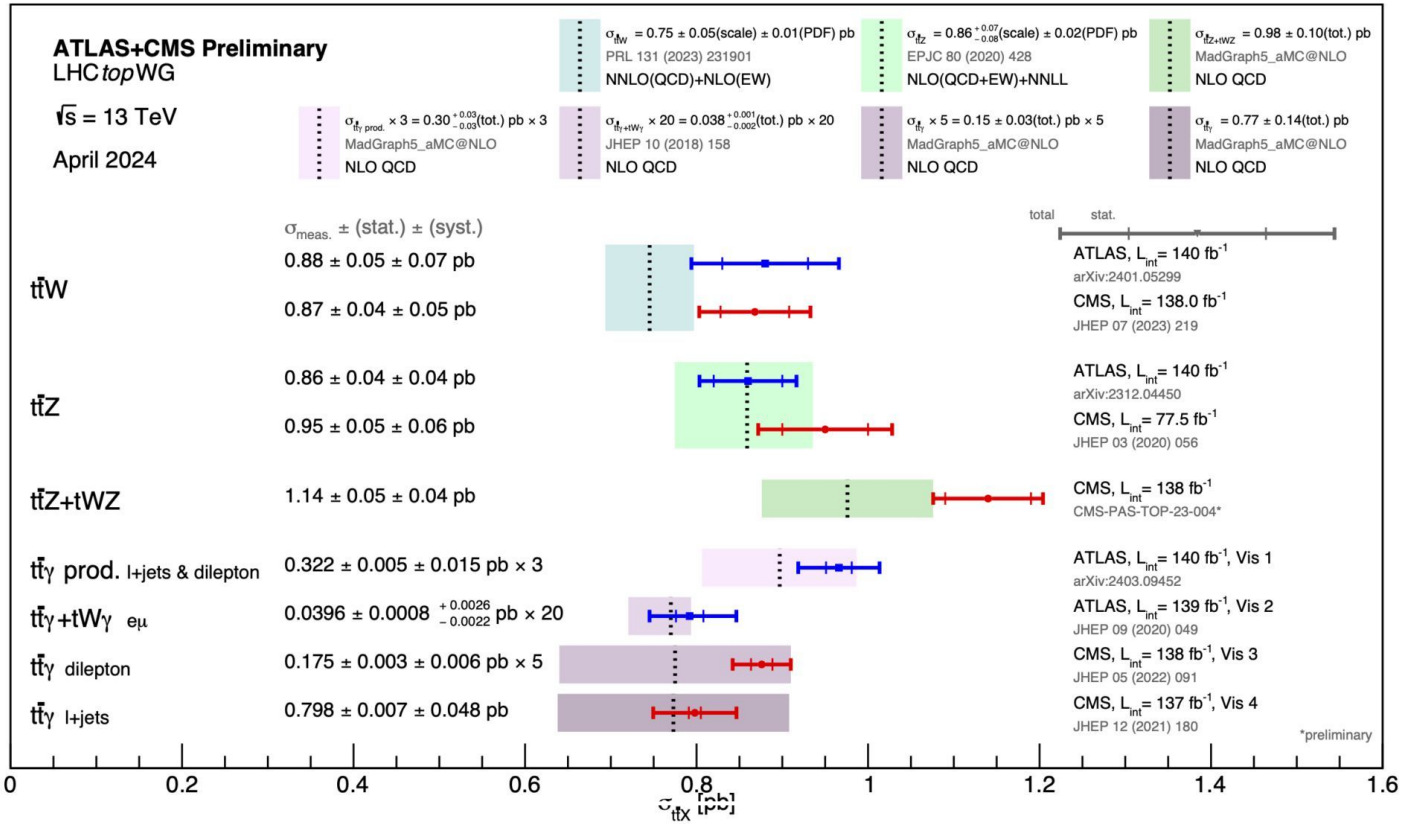


[arXiv:2405.18661]



Summary

- The large amount of LHC data recorded up to date allows probing **very rare SM processes**, very small production cross sections (**t/tt + V**)
- First evidence for **tWZ** production
- **First simultaneous differential measurement of tZq and ttZ + tWZ**



- **Stay tuned:** New results with more data are on their way…

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/TOP/index.html

Back-up Slides

tWZ modelling - arXiv:2312.11668 (submitted to PLB)

- LO → NLO (QCD): one extra QCD vertex can give rise to tt/ttZ diagrams, intermediate top becomes resonant ⇒ **overlap with tt/ttZ** that needs to be removed
- 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 $|A|^2$, 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 $\beta \longrightarrow \delta + \gamma$

