Associated production of top quarks with vector bosons in CMS

Recontres de Blois on Particle Physics and Cosmology

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EUROPEAN UNION
European Regional Development Fund
Grant PID2020-113341RB-I00 funded by:
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
AGENCIA ESTATAL DE INVESTIGACIÓN

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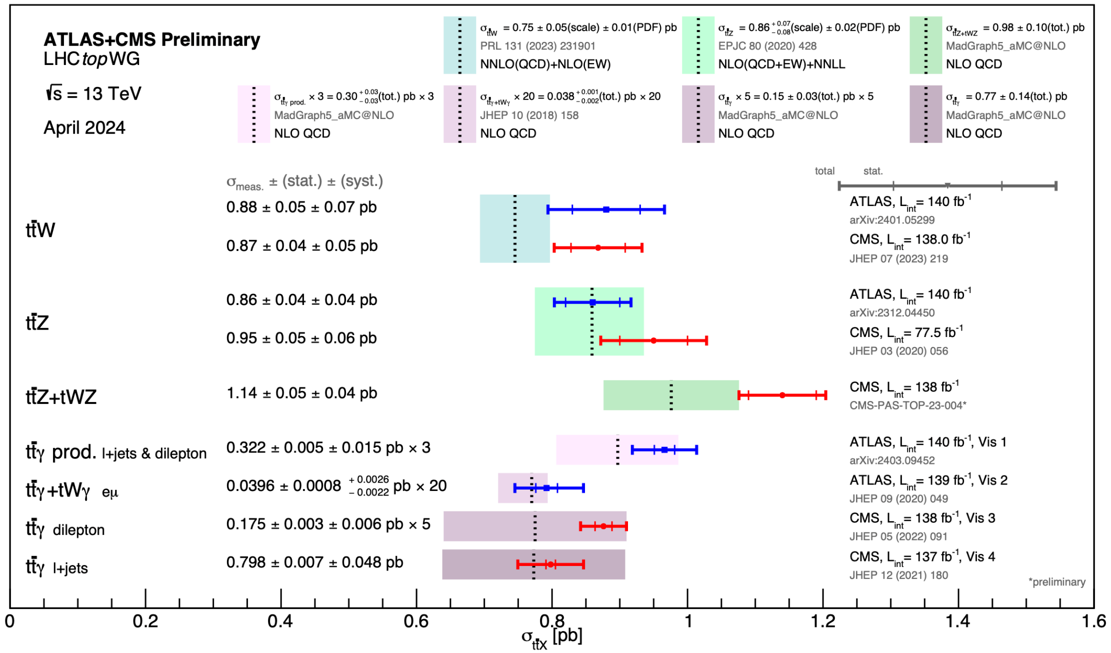
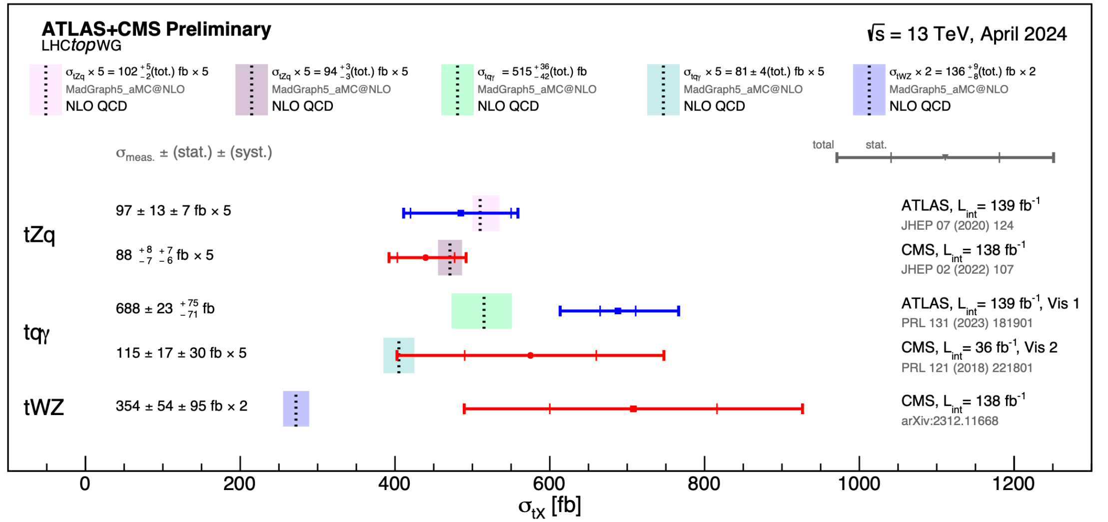
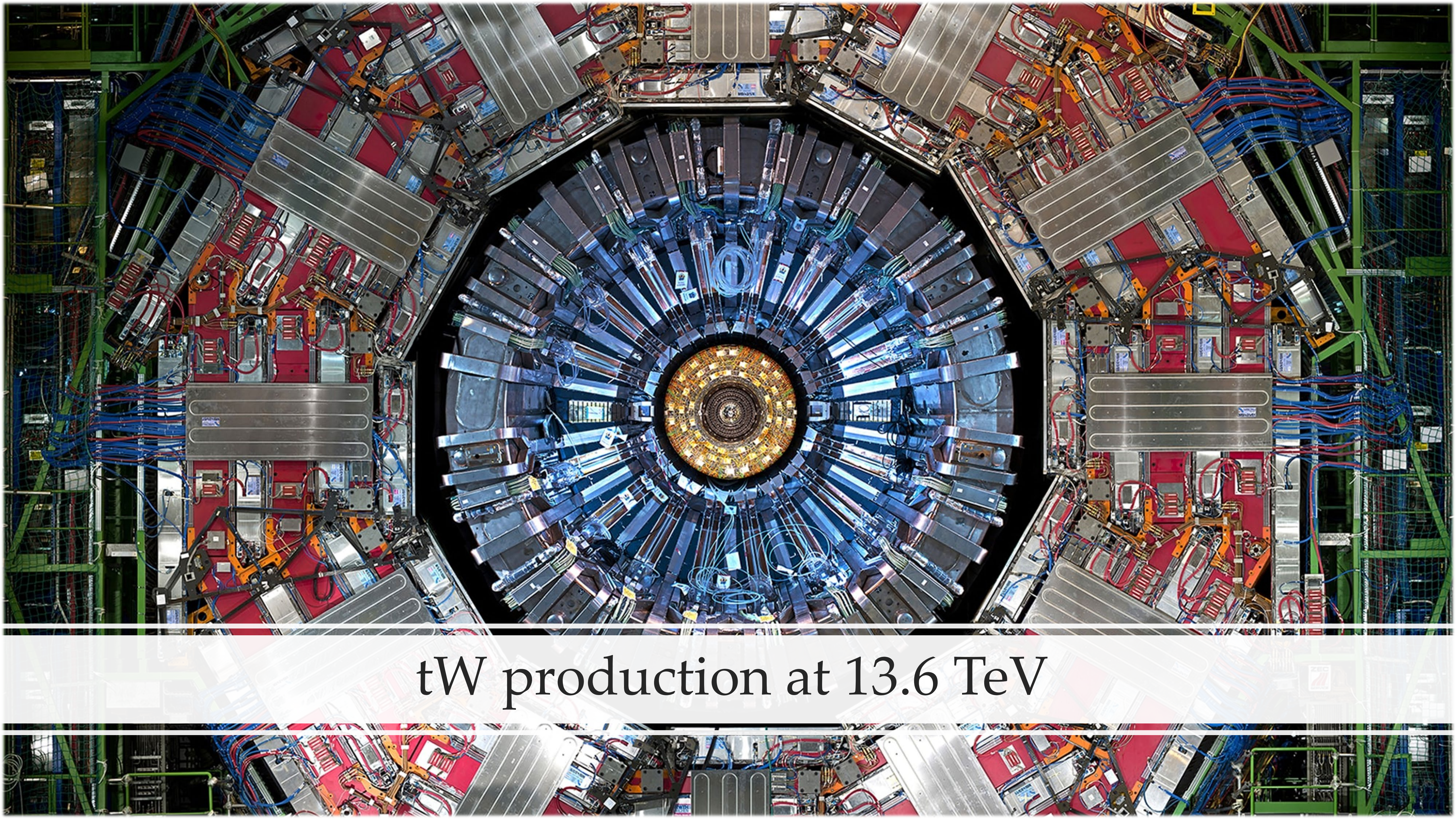
- **(In this talk!) associated production:** simultaneous appearance of top quarks and vector bosons
- **At the LHC, associated production can happen in two ways:**
  - Single top production (t+X)
  - Top quark pair production (tt+X)
  - X = (W, Z, γ)
- **TOP quark physics programme covers a wide range of different channels** accesible at the LHC.
- **CMS has thoroughly studied the top quark and its properties.**





In this talk, recent t+X and tt+X CMS measurements will be covered!



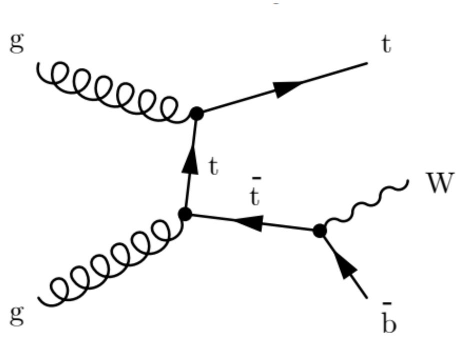
tW production at 13.6 TeV

tW measurements at 13.6 TeV

- **the tW process** is the second most common production channel of top quarks via electroweak mechanisms (single top modes).
- tW (NLO) interferes with $t\bar{t}$.
    - Clearly background dominated.
    - Two methods can be used to remove the interferences: **Diagram Removal** (DR) and **Diagram Subtraction** (DS).

