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$t\bar{t}X$ results from ATLAS and CMS

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The associated production of top-quark pairs with W bosons or heavy-flavour jets are rare Standard Model phenomena compared to the inclusive top-quark pair production. Both processes are important background sources for Standard Model measurements like e.g. $t\bar{t}H$ production in the multilepton and $b\bar{b}$ Higgs decay channels or $t\bar{t}t\bar{t}$ production, and thus a precise knowledge of their properties is crucial. Additionally, these production channels can be significant background sources in searches for new physics. The current status of $t\bar{t}W$ and $t\bar{t}$+HF measurements performed by the ATLAS and CMS Collaborations is summarised in this article. The measurements are based on data collected from proton-proton collisions with a centre-of-mass energy of 13 TeV at the Large Hadron Collider at CERN.

The Ninth Annual Conference on Large Hadron Collider Physics - LHCP2021
7-12 June 2021
Online

*Speaker

PoS(LHCP2021)096

1. Introduction

The Standard Model (SM) of particle physics is a predictive theory that describes the fundamental constituents of nature and the interactions between them (with the exception of gravity). It has been tested with numerous measurements at different experiments and accelerators, and successfully describes the observations from high energy particle physics measurements at various energy scales. Despite the success of the SM, e.g. the cosmological observations associated with dark matter and dark energy cannot be explained within the SM.

The ATLAS [1] and CMS Experiments [2] at the Large Hadron Collider (LHC) [3] at CERN facilitate studies of particle collisions and probe the SM in terms of precision measurements of the SM properties and searches for new physics. This article focusses on measurements of $t\bar{t}W$ (Section 2) and $t\bar{t}$ + HF (Section 3) production at a centre-of-mass energy of 13 TeV, based on data collected during the Run 2 data-taking period between 2015 and 2018.

2. Top-quark pair production in association with a W boson

The associated production of top-quark pairs with a W boson arises from $q\bar{q}'$ inital states at leading order, while for next-to-leading order QCD corrections $gq/g\bar{q}'$ initial states are also possible and contribute significantly to the total cross-section (see e.g. Ref. [4]). Additionally, subleading electroweak corrections result in a comparably large change of the predicted cross-section by about 10% (see e.g. Ref. [5]). $t\bar{t}W$ production is a significant background source e.g. for measurements of the $t\bar{t}H$ and $t\bar{t}t\bar{t}$ processes in multilepton final states, such that a precise theoretical and experimental knowledge of $t\bar{t}W$ production is important for these measurements.

ATLAS and CMS published measurements of the inclusive $t\bar{t}W$ production cross-section in combination with the measurement of $t\bar{t}Z$ production on datasets with integrated luminosities of 36.1 fb^{-1} and 35.9 fb^{-1}, respectively [6, 7]. Both analyses cover the channel with two same-sign leptons, 2ℓSS, in their selection, while ATLAS additionally includes the three lepton, 3ℓ, channel.

The selected events are split into several signal categories based on the number of b-jets and the lepton charge by both experiments. ATLAS additionally splits the categories based on the lepton flavours, while CMS additionally splits them based on the number of jets. Further cuts are applied to reduce the event yields from background sources and a veto is applied for events with additional leptons that are identified with looser selection criteria ("loose leptons") and do not pass the nominal selection requirements. An additional background reduction in the signal categories is achieved by CMS with a BDT trained on several input variables.

The main backgrounds in the $t\bar{t}W$ signal regions are due to fake and non-prompt leptons, electrons with a misidentified charge and prompt processes like e.g. $t\bar{t}H$, $t\bar{t}Z$ and WZ production. Their estimation is partially performed with data-driven techniques and control regions are used to validate the agreement between data and simulation in regions dominated by specific background sources or to contrain their normalisation in the statistical analysis.

