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Electroweak and associated top-quark production at CMS

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Abstract

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PROCEEDINGS OF SCIENCE

Electroweak and associated top-quark production at CMS

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Top quark measurements are central to the LHC program. In particular, the associated production of top quarks with vector bosons is interesting as it offers insight into both the electroweak and the strong interactions of the standard model. These processes, although rare, can be now accessed and in many cases even measured precisely at the LHC. In this talk, several recent results from the CMS experiment on top-quark associated production with vector bosons are presented, using data collected during the Run 2 and Run 3 of the CERN LHC. Three different results are shown: the first evidence for the production of tWZ, a simultaneous measurement of $\mathrm{t\bar{t}Z + tWZ}$ and tZq, and the first tW measurement at 13.6 TeV.

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1. Introduction

Processes where top quarks are produced in association with a vector boson (W/Z/γ) present a unique opportunity to perform stringent tests of the standard model (SM) of particle physics. With cross sections ranging from about 10 fb to a few pb at the CERN LHC [3], these processes are hundreds of times more rare than the standard top quark-antiquark ($\mathrm{t\bar{t}}$) production. However, with the data collected so far by the CMS experiment during the LHC Runs 2 and 3, all these processes are accessible and most can even be measured precisely.

This document (and the corresponding talk) focuses on the three most recent results by CMS: the first evidence for the production of tWZ, a simultaneous measurement of $\mathrm{t\bar{t}Z}$ + tWZ and tZq, and the first tW measurement at 13.6 TeV.

2. Evidence for the tWZ process

The production of a single top quark in association with a W and a Z boson is a very rare process (expected cross section at 13 TeV ~ 136 fb) that allows us to probe two top quark electroweak couplings in one single process. The main challenge when looking for it is the overwhelming and irreducible $\mathrm{t\bar{t}Z}$ background. Moreover, the tWZ process itself has interference with $\mathrm{t\bar{t}Z}$ beyond the leading order. In Ref. [4], we present the first analysis using state-of-the-art tWZ signal modelling at NLO, where the interference is consistently removed using the diagram removal scheme known as DR1 [5].

The analysis uses data collected in 2016-2018 (LHC Run 2), corresponding to 138 fb^{-1}. Events are triggered on the presence of one, two, or three electrons or muons, and signal (SR) and control regions (CR) are subsequently built based on the number of leptons and b jets. In total, five SRs (including two with boosted top quarks) and two CRs (to control the ZZ and WZ backgrounds) are defined. The background arising from nonprompt leptons is estimated from data. In the SRs, neural network (NN) classifiers are trained to enhance the signal-to-background discrimination. An example of data/simulation comparison for two output nodes of the NN used in the two most sensitive SRs is shown in Fig. 1.

A simultaneous fit to the seven regions yields an observed (expected) significance of 3.4σ (1.4σ), which results in the first evidence for the production of tWZ. The cross section is measured to be σ_{tWZ} = 354 ± 54 (stat) ± 95 (syst) fb, about two standard deviations above the SM, as shown in Fig. 1 (right).

The measurement is limited by the statistical uncertainties, but the main systematic uncertainties are those on the normalization of $\mathrm{t\bar{t}Z}$ and other backgrounds.

3. Simultaneous measurement of $\mathrm{t\bar{t}Z}$ + tWZ and tZq

The processes where one or two top quarks are produced in association with a Z boson, $\mathrm{t\bar{t}Z}$ and tZq, have expected cross sections of the order of 1 pb and have both already measured, inclusively and differentially. However, they were only measured separately, assuming the SM cross section for the other, whereas deviations from the SM may affect both processes in a correlated way. Additionally, the recent evidence for tWZ production, reported in the previous section, highlights