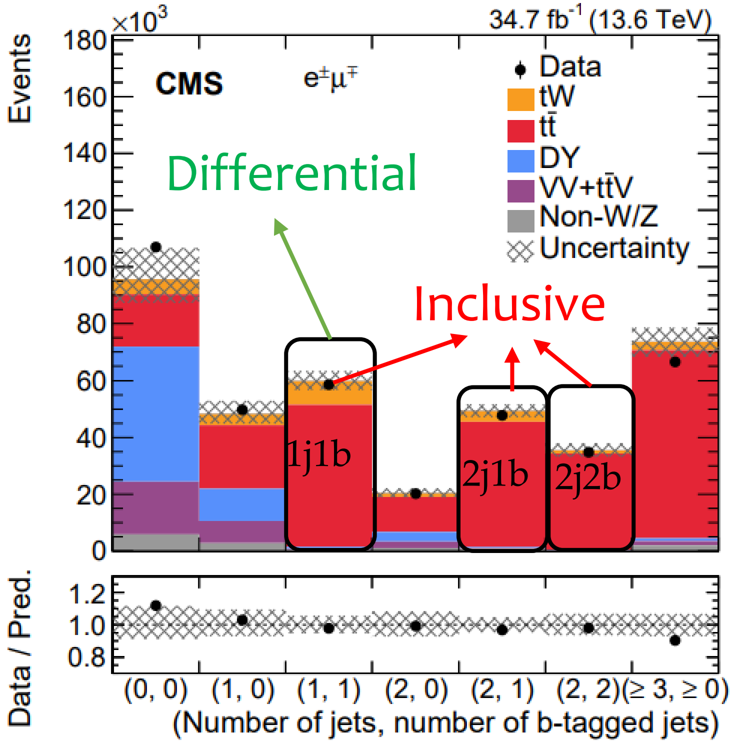
First measurement at 13.6 TeV!

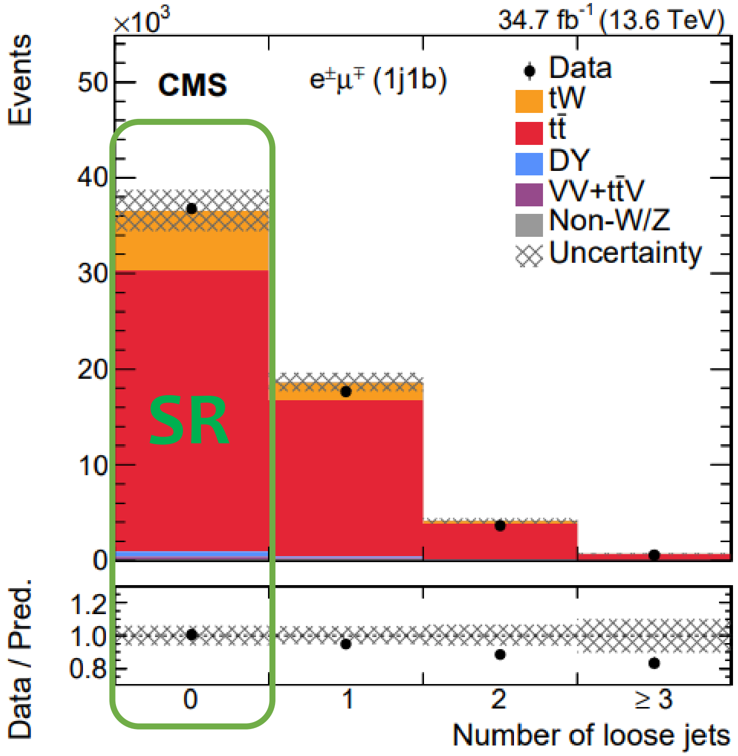
Arxiv: 2409.06444
Submitted to JHEP



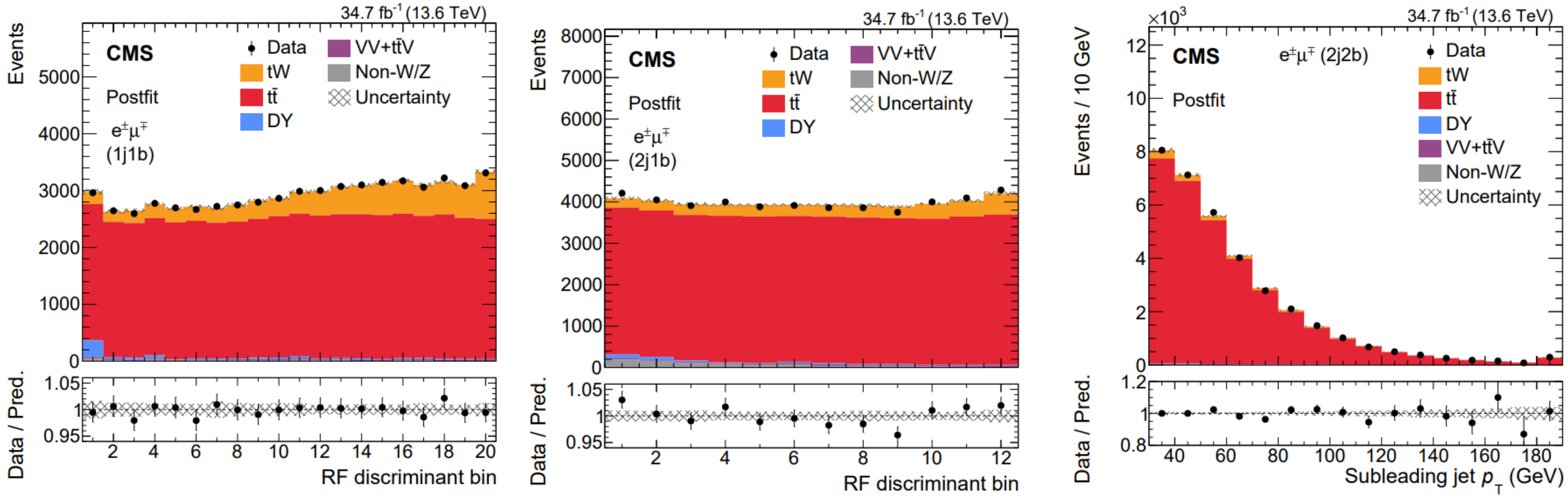
DR scheme is used for the nominal analysis, and the difference with respect to DS scheme is taken as an uncertainty.

- Baseline selection:
    - Dilepton channel: $e^{\pm}\mu^{\mp}$.
    - Leading lepton $p_T > 25$ GeV
    - $m_{\ell\ell} > 20$ GeV.
    - Categorisation based on number of jets and b tags.



