PROCEEDINGS OF SCIENCE

Single and double top quark production at CMS

Jose Enrique Palencia Cortezon[a,*] **on behalf of the CMS Collaboration**

[a] *Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Spain*

E-mail: enrique.palencia@uniovi.es

The most recent inclusive measurements of single and double top quark pair production are presented. Data collected with the CMS experiment in proton-proton collisions at the LHC at different centre-of-mass energies are used and the results are compared to the standard model predictions.

The European Physical Society Conference on High Energy Physics (EPS-HEP2025)
7-11 July 2025
Marseille, France

*Speaker

https://pos.sissa.it/

PoS(EPS-HEP2025)271

1. Introduction

Top quarks are produced at a high rate at the CERN LHC, more than 100 million top quark pairs ($\mathrm{t\bar{t}}$) were produced in Run 2 and Run 3. While the dominant top quark production channels of pair production and t channel single production have been measured with high precision, other more rare production modes are becoming fully accessible. This document provides a review of the latest experimental studies of measurements of single and double top quark production with the CMS detector [1, 2] at the LHC in proton-proton (pp) collisions at different centre-of-mass energies ($\sqrt{s}$). The results are compared to the standard model (SM) predictions.

2. Measurement of the inclusive $\mathrm{t\bar{t}}$ cross section in final states with at least one lepton and additional jets with 302 pb^{-1} of pp collisions at $\sqrt{s}$ = 5.02 TeV

A measurement of the inclusive $\mathrm{t\bar{t}}$ production cross section in pp collisions at $\sqrt{s} = 5.02$ TeV [3] is performed by the CMS experiment, in dedicated runs with low-energy and low-intensity conditions with respect to the default configuration, in conditions of low number of additional interactions per bunch crossing, with data recorded in 2017 corresponding to an integrated luminosity of 302 pb^{-1}.

The measurement is performed using events with one electron or muon, and at least three jets, at least one of them being identified as b quark (b tagged). The dominant background sources in the analysis, the W+jets and tW processes, are estimated using Monte Carlo (MC) simulations. In addition, the contribution from quantum chromodynamics (QCD) multijet events is estimated from data. As shown in Fig. 1 (left), selected events are classified based on the number of all reconstructed jets and of b-tagged jets. All regions are signal-dominated, the ℓ+3j2b and ℓ+4j2b are the purest in signal (89% of the total yield) and ℓ+3j1b provide the greatest contribution from tW and W+jets backgrounds (12% and 18% of the total, respectively). In order to separate the $\mathrm{t\bar{t}}$ signal from the W+jets background in this region, a multivariate-analysis (MVA) classifier based on random forests is used.

The cross section is obtained by performing a profiled maximum likelihood (ML) fit to the distribution of the median ΔR between all possible combinations of two jets, ΔR_{med}(j, j'), in the different jet/b-jet multiplicity and lepton flavour categories, except for the 3j1b category, where the MVA score distribution is used. In the fit, seven bins are used for ΔR_{med}(j, j') and six bins for the MVA score distributions, for a total of 54 bins (27 per lepton flavour), see Fig. 1 (right). The most sensitive category is found to be the μ+3j1b one.

The cross section is found to be 62.5 ± 1.6 (stat) $^{+2.6}_{-2.5}$ (syst) ± 1.2 (lumi) pb. This measurement is combined with the result obtained in the dilepton channel [4], based on the same data set, resulting in a value of 62.3 ± 1.5 (stat) ± 2.4 (syst) ± 1.2 (lumi) pb, with a total relative uncertainty of 4.9%. In both cases, the dominant uncertainties are those associated with the integrated luminosity and with the b tagging scale factors for heavy flavours. These values are consistent within two standard deviations with the SM prediction.