The final combined estimation of the $t\bar{t}W$ and $t\bar{t}Z$ cross-sections is based on a profile-likelihood fit and the extracted values are shown in Fig. 1. The measured $t\bar{t}W$ cross-sections from ATLAS and CMS are about 45% and 30% above the SM prediction, respectively, but the prediction is still within

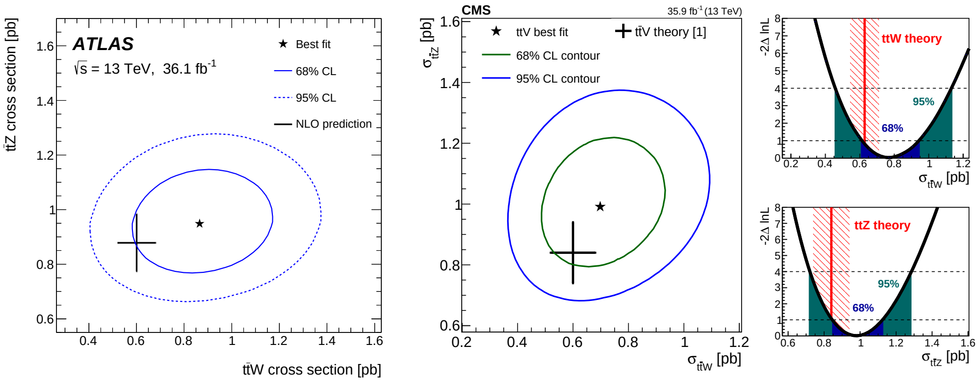

Figure 1: Measured cross-sections for $t\bar{t}W$ and $t\bar{t}Z$ obtained from a simultaneous fit of the processes, together with the 68% and 95% confidence level (CL) contours and the SM prediction, for ATLAS (left) and CMS (middle). On the right, the individual measured cross-sections for CMS are shown. Taken from Refs. [6, 7].

the 68% confidence level regions of both measurements. The $t\bar{t}W$ signal regions are included in an Effective Field Theory (EFT) interpretation of the measurement for the CMS analysis.

Recent $t\bar{t}H$ measurements in the multilepton final state [8, 9] and measurements of $t\bar{t}t\bar{t}$ production [10], based on datasets of about 80 fb^{-1} and 140 fb^{-1}, are sensitive to $t\bar{t}W$ production through their background estimates. These analyses found increased $t\bar{t}W$ yields by a factor of 1.3 to 1.7 compared to the theory prediction. Additional discrepancies between data and simulation were covered through systematic uncertainties in some of these analyses.

3. Top-quark pair production in association with heavy-flavour jets

The production of top-quark pairs in association with additional jets pairs, especially $t\bar{t} + b\bar{b}$ and $t\bar{t} + c\bar{c}$, is an important background in $t\bar{t}H(b\bar{b})$ measurements. The theoretical prediction for these processes is challenging, e.g. because of large uncertainties from the factorisation and renormalisation scale choices. A measurement of these processes can thus provide insight into the modelling quality of these production channels.

CMS recently published the first dedicated measurement of $t\bar{t} + c\bar{c}$ production at the LHC performed on a dataset of 41.5 fb^{-1} [11]. The analysis is based on a selection of $t\bar{t}$ events with dileptonic decays of the top-quark pair. At least four jets are required in the event and the jets must be spatially separated from the two leptons by $\Delta R(\ell, \text{jet}) > 0.5$.

The matching of four jets to the two generator-level b-quarks from the top-quark decays and the quark pair from the additional heavy-flavour radiation is done using a technique based on neural networks. The two jets assigned to the top-quark decays are required to be identified as b-jets. The jet pair from the additional radiation is correctly identified in 50% and 30% of the cases for $c\bar{c}$ and $b\bar{b}$ pairs, respectively, for events where reconstructed b-jets are found within $\Delta R < 0.3$ of the generator-level b-quarks from the top-quark decays. The multi-class DeepCSV algorithm [12] is used in the analysis to define two scores to separate c-jets from light jets and b-jets, respectively, for each of the two additional jets. Finally, an overall event-level categorisation is done using a multi-class neural network to define two discriminators to separate $t\bar{t} + b\bar{b}$, $t\bar{t} + bL$, $t\bar{t} + c\bar{c}$, $t\bar{t} + cL$ and $t\bar{t} + LL$ events, where L denotes light quarks, as well as a $t\bar{t}$ + other class.