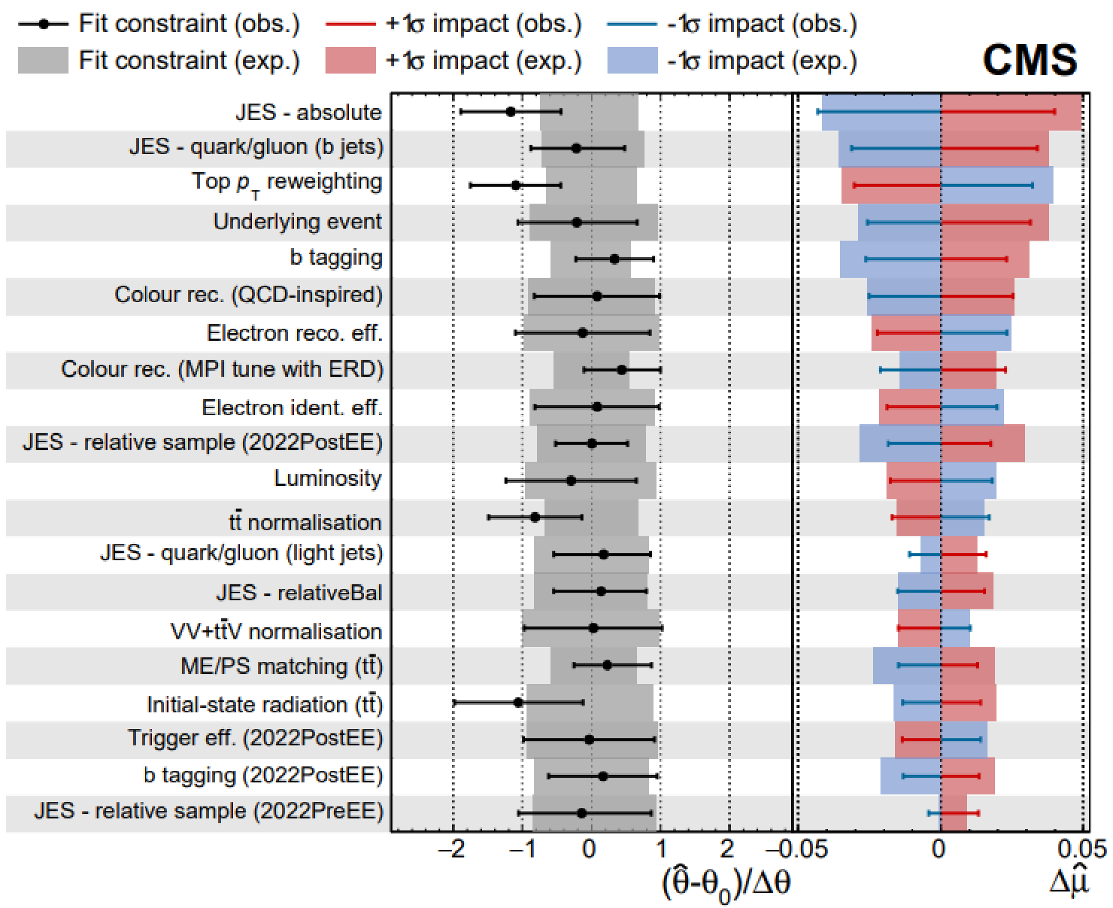


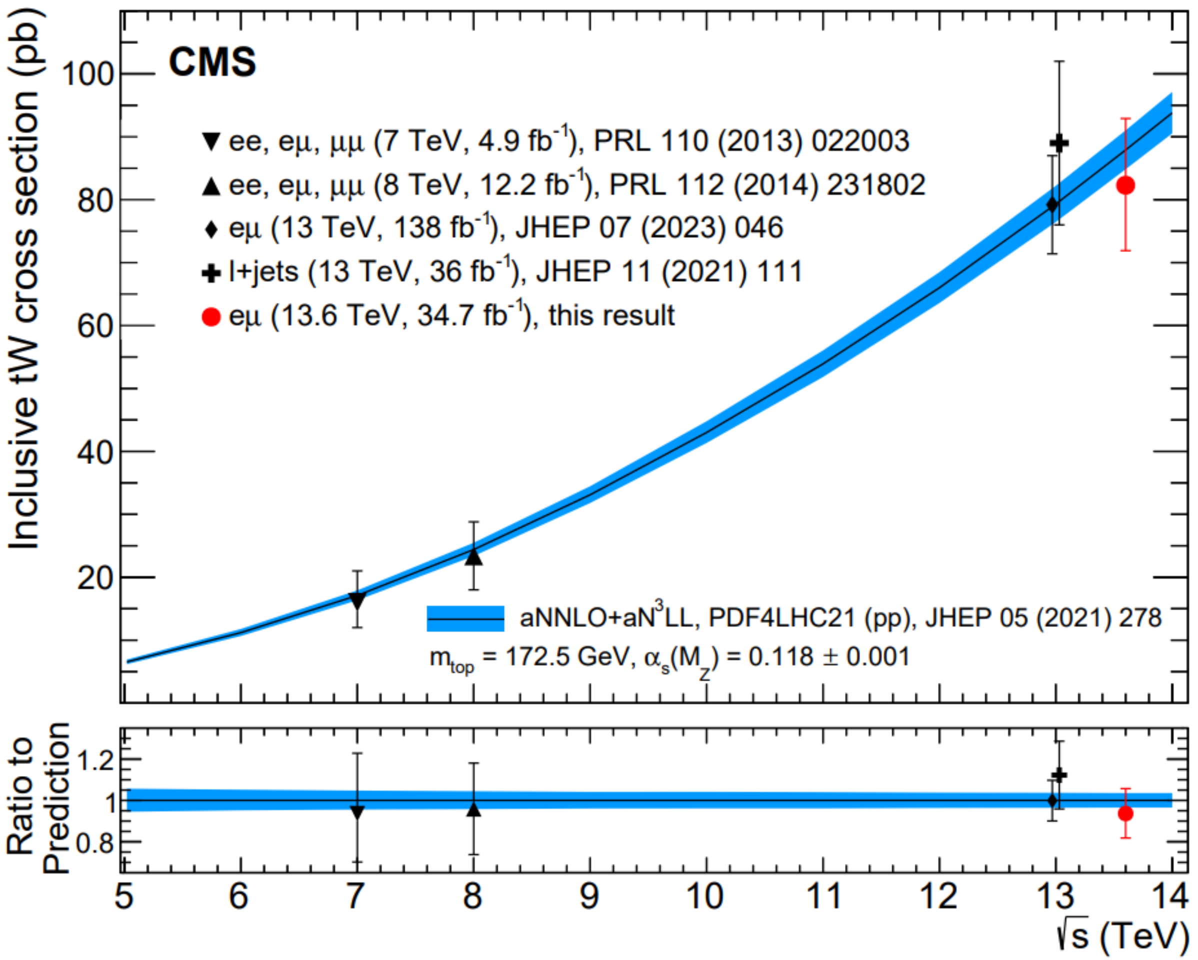
- A Random Forest (RF) is used to discriminate tW from $t\bar{t}$ and DY.
- To extract the signal, a maximum likelihood fit is performed using the two RF distributions and the subleading jet p_T distribution in the 2j2b region (which is used as a control region).



tW measurements at 13.6 TeV

- The measured cross section is: $\sigma_{tW} = 82.3 \pm 2.1\ (\text{stat}) \pm 9.8\ (\text{syst}) \pm 3.3\ (\text{lumi})\ \text{pb}$.
  - Compatible with SM predictions at aNNLO+aN³LL [JHEP05(2021)278]

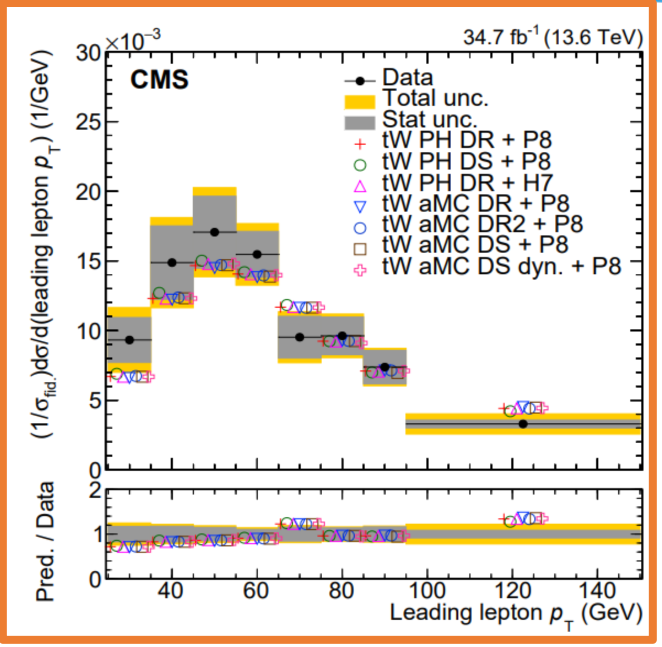


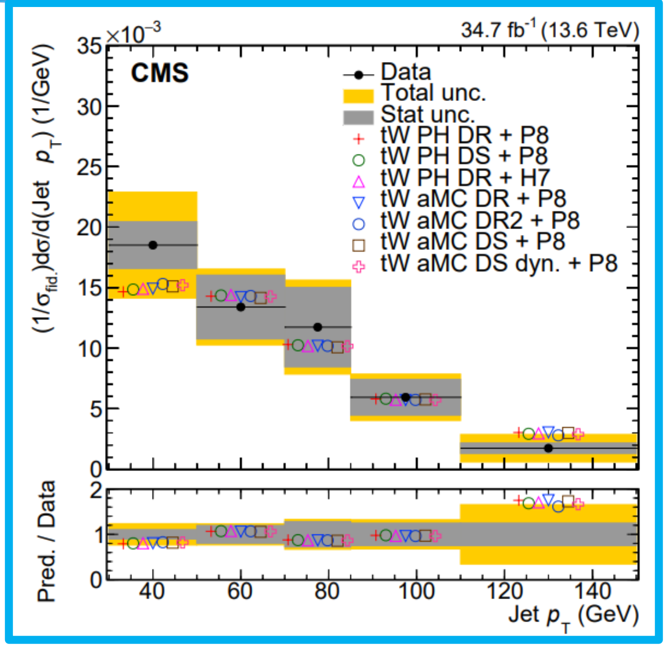


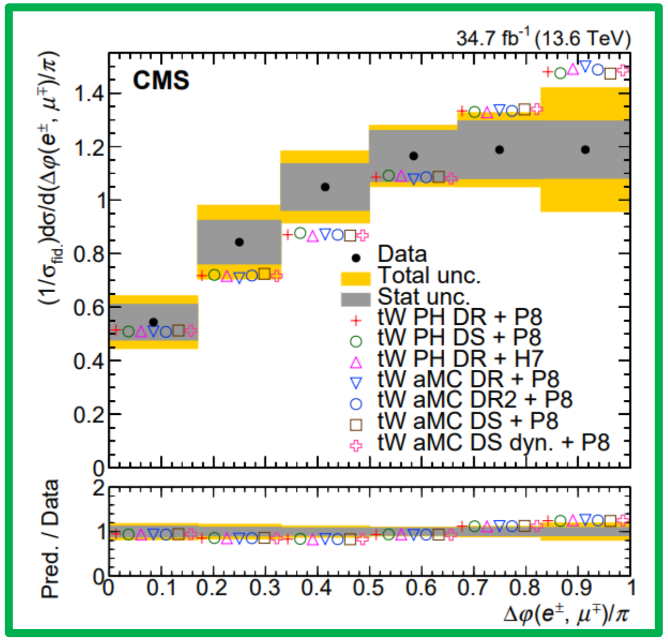
tW measurements at 13.6 TeV

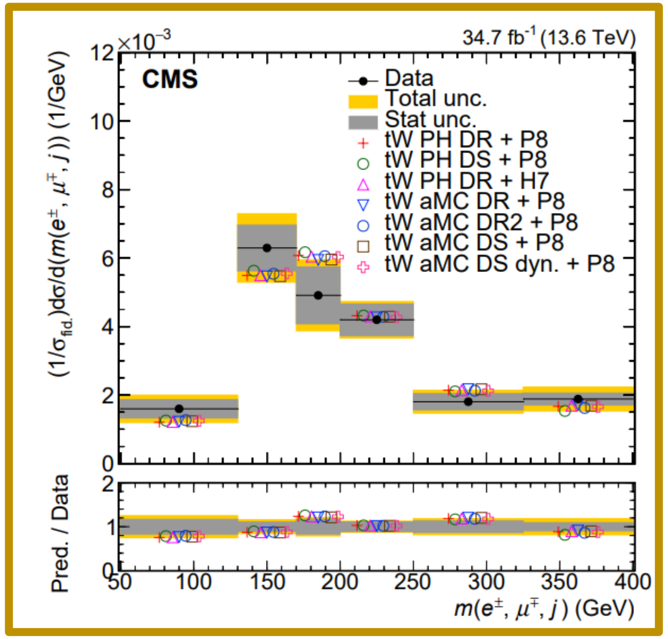
- The differential measurement is performed using 1j1b with a veto on the presence of loose jets in the final state.

- Differential cross sections are measured as a function of several variables.
  - Leading lepton p_T
  - jet p_T
  - $\Delta\phi(e^{\pm},\mu^{\mp})$
  - $m(e^{\pm},\mu^{\mp})$
  - $p_Z(e^{\pm},\mu^{\mp},j)$
  - $m_T(e^{\pm},\mu^{\mp},j,\ p_T^{miss})$
- Signal extraction and unfolding to fiducial region at particle level are performed using `TUnfold`.
- The results are normalised to the fiducial cross section
- Overall agreement between data and expectations within uncertainties
- Compatible results between the DR and DS schemes.