PoS(EPS-HEP2025)271

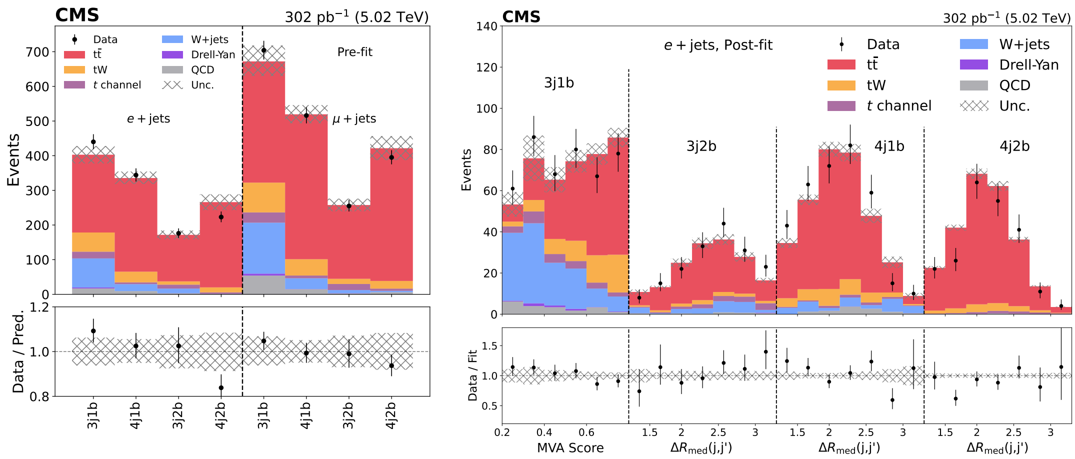

Figure 1: Left: observed and predicted number of events in each of the eight categories of the signal region, before the maximum likelihood fit. The vertical error bars represent the statistical uncertainty in the data, and the shaded band the uncertainty in the prediction. All uncertainties considered in the analysis are included in the uncertainty band. The lower panel shows the data-to-prediction ratio. The normalizations are taken with respect to the SM predictions except for QCD, which is estimated from data [3]. Right: distributions for the e+jets final state after the maximum likelihood fit: MVA score bins for the 3j1b category and ΔR_{med}(j, j') bins for the other categories. The vertical error bars represent the statistical uncertainty in the data, and the shaded band the uncertainty of the prediction. All uncertainties considered in the analysis are included in the uncertainty band. The lower panel shows the ratio of data to the fit. The first and last bins in each distribution include underflow and overflow events, respectively [3].

3. Measurement of inclusive and differential cross sections of single top quark production in association with a W boson in pp collisions at $\sqrt{s}$ = 13.6 TeV

Inclusive and normalised differential cross sections of top quark production in association with a W boson (tW) are measured for the first time in pp collision data at $\sqrt{s}$ = 13.6 TeV [5]. The selected data, which correspond to an integrated luminosity of 34.7 fb^{-1}, contain events with an electron and a muon of opposite charge ($e^{\pm}\mu^{\pm}$). These events are categorised depending on the number of jets and b-tagged jets, as shown in Fig. 2. The 1j1b region corresponds to the most signal-enriched region, with a signal-to-background ratio of about 16% compared to 8% in the 2j1b region.

For the inclusive measurement, the information from three regions with one or two jets and one or two b jets (1j1b, 2j1b, and 2j2b) is considered. The signal is measured using a ML fit to the distribution of random forest discriminants in the 1j1b and 2j1b regions, and to the transverse momentum (p_{T}) distribution of the second-highest p_{T} jet in the 2j2b category. These distributions are shown in Fig. 3.

The measured inclusive cross section is 82.3 ± 2.1 (stat) $^{+9.9}_{-9.7}$ (syst) ±3.3 (lumi) pb, with a total relative uncertainty of about 13%. This measurement is in agreement with the latest theoretical prediction at approximate next-to-next-to-next-to-leading order accuracy in perturbative quantum chromodynamics and with other measurements.

For the differential measurements, only the 1j1b region is used. In order to decrease the

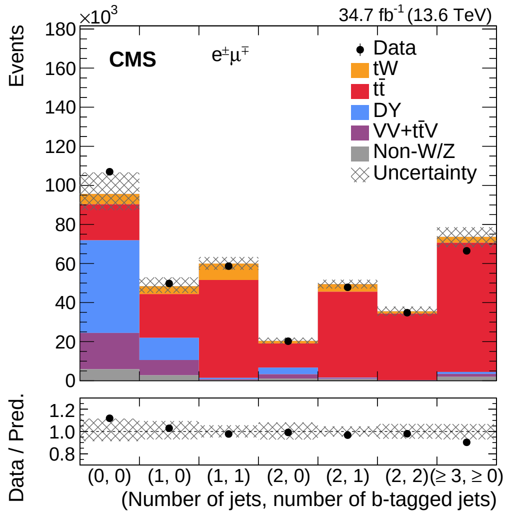

Figure 2: Distribution of the number of events observed in data (points) and predicted from simulation (filled histograms) in the $e^{\pm}\mu^{\pm}$ final state as a function of the number of jets and b-tagged jets before the maximum likelihood fit. The vertical bars on the points show the statistical uncertainties in the data. The hatched band represents the sum of the statistical and systematic uncertainties in the MC predictions. The lower panel shows the ratio of data to the sum of the expected yields [5].

relative contribution from the $t\bar{t}$ background, only the events in the 1j1b region with zero loose jets are selected. The signal-to-background ratio in this region is about 20%. The differential cross section measurements are performed as functions of six kinematic observables of the events in the fiducial phase space corresponding to the selection criteria. The results have relative uncertainties in the range of 20-40%, depending on the measured observable. The uncertainties are mainly statistical. There is good agreement between the measurements and the predictions from the different event generators. The different approaches used to simulate tW events give similar values in all distributions, which points to small effects related to the tW/ $t\bar{t}$ interference on these distributions in the defined fiducial region.