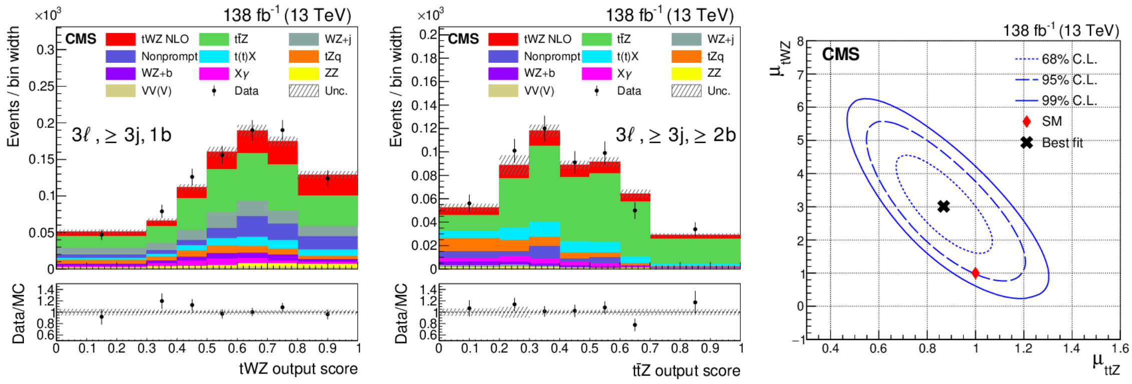

Figure 1: Scores of the output nodes for the tWZ (left) and tt̄Z (center) processes for different SRs of the analysis. The black points represent the data while the filled histograms represent the simulated signal and background events. In particular, the red histogram represents the signal process (tWZ). The 2D contour on the right hand side shows the ratio μ between the observed and predicted cross sections of the tWZ and tt̄Z processes, when leaving both parameters freely floating in the fit. The solid and dashed lines represent the 1, 2, and 3 standard deviation confidence levels.

the interplay between tWZ and tt̄Z, further motivating a simultaneous measurement. In the CMS analysis of Ref. [6], the tt̄Z and tWZ processes are measured as one, simultaneously with tZq, for the first time, using data collected by CMS in 2016-2018.

A single signal region (SR) is built by requiring events to have three leptons (electron or muon), at least 2 jets, of which at least one is tagged as coming from a b quark. The contribution from nonprompt leptons is estimated from data, while the WZ process and other smaller backgrounds are taken from simulation. A multi-class classifier NN is trained to disentangle different signals and backgrounds, with three output nodes for tt̄Z + tWZ, tZq, and background. The comparison between data and simulation for the three nodes is shown in Fig. 2.

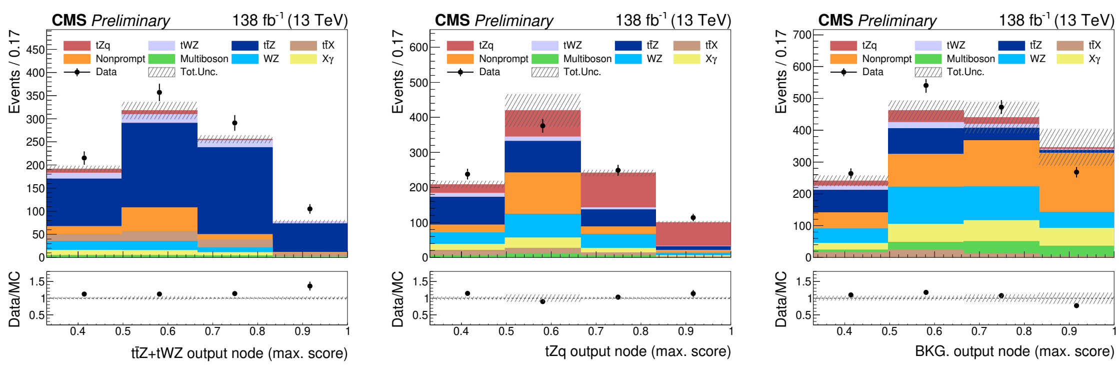

Figure 2: Scores of the output nodes for the tt̄Z + tWZ (left), tZq (center), and background (right) processes. The black points represent the data while the filled histograms represent the simulated signal and background events. In particular, the dark blue histogram represents tt̄Z, the lilac tWZ, and the pink tZq.

A simultaneous fit is performed to the three maximum-score output nodes in the SR and to two CRs. The inclusive cross sections are measured to be $\sigma_{t\bar{t}Z+tWZ} = 1.14 \pm 0.07$ pb and $\sigma_{tZq} = 0.89 \pm 0.10$ pb. The reults are consistent with the SM for tZq, while a slight excess is visible for $t\bar{t}Z+tWZ$, as seen in Fig. 3. The measurement is still limited by the statistical uncertainties, and the main systematic uncertainties are those on background modelling and b tagging.

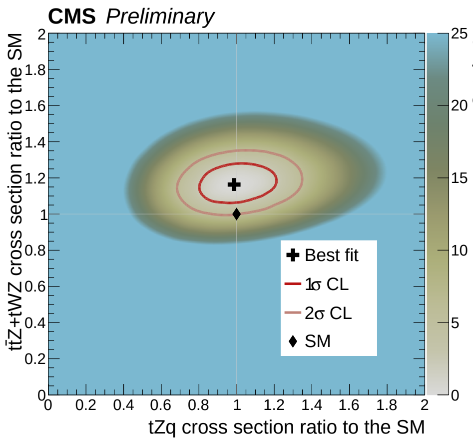

Figure 3: Two-dimensional contour of the ratio μ between the observed and predicted cross sections of the tWZ and $t\bar{t}Z$ processes, when leaving both parameters freely floating in the fit. The solid and dashed lines represent the 1 and 2 standard deviation confidence levels.