Evidence of tWZ at 13 TeV

Evidence of tWZ at 13 TeV

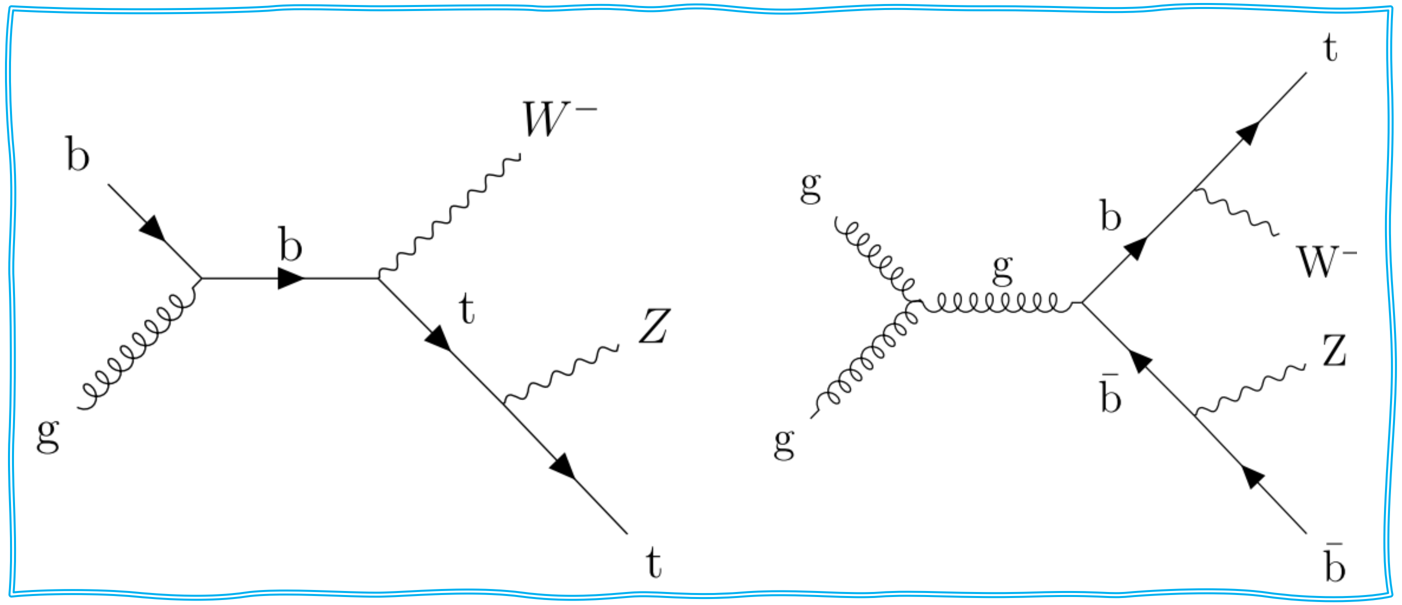
- **The** tWZ process occurs in the electroweak production of a top, a W and a Z boson.
- It has several interesting features:
  - Never been observed.
  - **Very small cross section** (σ_{theo}(NLO QCD) ~136 fb)
  - **Sensitive to couplings of three of the most studied particles at the LHC!**
- Measuring its properties also constitute a **challenge** given the **large ttZ background.**
  - Similar issue to tt vs tW… **tWZ and ttZ interfere at NLO.**
  - Also similarly → **DR/DS schemes are used here for signal modeling.**

PLB 855 (2024) 138815

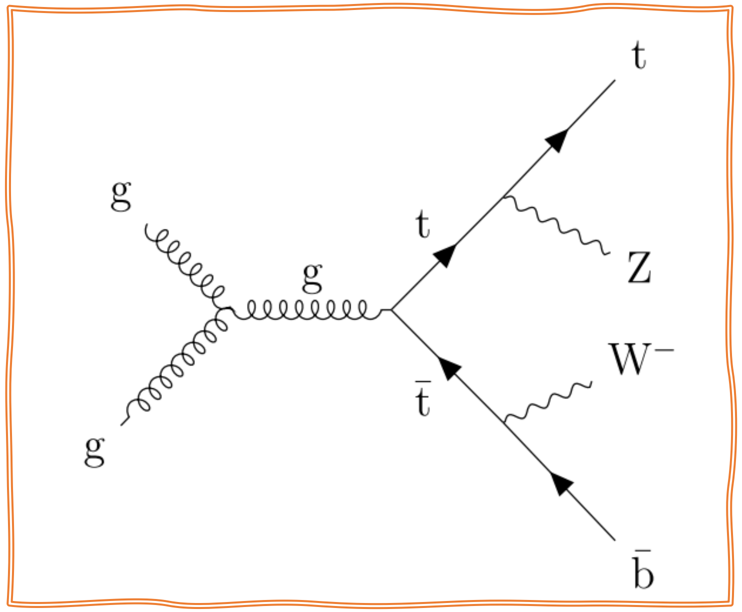
Published in PLB

First evidence of tWZ!!

Pure tWZ production



ttZ production

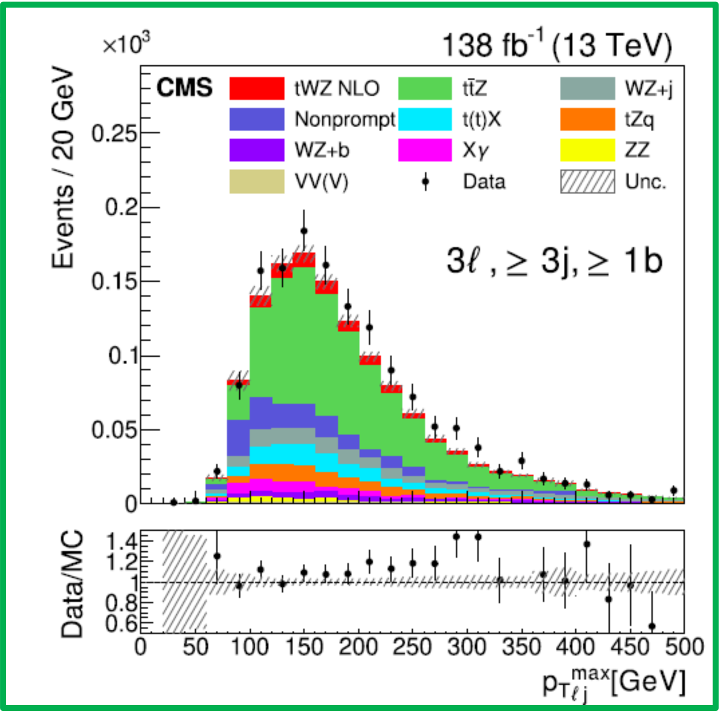


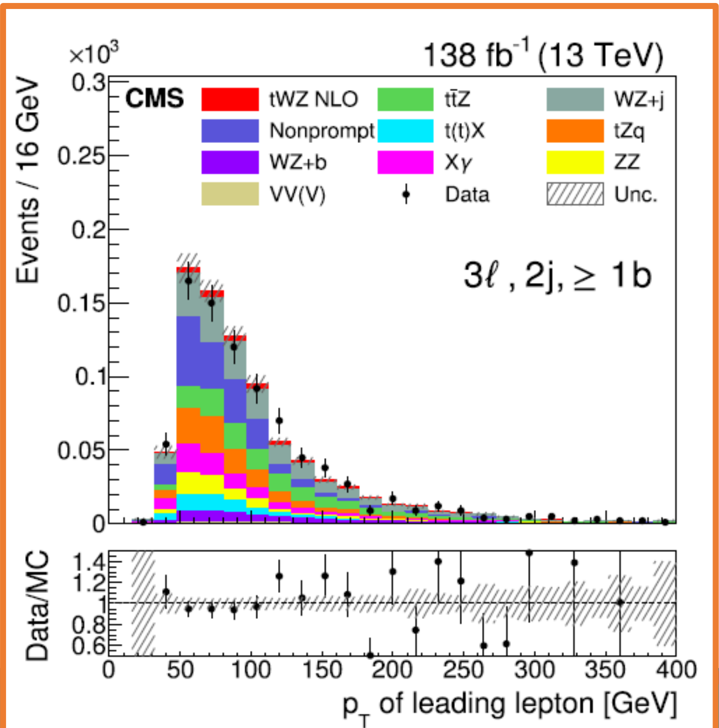
Evidence of tWZ at 13 TeV

- Four signal regions are defined

	$SR_{3\ell,3j}$	$SR_{3\ell,2j}$	$SR_{4\ell}$	$SR^{Boosted}$
tWZ signal	77.47 ± 0.12	28.19 ± 0.07	15.98 ± 0.06	5.44 ± 0.02
$t\bar{t}Z$	657.9 ± 1.6	122.76 ± 0.61	113.86 ± 0.64	59.03 ± 0.50
Nonprompt leptons	139 ± 42	170 ± 51	1.02 ± 0.31	1.94 ± 0.58
tZq	86.45 ± 0.78	108.69 ± 0.71	0.29 ± 0.04	4.37 ± 0.17
ZZ	22.7 ± 2.4	60.6 ± 4.1	20.0 ± 2.3	0.30 ± 0.29
WZ	166.4 ± 3.3	227.8 ± 4.0	0.59 ± 0.19	6.84 ± 0.66
VV(V)	15.51 ± 0.11	10.55 ± 0.09	1.35 ± 0.03	0.64 ± 0.02
$t(\bar{t})X$	108.30 ± 0.99	49.4 ± 1.2	17.32 ± 0.34	6.26 ± 0.19
γ	54.1 ± 2.6	78.3 ± 3.7	6.92 ± 0.95	1.08 ± 0.31
Total backgrounds	1249 ± 42	822 ± 51	159.9 ± 2.6	80.8 ± 1.1
Data	1463	849	180	77

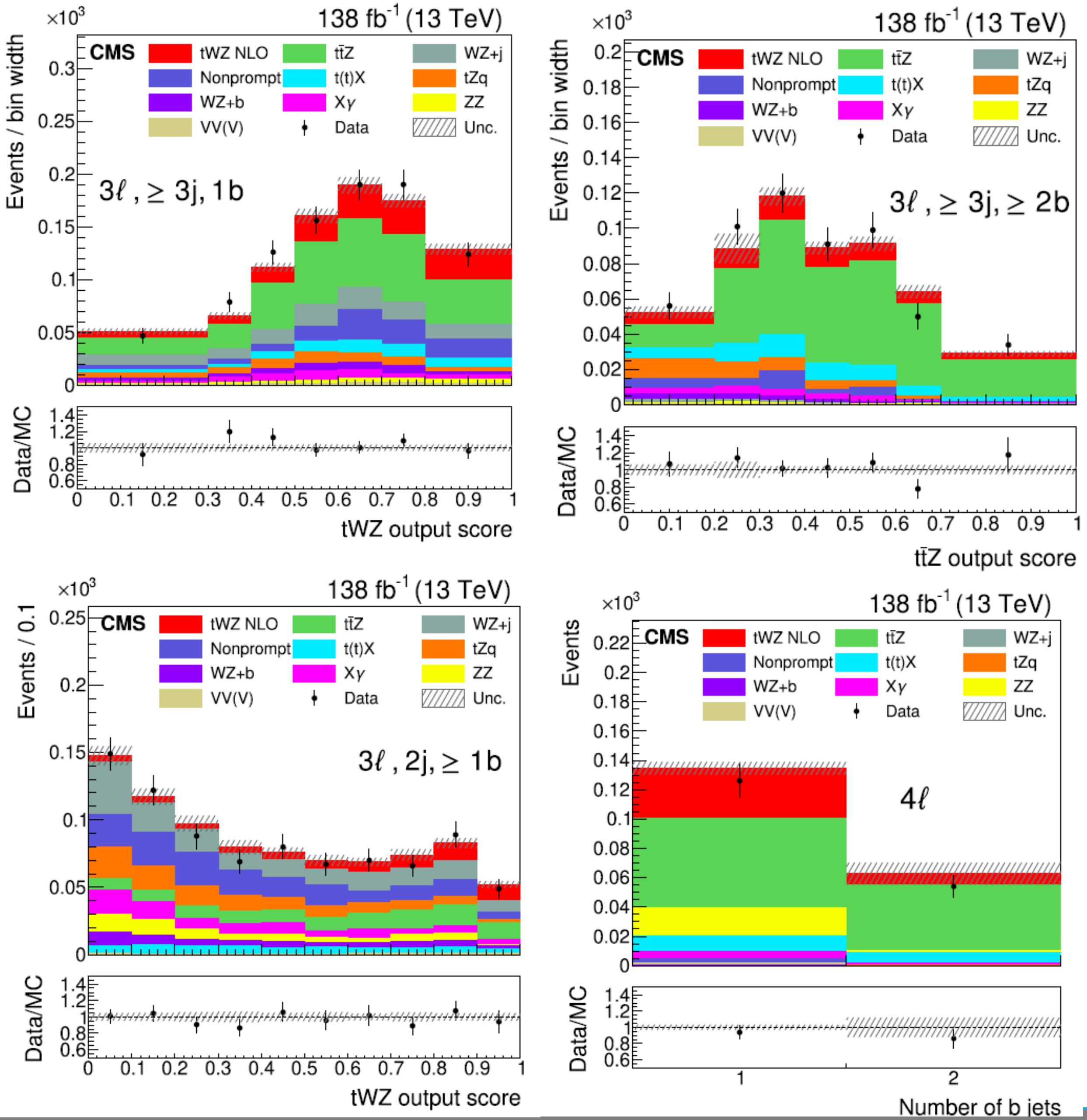
- In order to increase the discrimination power between signal and backgrounds, DNNs are trained