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

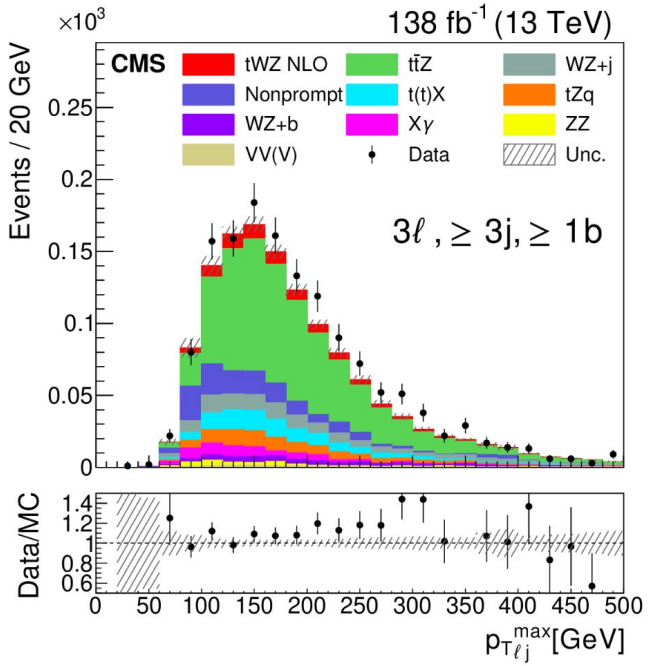
non-resonant resonant

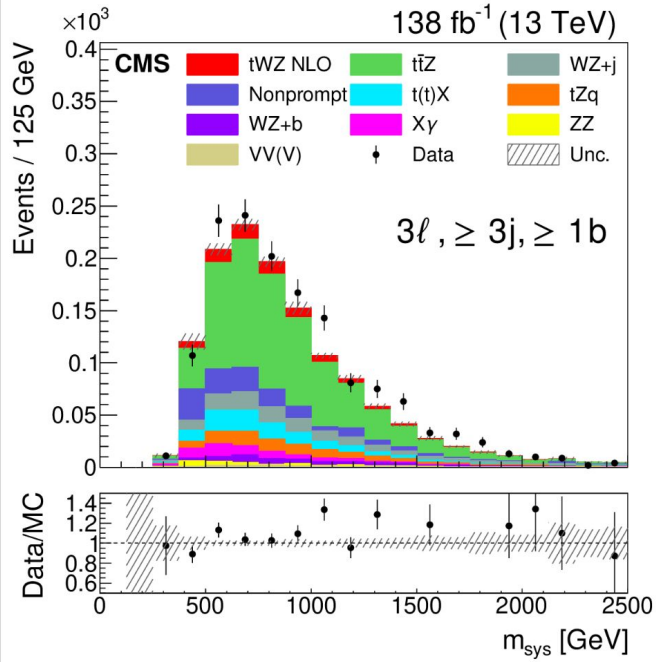
$$|\mathcal{A}_{ab\to\delta\gamma X}|^2 = \left|\mathcal{A}^{(\not\beta)}_{ab\to\delta\gamma X}\right|^2 + 2\Re\left(\mathcal{A}^{(\not\beta)}_{ab\to\delta\gamma X}\mathcal{A}^{(\beta)\dagger}_{ab\to\delta\gamma X}\right) + \left|\mathcal{A}^{(\beta)}_{ab\to\delta\gamma X}\right|^2$$

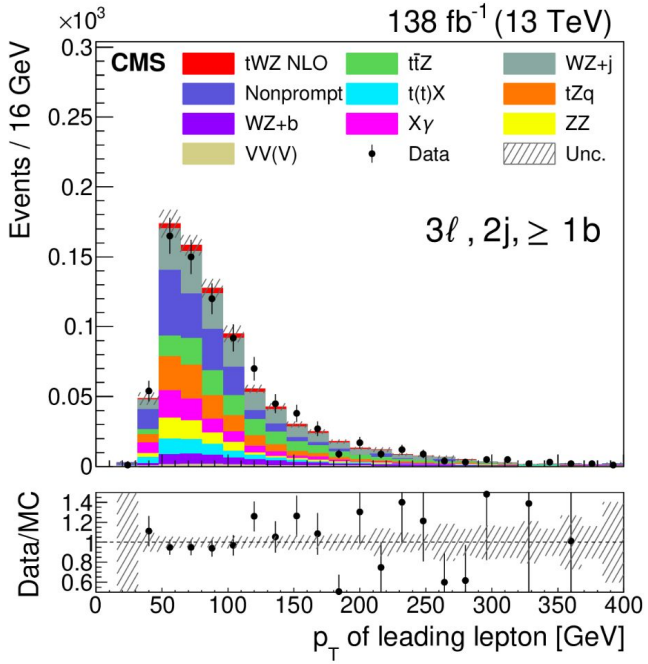
- DR+I (DR1): removes both resonance and interference term
- DR2: removes only the resonant term
- The diagram subtraction (DS) scheme implements removal at the cross section level