3.1 Differential measurements

The cross sections of $t\bar{t}Z+tWZ$ and tZq are also measured as a function of lepton and Z observables, using maximum likelihood unfolding. The measurements are compared to predictions from aMC@NLO. A good agreement is overall found for tZq, while some excess is seen for $t\bar{t}Z+tWZ$, located especially at low lepton p_T, as shown in Fig. 4.

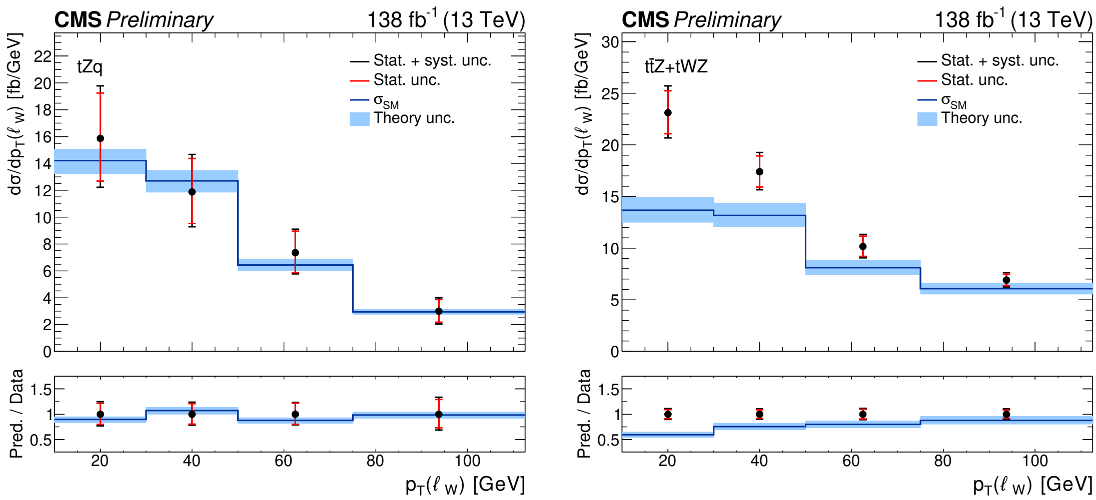

Figure 4: Distributions of the p_T of the lepton coming from the W boson, unfolded to parton level, for the tZq (left) and the $t\bar{t}Z+tWZ$ (right) processes. The blue band includes the uncertainties on the renormalization and factorization scales, PDFs, and parton shower.

4. Measurement of tW using data collected in Run 3

The tW process has a much larger cross section when compared to the other processes mentioned in this document. For this reason, it could already be measured by CMS using the 34.7 fb^{-1} of data collected in 2022 at 13.6 TeV [7]. This work focuses on final states with an electron and a muon. Two SRs and one CR are defined based on number of jets and b jets. A set of MVA classifiers (Random Forests) are trained to separate tW from the irreducible $t\bar{t}$ background in the SRs. An example of the output of such a classifier for one of the SRs is shown in Fig. 5 (left).

The fit results in a measured cross section of $\sigma_{tW} = 84.1 \pm 2.1(\text{stat.})^{+9.8}_{-10.2}(\text{syst.}) \pm 3.3(\text{lum})$ pb, compatible with the SM prediction at N^{3}LO, as illustrated in Fig. 5 (right). The measurement is limited by the systematic uncertainties, mainly those related to the jet energy scale, b tagging and background modelling.

