PROCEEDINGS OF SCIENCE

CMS measurements of top quark pair/single top production in association with an additional boson

Kathryn Coldham[a] **for the CMS Collaboration**

[a] *Princeton University, Princeton, U.S.A.*

E-mail: kathryn.coldham@cern.ch

The top quark is the heaviest of the elementary particles and decays before hadronisation can occur, providing the unique opportunity to study its properties. The dominant top quark production mechanism is $\mathrm{t\bar{t}}$ and single top quark production can also occur. This talk presents the latest results from the CMS Collaboration of top quark pair production in association with an additional boson ($\mathrm{t\bar{t}X}$) and single top production in association with an additional boson (tX). The $\mathrm{t\bar{t}X}$ mechanisms covered are: effective field theory (EFT) models using $\mathrm{t\bar{t}}$+X in multi-lepton final states, a measurement of the inclusive $\mathrm{t\bar{t}W}$ cross section, inclusive and differential measurements of $\mathrm{tt}\gamma$ production and probing EFT using $\mathrm{t\bar{t}}$ production associated with a boosted Z or Higgs boson. The tX production processes covered are inclusive and differential tW with dileptonic events, Standard Model (SM) tWZ production in multi-lepton final states and a probe of electroweak field theory operators in the associated production of top quarks with a Z boson in multilepton final states. The results and the novel machine learning techniques used are expected to be beneficial for future Run 3 analyses.

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1. Introduction

At 27 kilometres in circumference, the Large Hadron Collider (LHC) at CERN is the largest particle accelerator in the world. Protons, and sometimes heavy ions, are accelerated to nearly the speed of light and collide and four main collision points. A detector is located at each collision point, which are: ALICE [1], ATLAS [2], CMS [3] and LHCb [4]. The CMS (Compact Muon Solenoid) detector is one of two general-purpose detectors of the Large Hadron Collider, the other being the ATLAS detector. Top physics is among the many domains studied by members of the CMS Collaboration. The top quark is the heaviest of the quarks with a mass of around 173 GeV. Its heavy mass leads to it having a lifetime of 10^{-25}s [5], shorter than the timescale required for hadronisation to occur. Thus, the top quark is the only quark that does not undergo hadronisation. The dominant top quark production mode at the LHC is $t\bar{t}$ and, rarely, single top production can occur. Top quark production mechanisms include top quark pair production in association with a heavy vector boson ($t\bar{t}$X) and single top production in association with a heavy vector boson (tX). Latest results from the CMS Collaboration for ttX and tX production are discussed in Section 2 and the results are summarised in Section 3.

2. Results

2.1 EFT models using $t\bar{t}$+X (multi-lepton final states)

The analysis studied the effects of 26 dimension-six Electroweak Field Theory (EFT) operators (Wilson Coefficients, WCs) that couple top quarks to leptons, bosons and other heavy quarks. Final states containing either two same sign, three or four leptons were considered [6]. Data recorded by the CMS detector between 2016 and 2018 was analysed, corresponding to 138 fb^{-1} of proton-proton collisions at $\sqrt{s}$ =13 TeV. Simulated samples and data-driven techniques were used to assess the contributions of background processes. Differential distributions were then obtained by using events in three defined categories and a likelihood fit was performed. The 2D likelihood scans were performed in order to extract the confidence intervals (CIs) for the WCs.

2.2 Measurement of inclusive $t\bar{t}$W cross section

Some 138fb^{-1} of data recorded between 2016 and 2018 [7] was analysed, corresponding to proton-proton collisions at $\sqrt{s}$ = 13 TeV. Events containing either two or three leptons and additional jets in their final states were selected. For the dilepton channel, a multi-class neural network was used to distinguish between the $t\bar{t}$W signal process and three background processes. The non-prompt lepton background was estimated by using a tight-to-loose ratio method. Two control regions, WW and ZZ, were defined. The effects of systematic sources of uncertainty were also considered. A binned likelihood fit was performed and cross section measurements for the dilepton and trilepton channels were obtained.

2.3 Inclusive and differential $t\bar{t}\gamma$ in the dilepton channel

The production of $t\bar{t}\gamma$ was measured using 138 fb^{-1} of data recorded between 2016 and 2018 [8]. This corresponded to proton-proton collisions at $\sqrt{s}$ = 13 TeV. Events with two, oppositely-charged final state leptons, an isolated photon and at least one jet were selected. The dominant background was non-prompt leptons; photons that originate either from particles found inside hadronic jets or from additional proton-proton collisions, or hadronic jets that are misidentified as photons. The $t\bar{t}\gamma$ inclusive cross section was measured by performing a profile likelihood fit. Sources of systematic uncertainty was treated as nuisance parameters and limits on the WCs in the SMEFT framework were evaluated.