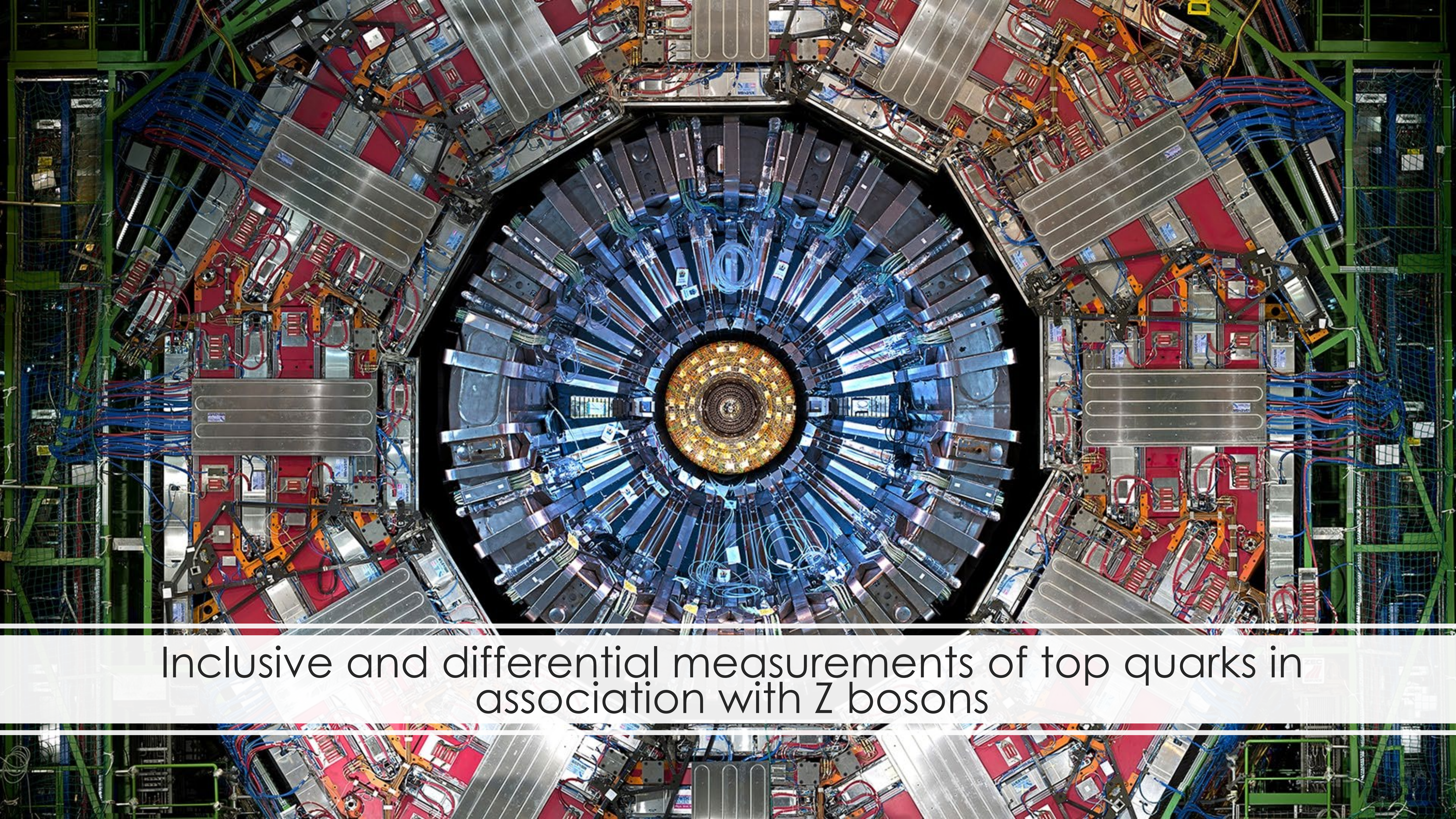




Evidence of tWZ at 13 TeV

- The signal extraction is performed in a binned likelihood fit to:
  - DNN score for $SR_{3\ell,3j}$
  - DNN score for $SR_{3\ell,2j}$ (splitted in two)
  - The b tag multiplicity for $SR_{4\ell}$
  - Summed event yields in both boosted SRs.
- The signal strength is measured:
  - $r_{tWZ} = 2.6 \pm 0.4$ (stat) ± 0.7 (syst)
  - $\sigma_{tWZ} = 354 \pm 54$ (stat) ± 95 (syst) fb
  - Two standard deviations above the SM!
  - Three standard deviations above the background only prediction.



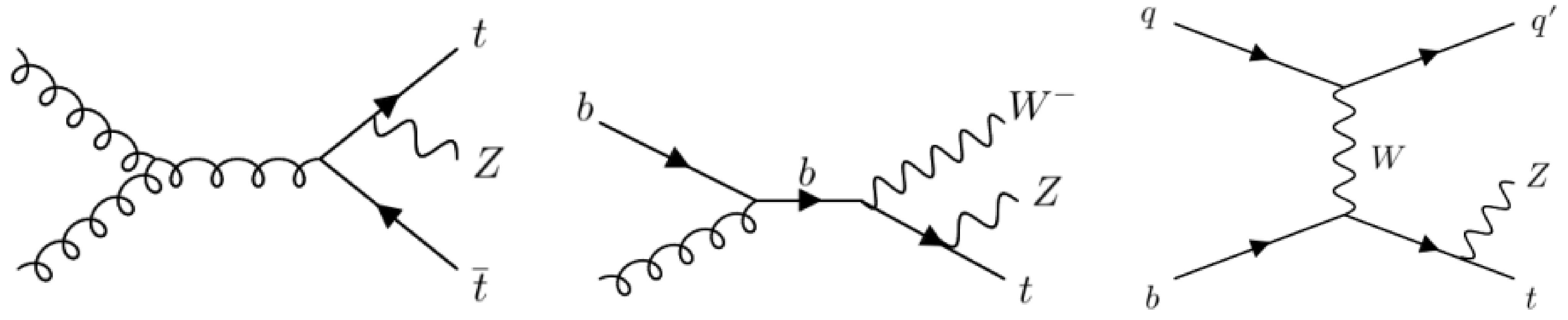


Inclusive and differential measurements of top quarks in association with Z bosons

CMS-PAS TOP-23-004

- The tZq process is also part of the **top+Z processes,** at least as much as tWZ and ttZ.
  - At LO the three process can be distinguished by their jet multiplicity
  - At NLO, interference terms between tWZ and ttZ appear.
- tWZ and ttZ have been historically measured separately.
  - But interference effects are non-negligible and to be better understood
- In this analysis: both ttZ and tWZ are measured jointly.
  - This can also provide sensitivity to EFT operators