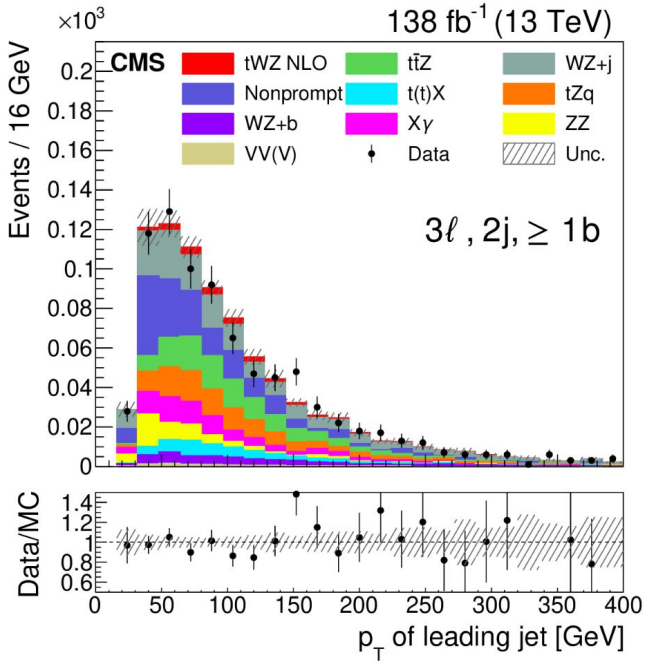
A. Saggio @LHCtopWG2023

tWZ - arXiv:2312.11668 (submitted to PLB)