2.4 Probing EFT using tt production associated with a boosted Z or Higgs boson

An analysis focusing on top quark pairs produced in association with a Lorentz-boosted Z or Higgs boson was conducted to search for signs of new physics using EFT [9]. Some 138fb^{-1} of data was analysed, corresponding to proton-proton collisions at $\sqrt{s}$ = 13 TeV. Events with leptons+jets in their final states were selected. A Deep Neural Network (DNN) was trained. The $t\bar{t}Z$ and $t\bar{t}H$ signal strengths were measured and upper limits were calculated for the differential cross sections. Sources of systematic uncertainty were treated as nuisance parameters and the 95% confidence level (CL) upper limits on $t\bar{t}Z$ and $t\bar{t}H$ cross sections were determined.

2.5 Inclusive and differential tW with dileptonic events

Inclusive and normalised differential cross sections were measured for tW with dileptonic events. Some 138 fb^{-1} of data recorded between 2016 and 2018 was analysed, corresponding to proton-proton collisions at $\sqrt{s}$ = 13 TeV [10]. Events were selected with final states containing one electron and one muon. Two independent BDTs were used to distinguish between the tW signal and $t\bar{t}$ background events. A maximum likelihood (ML) fit was performed. For the differential measurement, unfolding techniques were applied to determine the actual distributions for the spectra of different observables since they become distorted by the response and acceptance of the detector.

2.6 SM tWZ (multi-lepton final states)

The first evidence for tWZ production in multi-lepton final states is presented [11]. Some 138 fb^{-1} of data recorded between 2016 and 2018 was analysed, corresponding to proton-proton collisions at $\sqrt{s}$ = 13 TeV. Events were selected containing either four leptons or three leptons plus a neutrino. The NPL background was estimated using a data-driven method. Events were classified into three signal regions (SRs) and two further signal regions were defined in the high-pT analysis region to assess contributions from hadronically and leptonically decaying top quarks. Two control regions were defined to assess the WZ and ZZ background contributions. A Deep Neural Network (DNN) was trained. The tWZ significance and cross section values were measured, with sources of systematic uncertainty being treated as nuisance parameters.

2.7 Probing EFT operators in the associated production of top quarks with a Z boson in multilepton final states

A search for new top quark interactions was performed within the EFT framework using the associated production of either one or two top quarks with a Z boson in multilepton final states. The analysis paper is dedicated to the analysts' friend and colleague Nicolas Tonon, who passed away unexpectedly while the paper was in print [12]. Some 138 fb^{-1} of data recorded between 2016 and 2018 was analysed, corresponding to proton-proton collisions at $\sqrt{s}$ = 13 TeV. Events were selected with final states containing three or four prompt leptons. Two signal regions were defined and two control regions were used to assess the WZ and ZZ backgrounds. The NPL background contribution was estimated using misidentification probability method and MVA was conducted. Sources of uncertainty were treated as nuisance parameters. Five, dimension-six EFT operators were considered and a 1D likelihood scan was carried out for each WC to construct confidence intervals. Two-dimensional likelihood scans were also carried out, where two WCs were scanned simultaneously and the other three were fixed to zero. Finally, a single 5D maximum likelihood fit was performed where all five WCs were treated as parameters of interest and the corresponding 95% CL confidence intervals were computed.