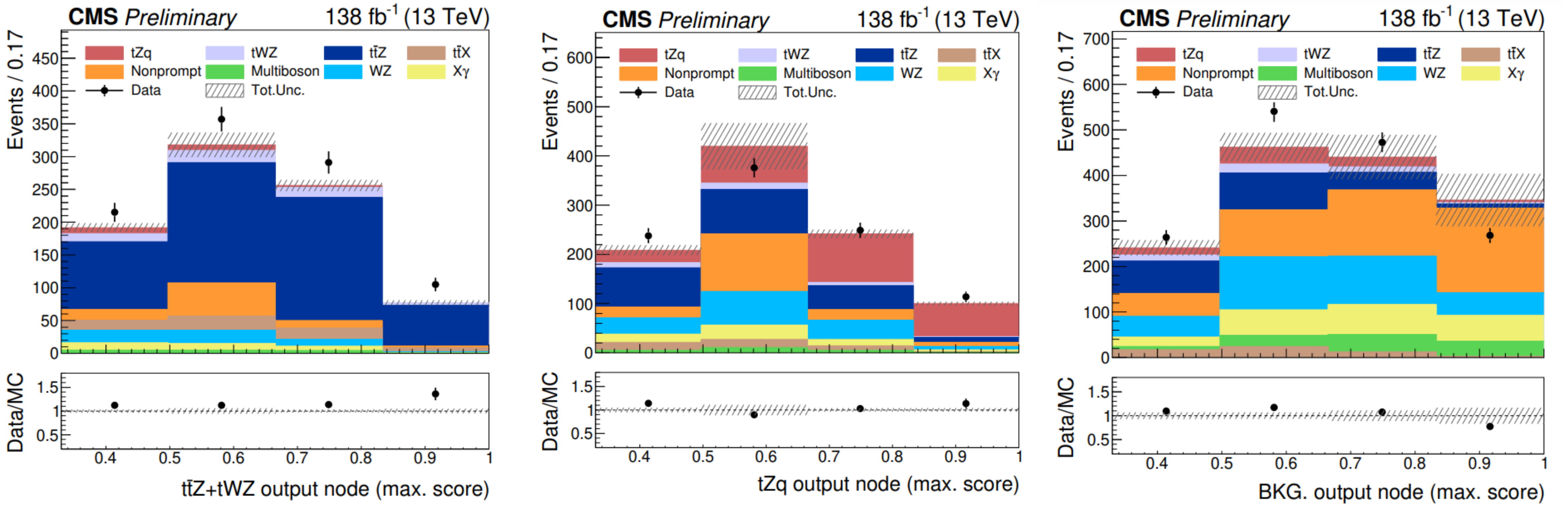
ttZ, tWZ and tZq at LO in QCD



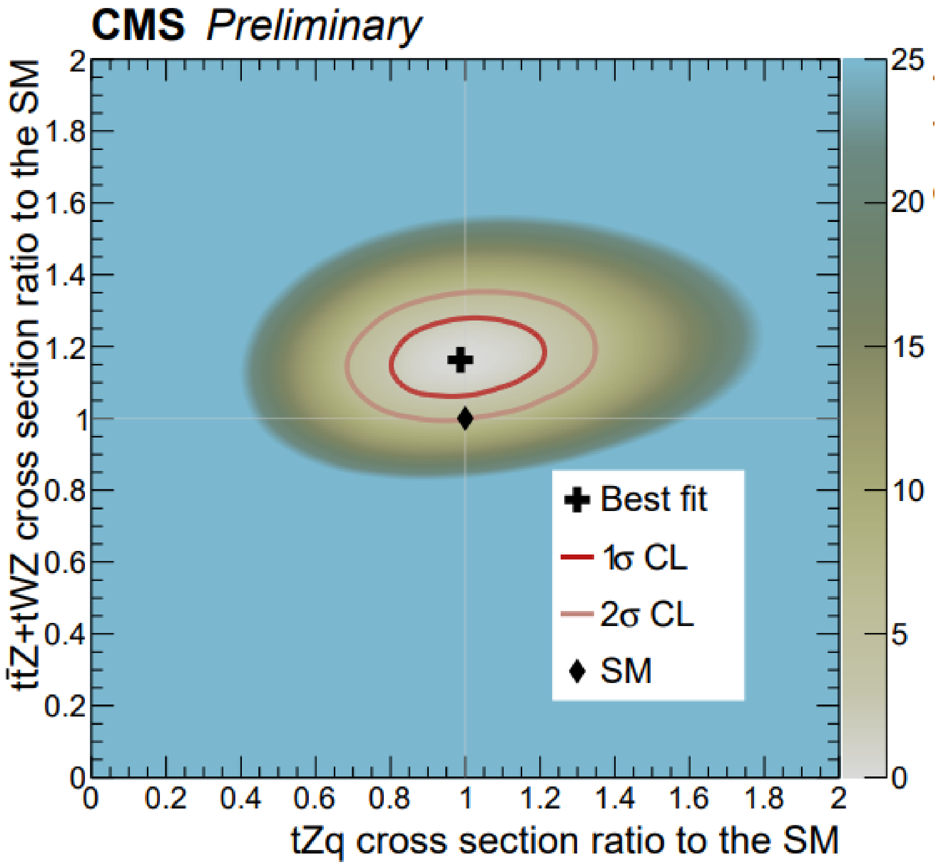
- **Events are selected** based on 3ℓ selections.

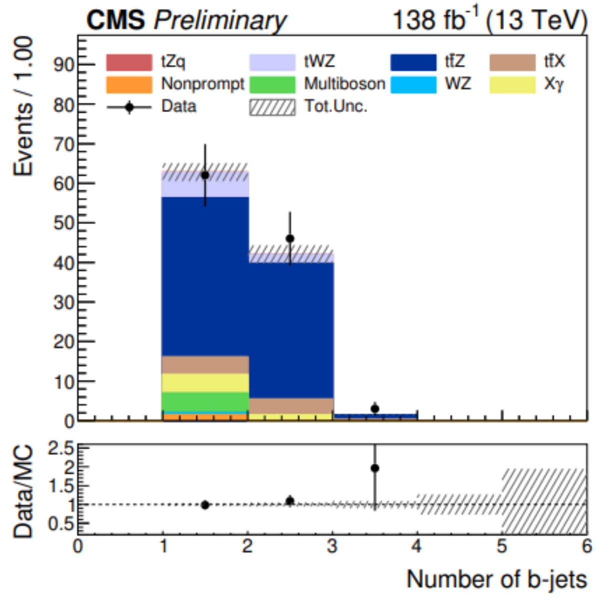
Region	Requirement
Baseline	At least 3ℓ with $p_T > 25, 15, 10$ GeV
	At least one opposite-charge same flavour pair (OCSF) with $m_{OCSF} \in [70, 110]$ GeV

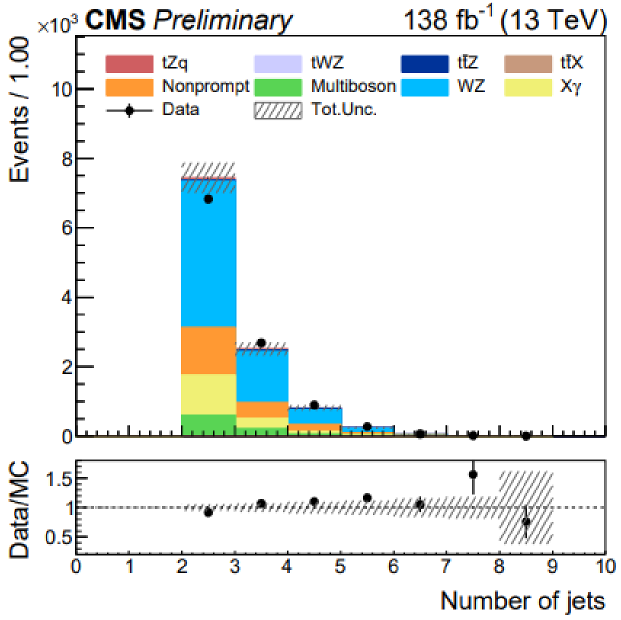
- **Further categorized** using a DNN with three output nodes for tWZ+ttZ, tZq and background.



- The cross sections for ttZ+tWZ and tZq are measured both **inclusively** and differentially.
- For the **inclusive cross section**
  - The selection from before is extended to include additional CRs for the main backgrounds.



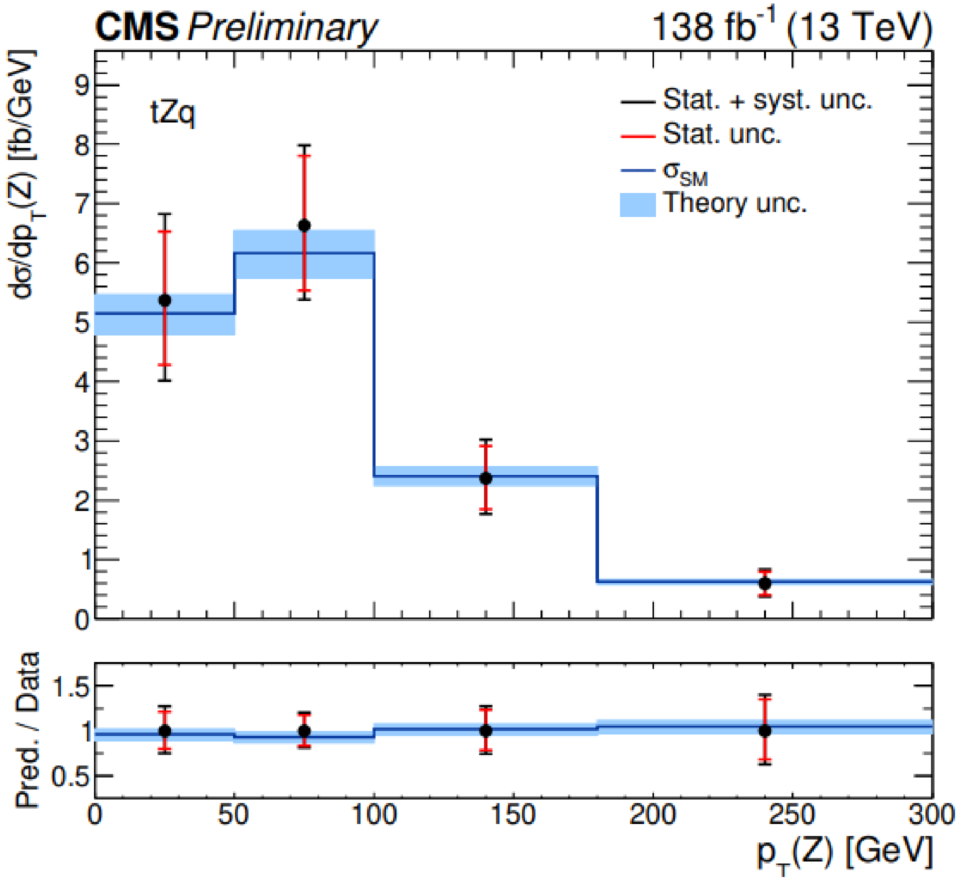


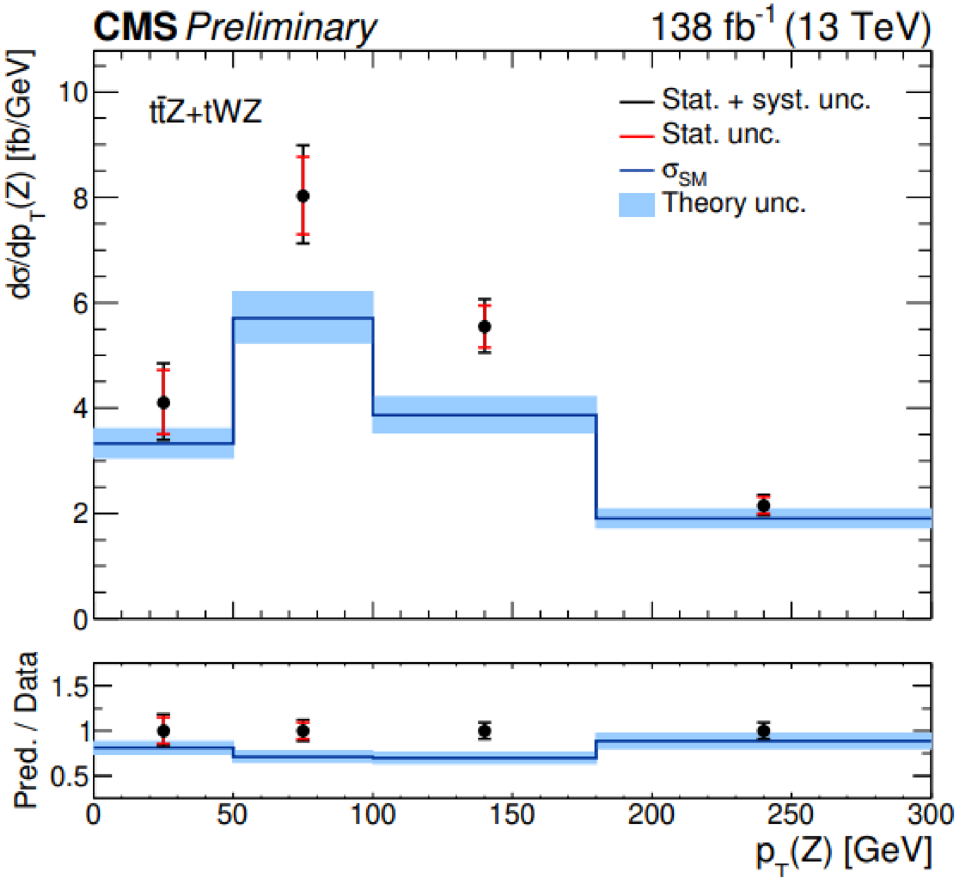


Fiducial cross sections (with branching ratio)

$$\sigma(t\bar{t}Z + tWZ) = 1.14 \pm 0.05\ (\text{stat}) \pm 0.04\ (\text{syst})\ \text{pb}$$
$$\sigma(tZq) = 0.81 \pm 0.07\ (\text{stat}) \pm 0.06\ (\text{syst})\ \text{pb}$$