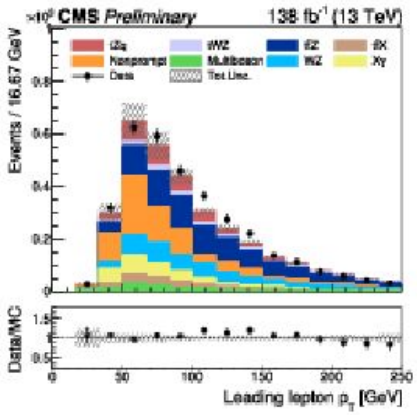


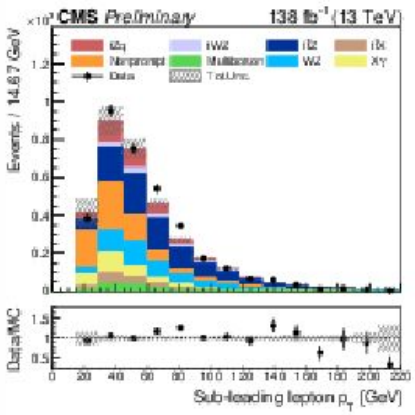


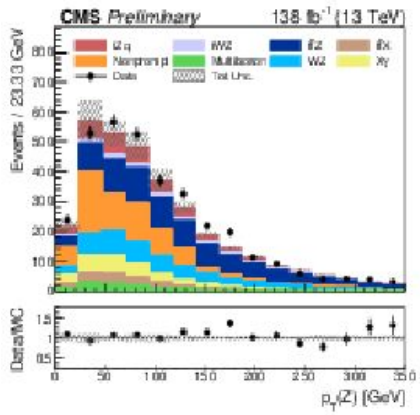


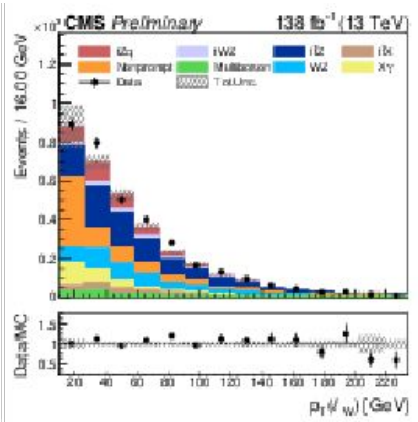


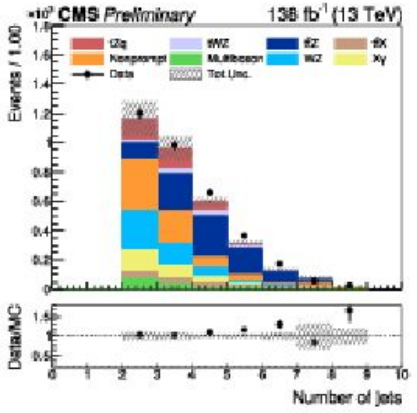
ttZ + tWZ and tZq - CMS-PAS-TOP-23-004

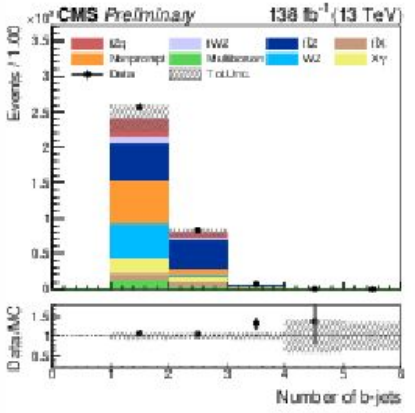