4. Measurement of the t-channel single top quark cross section in pp collision data at $\sqrt{s}$ = 5.02 TeV

A measurement of the single top quark t-channel production cross section in pp collisions at $\sqrt{s}$ = 5.02 TeV is performed [6]. The dataset used, collected by the CMS experiment, is the same one as the used in Sect. 2.

Events with one electron or one muon and multiple jets are selected and classified according to their jet and b-tagged jet multiplicities. Those events considered for the measurement have exactly two reconstructed jets, only one of which is b tagged, or exactly three reconstructed jets, with either one or two of them that are b tagged. These categories are denoted as 2j1b, 3j1b, and 3j2b, respectively. They are further split according to the flavour and the electrical charge of the selected lepton in the event, resulting in twelve mutually exclusive analysis categories. The observed number

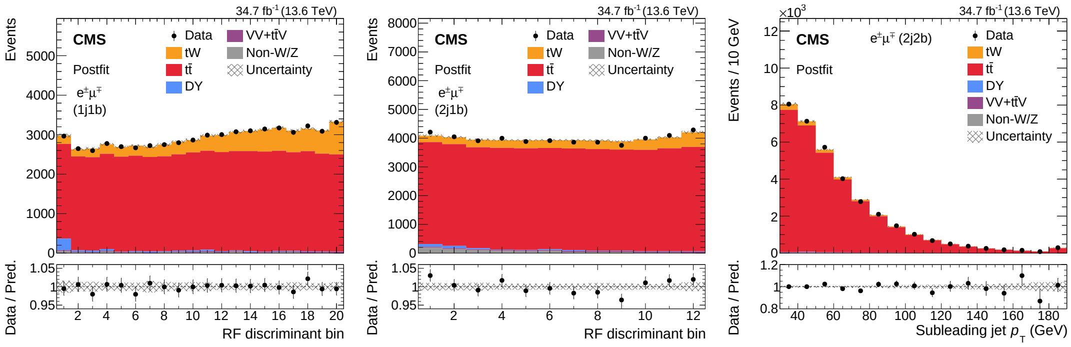

Figure 3: Distributions of the outputs of the random forests for events in the 1j1b (left) and 2j1b (middle) regions, and the subleading jet p_T for the 2j2b region (right). The number of observed events (points) and estimated signal and background events (filled histograms) from the maximum likelihood fit are shown. The last bin of the subleading jet p_T distribution includes the overflow events. The vertical bars on the points represent the statistical uncertainty in the data, and the hatched band the total uncertainty in the estimated events after the fit. The lower panels display the ratio of the data to the sum of the estimated events (points) after the fit, with the bands giving the corresponding uncertainties [5].

of events in data and the expected number of events for signal and background in each of the twelve categories of the analysis are shown in Fig. 4 (left).

The main background in the analysis originate from W+jets and top quark pair production, both estimated using MC simulation. Smaller contributions from quantum chromodynamics multijet events are derived from data. In the 2j1b categories, which contain most of the signal events, W+jets events constitute the largest source of background, while $t\bar{t}$ is dominating in the other categories. A dedicated MVA classifier has been developed for these categories in order to better discriminate signal from these backgrounds.

The cross sections are obtained by performing two independent profiled ML fits in the twelve analysis categories. The fits are performed on the distribution of the MVA score for the 2j1b categories and on the absolute value of the pseudorapìdity of the leading untagged jet ($|\eta_{u_0}|$) for the others, as shown in Fig. 4 (right).

The cross sections are found to be $\sigma(\mathrm{tq}+\bar{\mathrm{t}}\mathrm{q}) = 30.2^{+3.7}_{-3.6}$ (stat) $^{+4.4}_{-4.2}$ (syst) $\pm$ 0.6 (lumi) pb, $\sigma(\mathrm{tq}) = 21.1^{+3.0}_{-2.8}$ (stat) $^{+2.8}_{-2.7}$ (syst) $\pm$ 0.4 (lumi) pb and $\sigma(\bar{\mathrm{t}}\mathrm{q}) = 8.2^{+2.4}_{-2.3}$ (stat) $^{+1.9}_{-1.8}$ (syst) $\pm$ 0.2 (lumi) pb. The ratio, $\mathcal{R}_{t-ch}$, between the individual cross sections is found to be $\mathcal{R}_{t-ch}= 2.6^{+1.1}_{-0.7}$ (stat) $^{+0.7}_{-0.2}$ (syst). All the results are in good agreement with the SM predictions.