- The cross sections for ttZ+tWZ and tZq are measured both inclusively and **differentially.**
- For the **differential cross section**
  - The cross sections are extracted from a binned likelihood fit.
  - Each unfolded bin is assigned a free parameter in the fit.





Search for FCNC in the top sector

PRD 109 (2024) 072004
Published in PRD

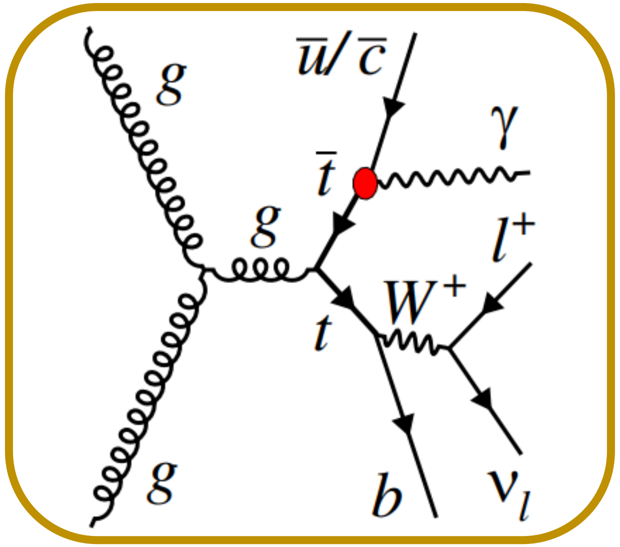
- Flavor Changing Neutral Currents (FCNC) are couplings of the top quark to neutral bosons (Z, γ) that modify the flavour of the top quark, but the charge remains intact.
    - Extremely suppresed in the SM. Low branching ratios (BRs).
    - But SM extensions can enhance the BRs.

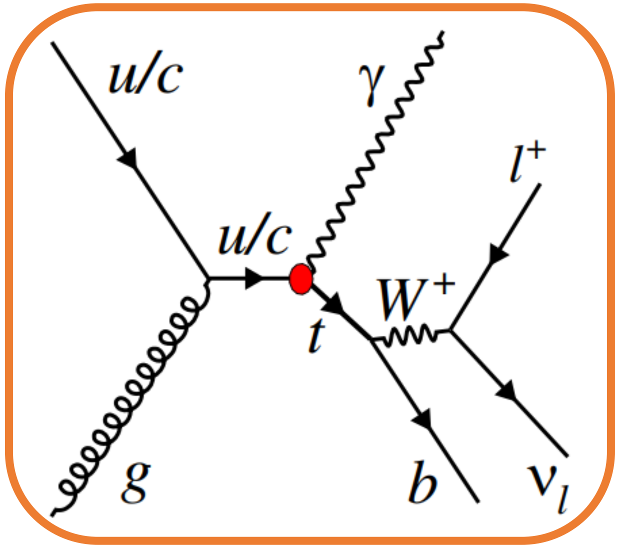
- These couplings can be studied as an Effective Field Theory in terms of a set of dimension-6 operators.

$$\mathcal{L}_{eff}^{full} = \mathcal{L}_{SM} + e\Sigma_{q=u,c}\kappa_{tq\gamma}\bar{q}\left(\lambda_{tq\gamma}^{L}P_L + \lambda_{tq\gamma}^{R}P_R\right)\frac{i\sigma^{\mu\nu}q_\nu}{m_t}tA_\mu + H.c.$$

- The $\kappa_{tq\gamma}$ operators are proportional to the Wilson Coefficients and the new physics scale.

- These operators of the extended theory are measured in $t\bar{t}$-like and single-top-like topologies.

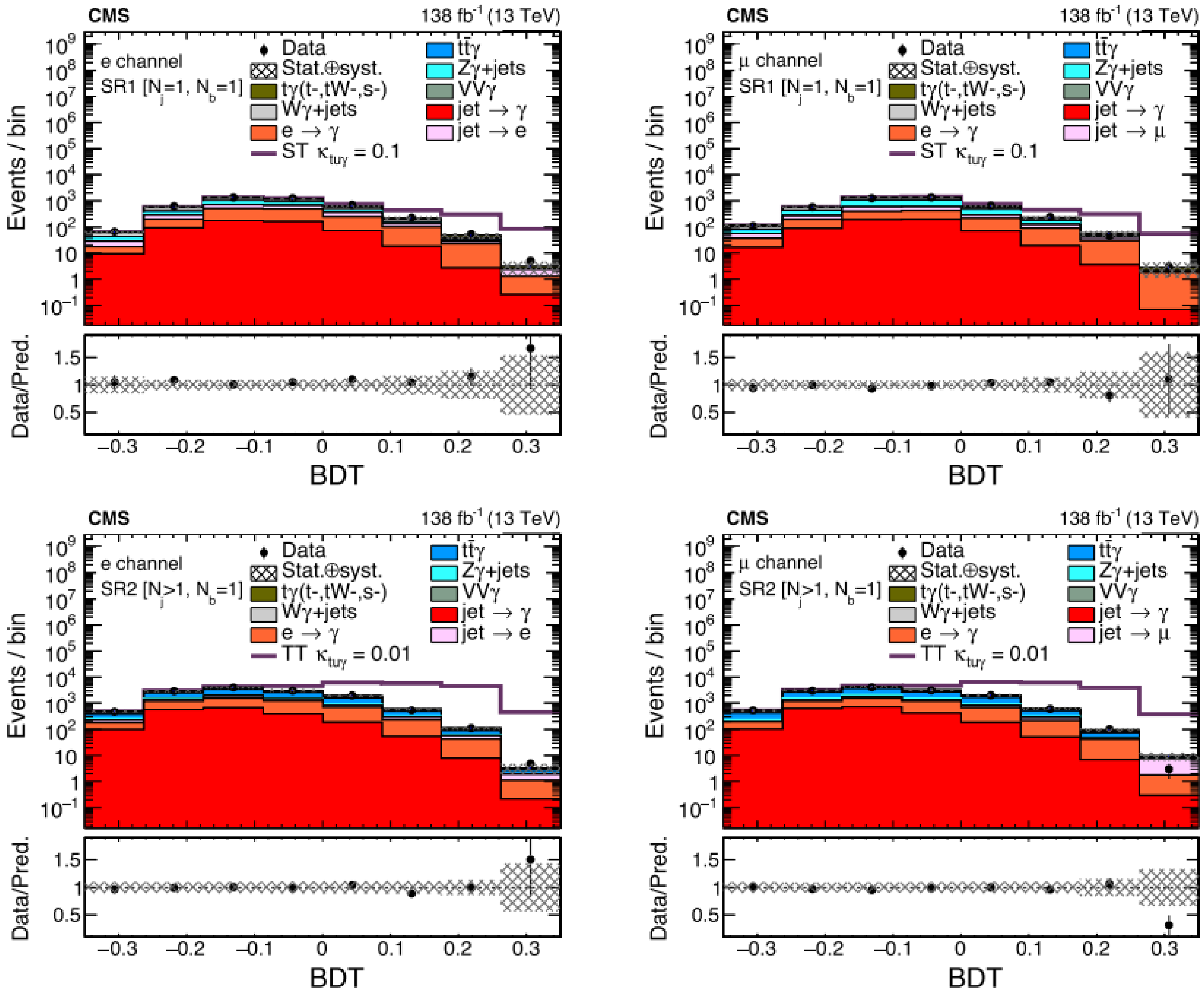




Search for FCNC in top quark decays

- Selection based on $1\ell + \gamma$ +jets
- Two signal regions are defined:
  - SR1: $N_j = 1, N_b = 1$
  - SR2: $N_j \geq 2, N_b = 1$

- The analysis distinguishes between the potential FCNC signatures and the backgrounds by combining information from several observables.
- This is done using Boosted Decission Trees (BDTs).
  - 8 different BDTs are trained:
    - Each lepton flavor (e, μ)
    - Each FCNC operator ($\kappa_{tu\gamma}, \kappa_{tc\gamma}$)
    - Each SR (SR1, SR2)



- The upper limits on the signal cross sections and branching fractions are obtained in a maximum likelihood fit to:
  - 4 BDT at once splitted into 3 data taking years (12 BDT in total per operator).