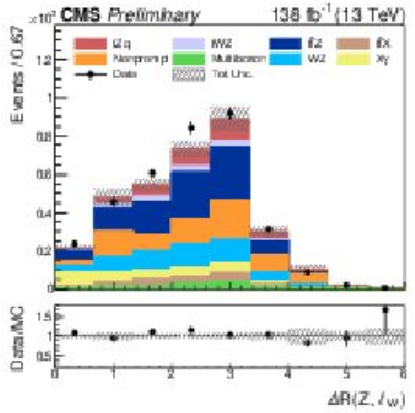


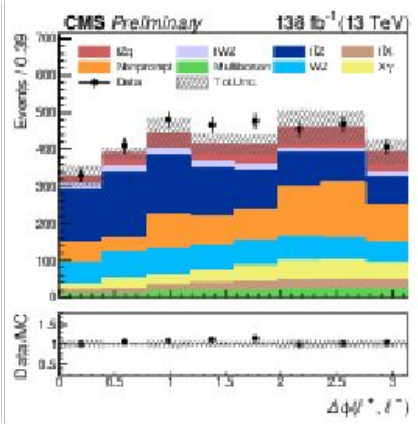


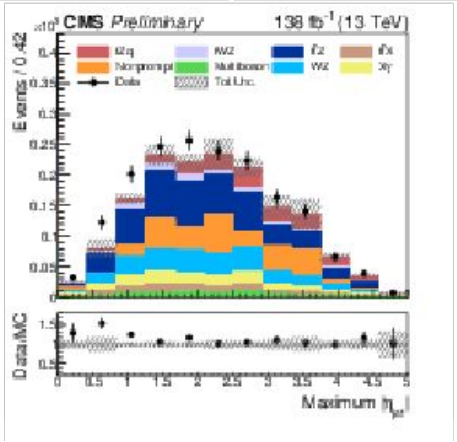


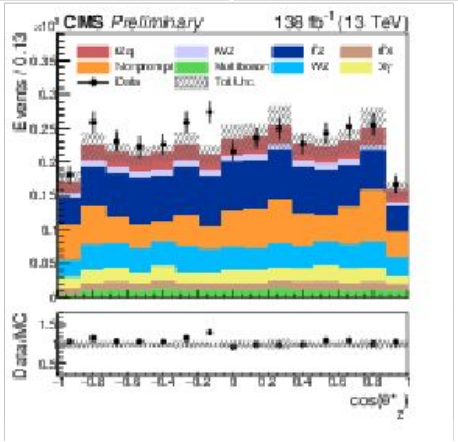




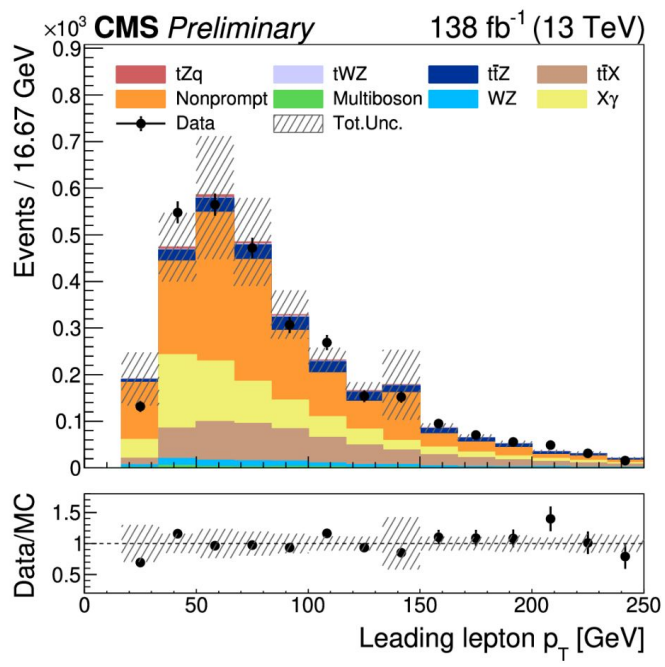


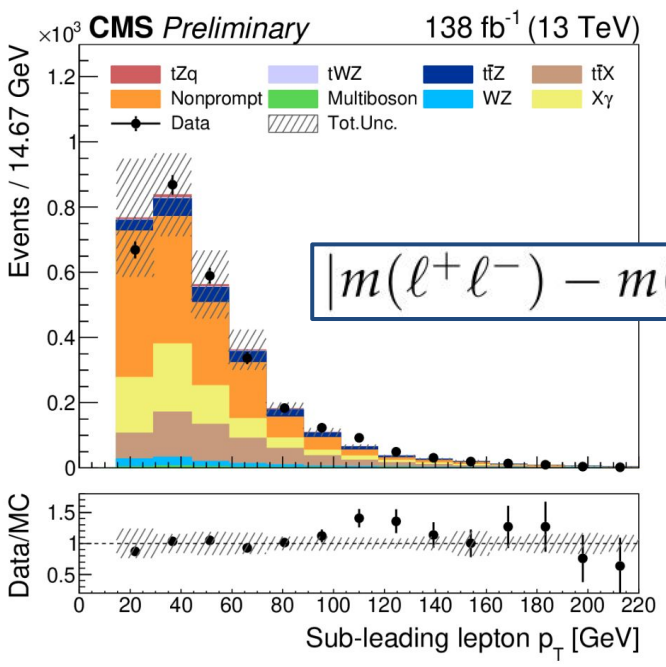