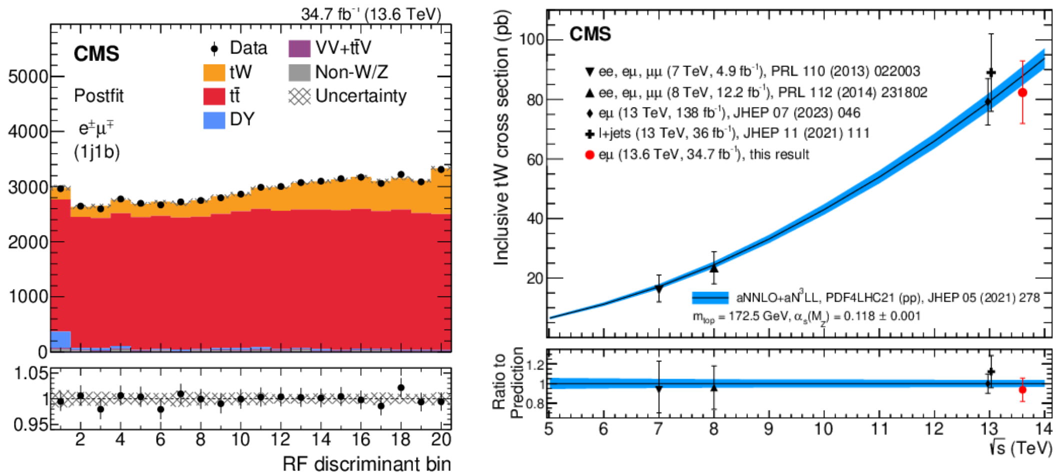

Figure 5: Left: Output of the Random Forest discriminant, showing the separation between the signal (tW, in orange) and the largest background ($t\bar{t}$, in red). Right: Cross sections of tW as a function of the centre-of-mass energy, highlighting in red the result of Ref. [7]; the blue band represents the uncertainty on the N^{3}LO prediction.

The tW cross section is also measured differentially in the SR region with exactly 1 jet and exactly one b-tagged jet, with an additional veto on jets with p_T between 20 and 30 GeV. Several jet and lepton observables are unfolded to particle level using the TUnfold package [8]. Good agreement with predictions from different generators and different schemes for treating the interference between $t\bar{t}$ and tW is found, as shown in Fig. 6.

5. Summary

This talk covered three recent CMS measurements of top quark processes involving electroweak couplings. Although these processes are rare, the data collected at the LHC so far allows us to measure all of them.

The first evidence for tWZ was presented, where a cross section about two standard deviations above the standard model is measured. The first simultaneous measurement of $t\bar{t}Z$ + tWZ and tZq

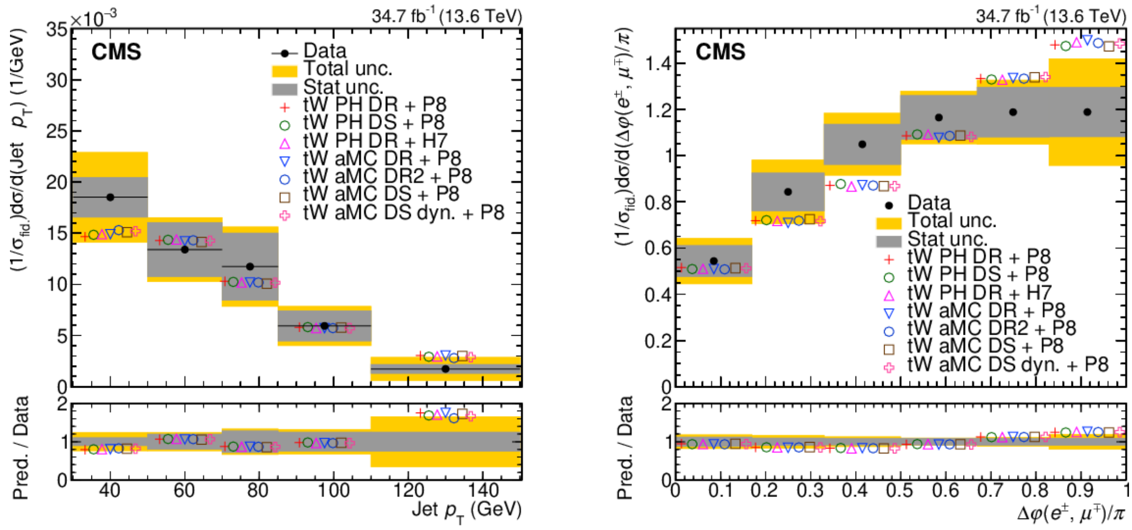

Figure 6: Distributions of the p_T of the jet and the azimuthal angular distance between the electron and the muon, unfolded to particle level, for the tW process.

was also shown, confirming the slight excess seen for tWZ and t$\bar{t}$Z, and proving a good agreement with the predictions for tZq. Finally, the first inclusive and differential tW measurement at 13.6 TeV was shown, also revealing very good agreement with the predictions.

Some of these measurements are still limited by their statistical uncertainty, and can thus still be improved in the near future, as more data is being collected. Furthermore, many improvements from both the experimental and the modelling side are on their way, paving the way to a better understanding of the top quark electroweak couplings and the standard model in general.

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