PoS(EPS-HEP2025)271

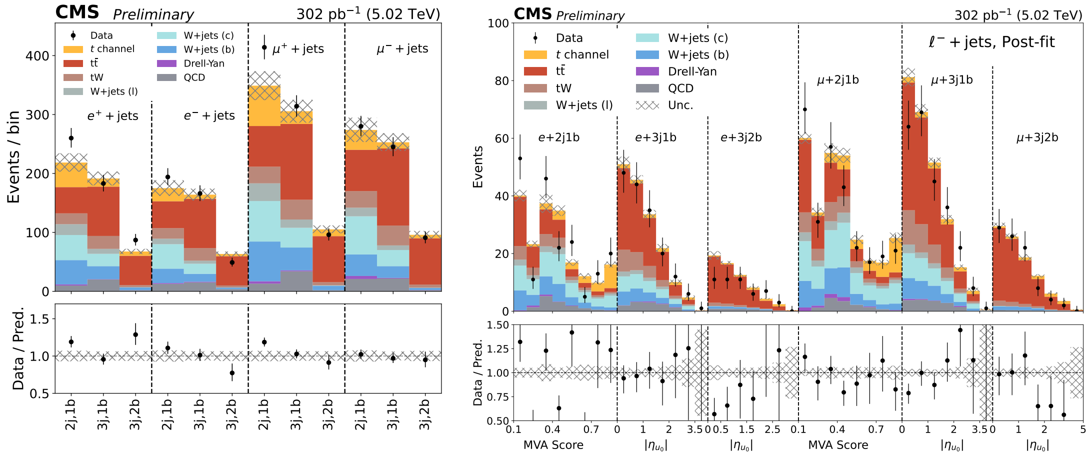

Figure 4: Left: observed and predicted number of events in each of the twelve categories of the signal region, before the maximum likelihood fit. The vertical error bars represent the statistical uncertainty associated to the data, and the hatched band the uncertainty in the prediction. All uncertainties considered in the analysis are included in the uncertainty band. The lower panel shows the data-to-prediction ratio. The normalizations of the processes are those of the SM predictions except for QCD, which is estimated from data [6]. Right: distribution for the ℓ^-+ jets category where the prediction parameters are set to the values obtained in the fit. They show the MVA score and $|\eta_{u_0}|$ distributions, which are the fitted variables in the maximum likelihood fit in the 2j1b category and the categories with three jets, respectively. The vertical error bars represent the statistical uncertainty associated to the data, and the hatched band the uncertainty of the prediction. All uncertainties considered in the analysis are included in the uncertainty band. The lower panel shows the ratio of data to prediction. The first and last bins in each distribution include underflow and overflow events, respectively [6].

References

[1] CMS Collaboration, *The CMS Experiment at the CERN LHC*, JINST **3** (2008) S8004, doi:10.1088/1748-0221/3/08/S08004.

[2] CMS Collaboration, *Development of the CMS detector for the CERN LHC Run 3*, JINST **19** (2023) P05064, doi:/10.1088/1748-0221/19/05/P05064.

[3] CMS Collaboration, *Measurement of the inclusive* $\mathrm{t\bar{t}}$ *cross section in final states with at least one lepton and additional jets with 302 pb^{-1} of pp collisions at $\sqrt{s}$ = 5.02 TeV*, JHEP **04** (2025) 099, doi:10.1007/JHEP04(2025)099.

[4] CMS Collaboration, *Measurement of the inclusive* $\mathrm{t\bar{t}}$ *production cross section in proton-proton collisions at $\sqrt{s}$ = 5.02 TeV*, JHEP **04** (2022) 144, doi:10.1007/JHEP04(2022)144.

[5] CMS Collaboration, *Measurement of inclusive and differential cross sections of single top quark production in association with a W boson in proton-proton collisions at $\sqrt{s}$ = 13.6 TeV*, JHEP **01** (2025) 107, doi:10.1007/JHEP01(2025)107.

[6] CMS Collaboration, *Measurement of the t-channel single top quark cross section in pp collision data at $\sqrt{s}$ = 5.02 TeV*, CMS-PAS-TOP-24-011.