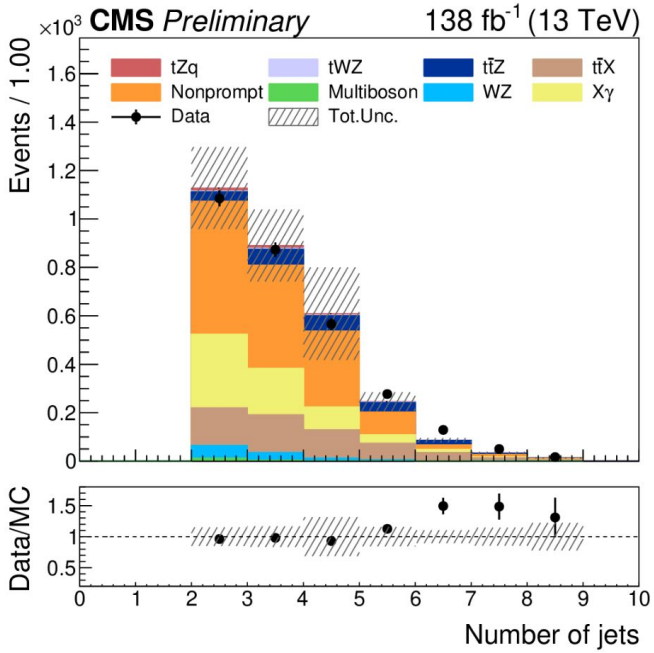


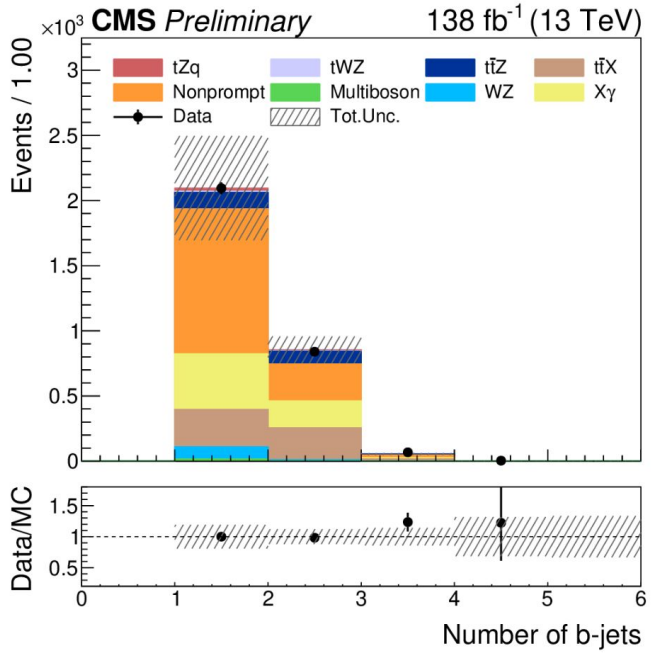
ttZ + tWZ and tZq - CMS-PAS-TOP-23-004



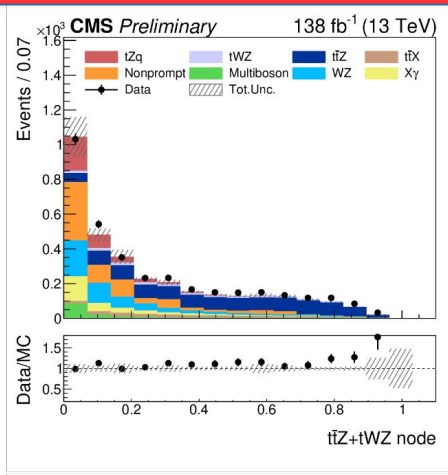


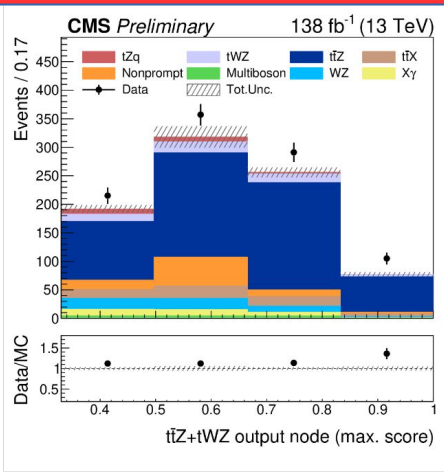
$$|m(\ell^+\ell^-) - m(\mathrm{Z})| > 20\,\mathrm{GeV}$$