		Observed limit	Expected limit	$\pm 1\sigma$ (expected limit)	$\pm 2\sigma$ (expected limit)
SR1	$\kappa_{tu\gamma}$	12.3×10^{-3}	11.6×10^{-3}	$(9.7 - 14.4) \times 10^{-3}$	$(8.1 - 17.4) \times 10^{-3}$
	$\kappa_{tc\gamma}$	15.3×10^{-3}	20.1×10^{-3}	$(16.9 - 24.4) \times 10^{-3}$	$(14.4 - 29.3) \times 10^{-3}$
	$\mathcal{B}(t \to u\gamma)$	3.79×10^{-5}	3.39×10^{-5}	$(2.33 - 5.16) \times 10^{-5}$	$(1.65 - 7.55) \times 10^{-5}$
	$\mathcal{B}(t \to c\gamma)$	5.85×10^{-5}	10.11×10^{-5}	$(7.13 - 14.95) \times 10^{-5}$	$(5.22 - 21.44) \times 10^{-5}$
SR2	$\kappa_{tu\gamma}$	6.3×10^{-3}	7.5×10^{-3}	$(6.3 - 9.1) \times 10^{-3}$	$(5.5 - 11.0) \times 10^{-3}$
	$\kappa_{tc\gamma}$	7.9×10^{-3}	8.3×10^{-3}	$(6.8 - 10.0) \times 10^{-3}$	$(6.0 - 11.8) \times 10^{-3}$
	$\mathcal{B}(t \to u\gamma)$	0.98×10^{-5}	1.41×10^{-5}	$(0.99 - 2.09) \times 10^{-5}$	$(0.75 - 3.02) \times 10^{-5}$
	$\mathcal{B}(t \to c\gamma)$	1.57×10^{-5}	1.71×10^{-5}	$(1.14 - 2.52) \times 10^{-5}$	$(0.89 - 3.51) \times 10^{-5}$
SR1 + SR2	$\kappa_{tu\gamma}$	6.2×10^{-3}	6.9×10^{-3}	$(5.9 - 8.4) \times 10^{-3}$	$(5.1 - 10.1) \times 10^{-3}$
	$\kappa_{tc\gamma}$	7.7×10^{-3}	7.8×10^{-3}	$(6.7 - 9.7) \times 10^{-3}$	$(5.7 - 11.5) \times 10^{-3}$
	$\mathcal{B}(t \to u\gamma)$	0.95×10^{-5}	1.20×10^{-5}	$(0.89 - 1.78) \times 10^{-5}$	$(0.64 - 2.57) \times 10^{-5}$
	$\mathcal{B}(t \to c\gamma)$	1.51×10^{-5}	1.54×10^{-5}	$(1.13 - 2.37) \times 10^{-5}$	$(0.81 - 3.32) \times 10^{-5}$

Conclusions

- In this talk we have covered some of the most recent analysis regarding **$t\bar{t}$X+tX** physics at the LHC from the CMS collaboration.

  - A measurement of single top production in association with a W boson (tW)
  - A measurement of single top production in association with a W and a Z boson (tWZ)
  - A measurement of tops with Z bosons (ttZ+tWZ, tZQ)
  - A search for new physics using top quarks and photons (tGq)

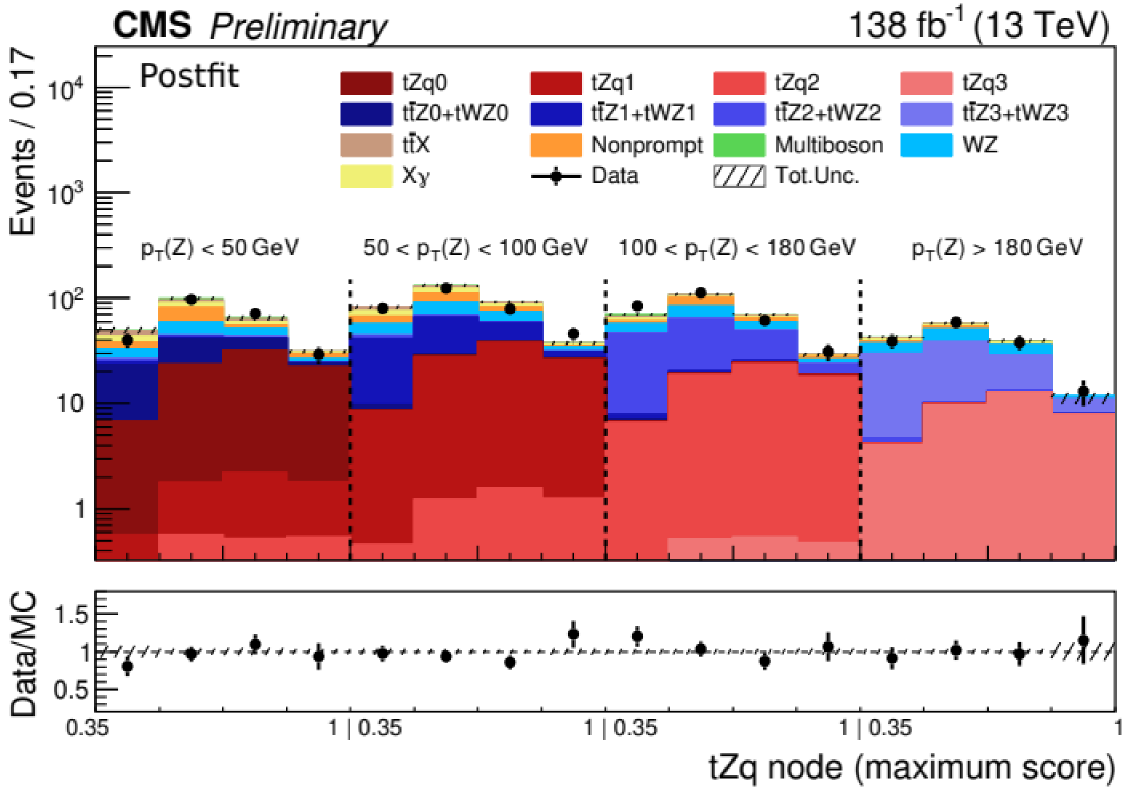
- The top quark proves himself again as an excellent handle for SM measurements, as well as searches for physics beyond-the-SM.

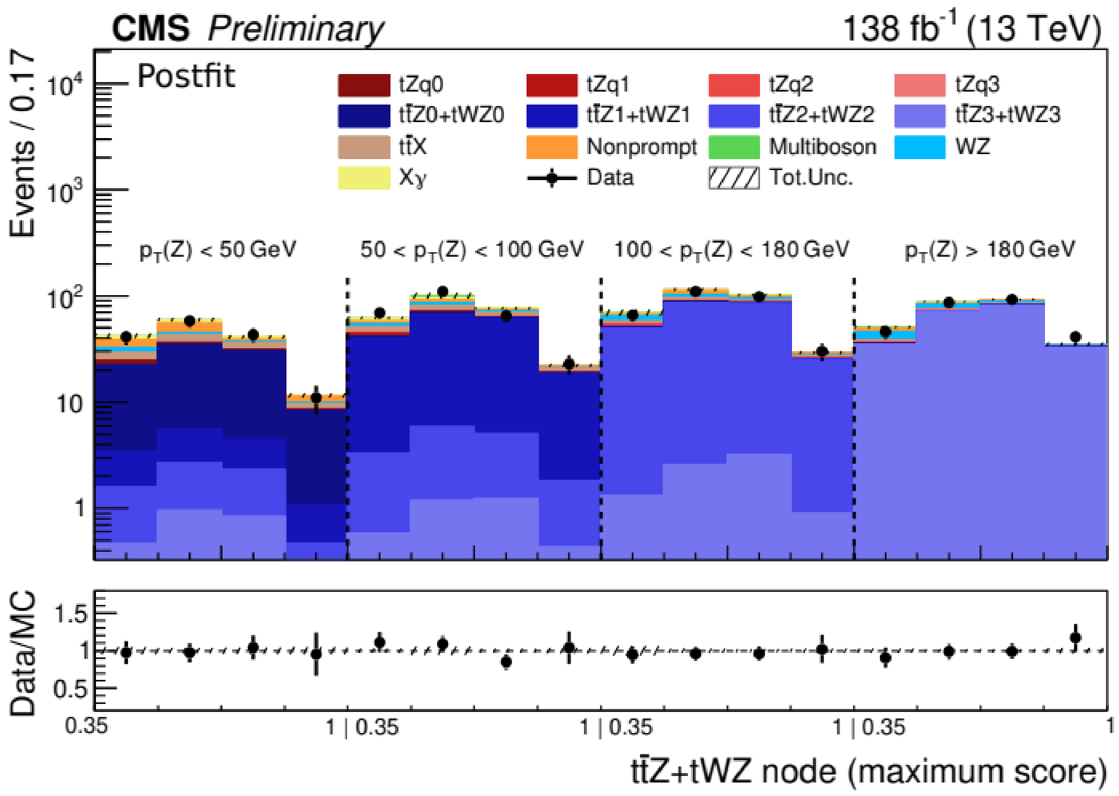
- The CMS website is filled with more results, so check them out!

Thank you very much for your attention (and to the organisers)

Backup

- The cross sections for ttZ+tWZ and tZq are measured both inclusively and **differentially**.
- For the **differential cross section**
  - The cross sections are extracted from a binned likelihood fit.
  - Each unfolded bin is assigned a free parameter in the fit.





Evidence of tWZ at 13 TeV

Region	Requirement	
Baseline	At least 3ℓ with $p_T > 25, 20, 20$ GeV	
	At least one opposite-charge same flavour pair (OCSF) with $\|m_{OCSF} - 91.2\| < 15$ GeV	
	>2 jets, at least one of these b-tagged	
Low-Pt	$SR_{3\ell,3j}$	>3 jets
	$SR_{3\ell,2j}$	== 2 jets
	$SR_{4\ell}$	Fourth lepton with $p_T > 10$ GeV
		The two leptons not OCSF are required not to be OCSF themselves, or to fail $\|m_{OCSF} - 91.2\| < 15$ GeV
High-pT	$SR_{Had}^{Boosted}$	A large R-jet with soft-drop mass between 105 and 200 GeV, close to a b tag with $\Delta R < 0.8$
	$SR_{Lep}^{Boosted}$	Non-Z lepton $p_T > 30$ GeV and close to a b tag with $p_T > 200$ GeV with $\Delta R < 2$

- **Additionally** two control regions are defined to control ZZ and WZ backgrounds.

Search for FCNC in top quark decays

Region	Requirement
Baseline	Exactly one tight lepton: electron (e) or muon (μ)
	At least 1 jet
	At least 1 photon
	$p_T\ (e, \mu, \gamma) \rightarrow (> 35, > 30, > 30)$ GeV
	$\lvert\eta\rvert\ (e, \mu, \gamma) \rightarrow (< 2.5, < 2.4, < 1.44)$
	AK4 Jets: p_T (j) > 30 GeV if $\lvert\eta\rvert$(j) < 2.7, p_T (j) > 60 GeV if $\lvert\eta\rvert$(j) $\in [2.7, 3.0]$
	Leptons must be isolated from jets (photons) by $\Delta R > 0.4\ (0.5)$
SR1	Exactly one b-tagged jet and no additional jets (Nj = 1, Nb = 1)
SR2	At least 2 jets, one of which is b-tagged (Nj >= 2, Nb = 1)

- SR1 aims at enhancing single-top-like FCNCs
- SR2 aims at enhancing tt-like FCNCs