3. Summary

Recent results by the CMS Collaboration for $t\bar{t}X$ production are presented. The first considers EFT models using $t\bar{t}$+X in multi-lepton final states. Kinematic variables were used to extract the 95% confidence intervals of the 26 dimension-six EFT operators. No significant deviation with respect to the SM prediction was found. Next, a measurement of the inclusive $t\bar{t}W$ cross section is presented. The inclusive $t\bar{t}W$ production cross section in the full phase space was measured to be 868 ± 40 (stat) ± 51 (syst) fb. The $t\bar{t}W^{+}$ and $t\bar{t}W^{-}$ cross sections were also measured as 553 ± 30 (stat) ± 30 (syst) and 343 ± 26 (stat) ± 25 (syst) fb, respectively. The corresponding ratio of the two cross sections was found to be 1.61 ± 0.15 (stat) +0.07-0.05(syst). The measured cross sections were found to be larger than but consistent with the SM predictions within two standard deviations, and represent the most precise measurement of these cross sections to date. Inclusive and differential measurements of $t\bar{t}\gamma$ in the dilepton channel is also presented. An inclusive cross section of 175.2 ± 2.5 (stat) ± 6.3 (syst) fb was measured, differential cross sections were measured as functions of several kinematic observables of the photon, leptons, and jets, and compared to SM predictions. Limits on Wilson Coefficients were determined. Next, a search for signs of new physics using effective field theory was conducted by analysing $t\bar{t}$ production in association with a boosted Z or Higgs boson. The signal strengths of boosted $t\bar{t}Z$ and $t\bar{t}H$ production were measured, and upper limits were placed on the $t\bar{t}Z$ and $t\bar{t}H$ differential cross sections as functions of the Z or Higgs boson transverse momentum. Additionally, eight possible dimension-six operators were added to the SM Lagrangian and their corresponding coefficients are constrained. Recent results for inclusive and differential tW with dileptonic events are also presented. A cross section of 79.2 ± 0.9 (stat) +7.7 -8.0 (syst) ± 1.2 (lumi) pb was measured, consistent with SM predictions. For the differential measurements, a fiducial region was defined and the resulting distributions were unfolded and are in agreement with the predictions at next-to-leading order in perturbative quantum chromodynamics. A search for SM tWZ production in multi-lepton final states is also presented. The cross section was measured to be 0.37 ± 0.05 (stat) ± 0.10 (syst) pb and corresponds to an observed (expected) significance of 3.5 (1.4) standard deviations; the first evidence for this process. Finally, a search for new top quark interactions is presented which was performed within the EFT framework using the associated production of either one or two top quarks with a Z boson in multilepton final states. Five Wilson coefficients were simultaneously fit to data and 95% CL intervals were computed. Results were found to be consistent with SM expectations.

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References

[1] ALICE Collaboration. The ALICE experiment at the CERN LHC. A Large Ion Collider Experiment. *JINST*, 3:S08002, 2008.

[2] ATLAS Collaboration. The ATLAS Experiment at the CERN Large Hadron Collider. *JINST*, 3:S08003, 2008.

[3] CMS Collaboration. The CMS experiment at the CERN LHC. The Compact Muon Solenoid experiment. *JINST*, 3:S08004, 2008.

[4] LHCb Collaboration. The LHCb Detector at the LHC. *JINST*, 3:S08005, 2008.

[5] R. L. et al. Workman. Review of Particle Physics. *PTEP*, 2022:083C01, 2022.

[6] CMS Collaboration. Search for new physics in top quark production with additional leptons in the context of effective field theory using $138\mathrm{fb}^{-1}$ of proton-proton collisions at $\sqrt{\mathrm{s}} = 13$ TeV. Technical report, CERN, Geneva, 2023. Available: http://cds.cern.ch/record/2851651.

[7] CMS Collaboration. Measurement of the cross section of top quark-antiquark pair production in association with a w boson in proton-proton collisions at $\sqrt{\mathrm{s}} = 13$ TeV. *Journal of High Energy Physics*, 2023(7), July 2023. Available: https://cds.cern.ch/record/2804479.

[8] CMS Collaboration. Measurement of the inclusive and differential $\mathrm{t\bar{t}}\gamma$ cross sections in the dilepton channel and effective field theory interpretation in proton-proton collisions at $\sqrt{\mathrm{s}} = 13$ TeV. *Journal of High Energy Physics*, 2022(5), May 2022. Available: https://cds.cern.ch/record/2799858.

[9] CMS Collaboration. Search for new physics using effective field theory in 13 TeV pp collision events that contain a top quark pair and a boosted Z or Higgs boson. *Phys. Rev. D*, 108:032008, 2023. Available: https://cds.cern.ch/record/2825447.

[10] CMS Collaboration. Measurement of inclusive and differential cross sections for single top quark production in association with a w boson in proton-proton collisions at $\sqrt{s} = 13$ TeV. *Journal of High Energy Physics*, 2023(7), July 2023. Available: https://cds.cern.ch/record/2823830.

[11] CMS Collaboration. Evidence for tWZ production in proton-proton collisions at $\sqrt{s} = 13$ TeV in multilepton final states. Technical report, CERN, Geneva, 2023. Available: http://cds.cern.ch/record/2859612.

[12] CMS Collaboration. Inclusive and differential cross section measurements of single top quark production in association with a Z boson in proton-proton collisions at $\sqrt{s} = 13$ TeV. *JHEP*, 2202:107, 2022. Available: https://cds.cern.ch/record/2789719.