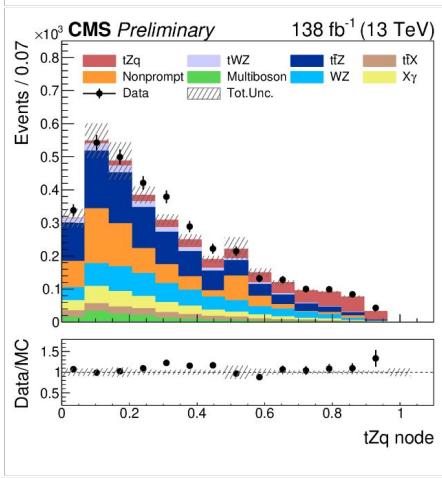


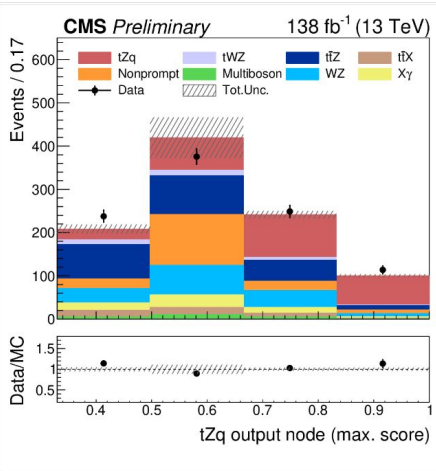


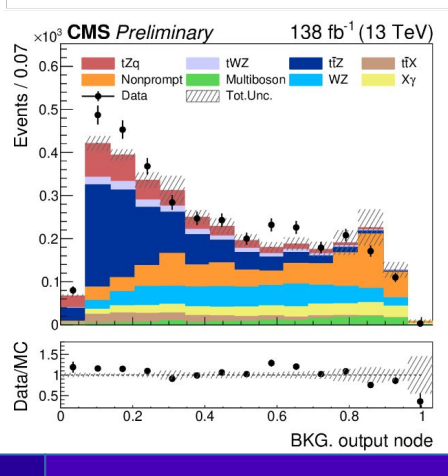
ttZ + tWZ and tZq - CMS-PAS-TOP-23-004

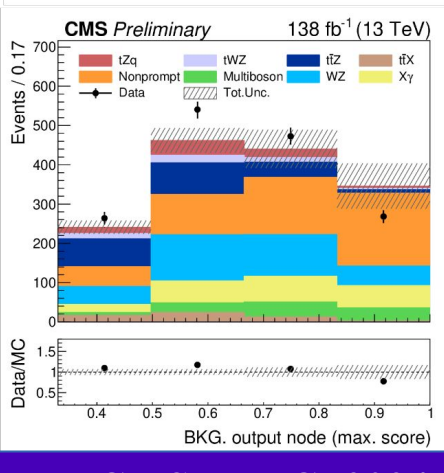




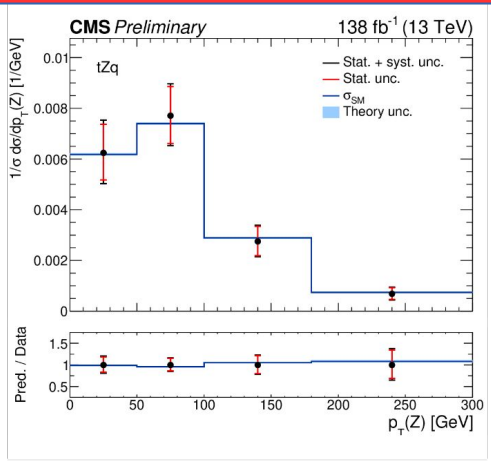


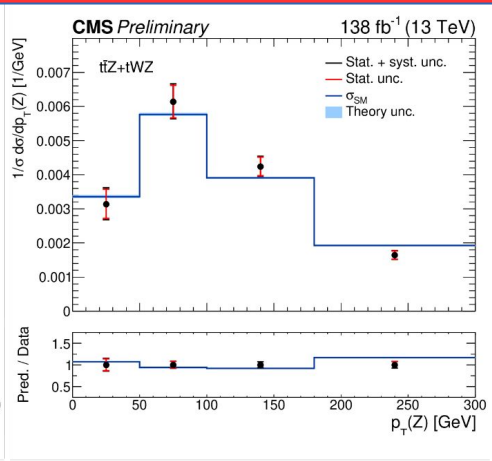


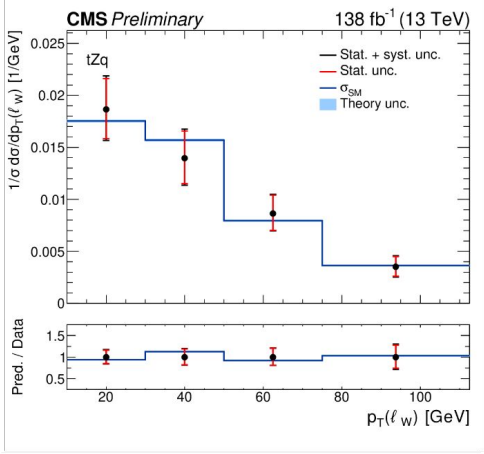


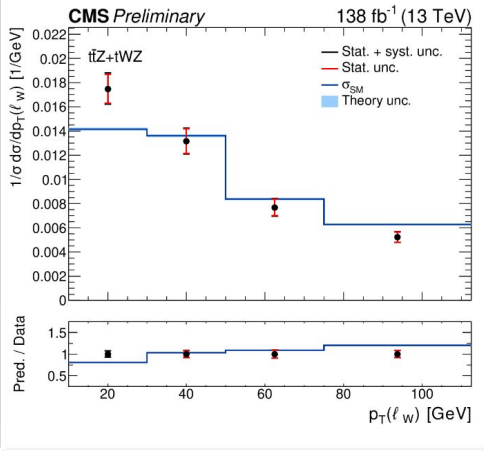


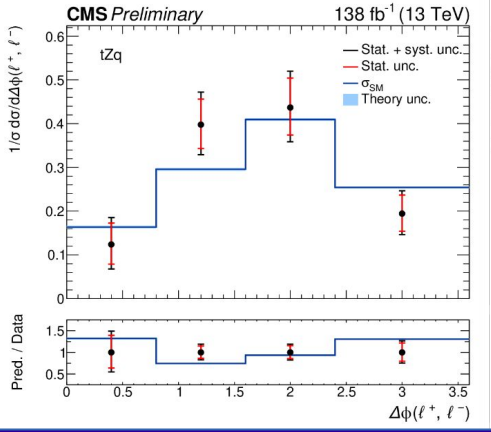
ttZ + tWZ and tZq Differential - CMS-PAS-TOP-23-004

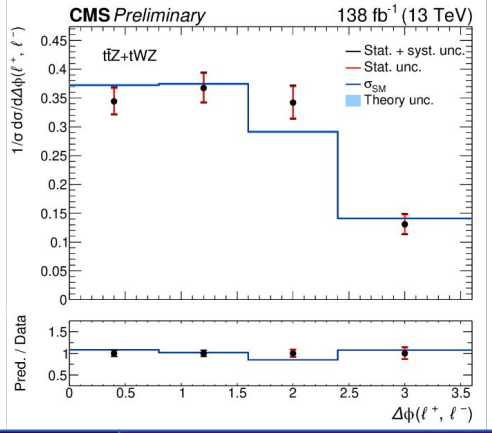


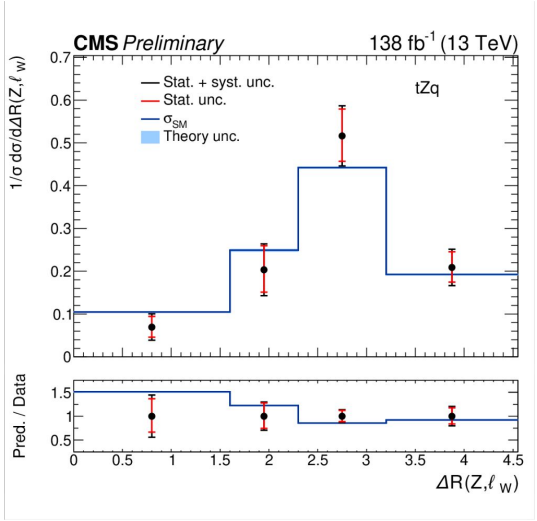


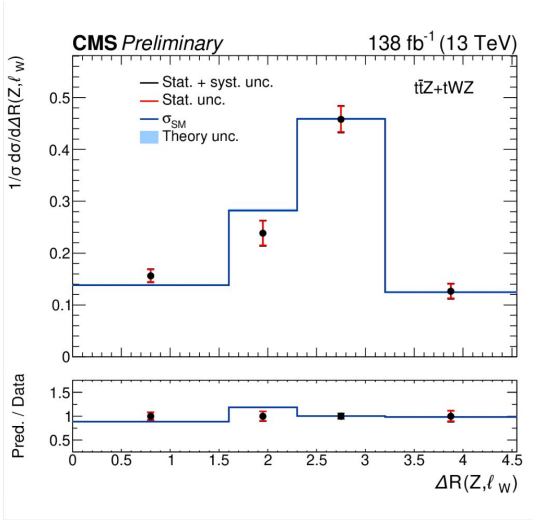


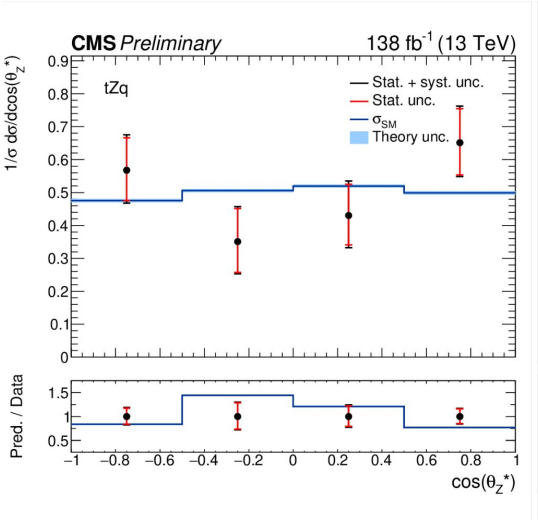


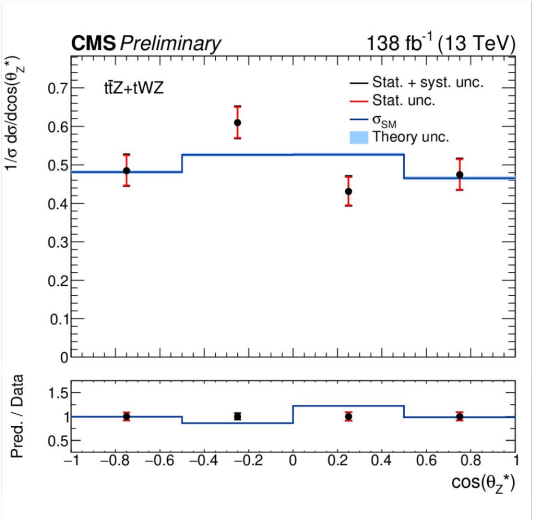












ttZ + tWZ and tZq Unc. - CMS-PAS-TOP-23-004

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 α_S	<1%	<1%
Underlying event and color reconnection	1%	2%
tWZ modeling	<1%	<1%
MC statistical	<1%	1%
Total	6%	13%