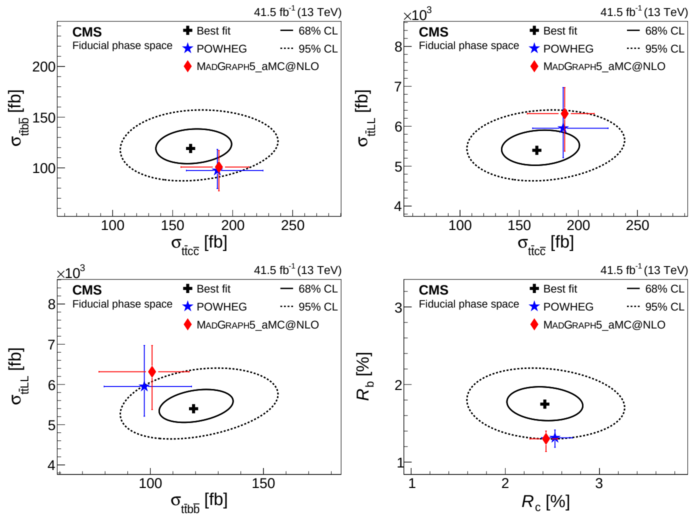

Figure 2: Measured cross-sections of $t\bar{t} + b\bar{b}$, $t\bar{t} + c\bar{c}$ and $t\bar{t} + LL$ production, as well as their combination in terms of $R_b = \sigma_{t\bar{t}+b\bar{b}}/\sigma_{t\bar{t}+jj}$ and $R_c = \sigma_{t\bar{t}+c\bar{c}}/\sigma_{t\bar{t}+jj}$, together with the 68% and 95% CL contours, from different two-dimensional likelihood scans in comparison with theoretical predictions. Figure from Ref. [11].

For the statistical analysis, the two-dimensional map of the event-level discriminators is unrolled and the measurement is done in the full phase space as well as a fiducial volume. The cross-sections of $t\bar{t} + b\bar{b}$, $t\bar{t} + c\bar{c}$ and $t\bar{t} + LL$ production are determined simultaneously, while $R_b = \sigma_{t\bar{t}+b\bar{b}}/\sigma_{t\bar{t}+jj}$ and $R_c = \sigma_{t\bar{t}+c\bar{c}}/\sigma_{t\bar{t}+jj}$ are measured together in a separate fit. The $t\bar{t} + b\bar{b}$ and $t\bar{t} + bL$ classes, as well as the $t\bar{t} + c\bar{c}$ and $t\bar{t} + cL$ classes, are merged within these fits, since in these events typically the second b- or c-jet is outside of the acceptance or merged with the first jet. Two-dimensional likelihood scans from the analysis are shown in Fig. 2. The extracted $t\bar{t} + c\bar{c}$ and $t\bar{t} + LL$ yields are slightly below the SM expectation, while the fitted cross-section for $t\bar{t} + b\bar{b}$ production is slightly above the SM predictions.

Dedicated analyses for $t\bar{t} + b\bar{b}$ production are available from ATLAS and CMS [13–15]. They are performed in different decay channels of the top-quark pairs and show increased yields of $t\bar{t}+b\bar{b}$ production compared to the SM expectation, while typically the inclusive $t\bar{t} + jj$ measurements, with j denoting an additional jet, show a better agreement with the predictions. Further material and the results of these analyses can be found in the referenced papers.

4. Conclusions

The current status of $t\bar{t}W$ and $t\bar{t}$ + HF measurements from the ATLAS and CMS Experiments at the LHC has been summarised in this article. The observed $t\bar{t}W$ yields are found to be higher than the SM prediction in the dedicated measurements, as well as several examples of $t\bar{t}H$ and $t\bar{t}t\bar{t}$ measurements in multilepton final states. The measured cross-sections of $t\bar{t} + b\bar{b}$ production in different $t\bar{t}$ decay channels are found to be above the SM expectation by several ATLAS and CMS analyses, while the $t\bar{t} + c\bar{c}$ and $t\bar{t} + LL$ yields are measured to be slightly below the SM expectation in a recent dedicated CMS measurement. While none of the observed deviations from the SM are statisically significant enough to be conclusive, they illustrate the need for more precise measurements of these processes and improvements in the theoretical calculations.

References

[1] ATLAS Collaboration, 2008 JINST 3 S08003.

[2] CMS Collaboration, 2008 JINST 3 S08004.

[3] L. Evans and P. Bryant (editors), 2008 JINST 3 S08001.

[4] G. Bevilacqua et al., JHEP 08 (2020) 043.

[5] R. Frederix and I. Tsinikos, Eur. Phys. J. C 80 (2020) 803.

[6] ATLAS Collaboration, Phys. Rev. D 99 (2019) 072009.

[7] CMS Collaboration, JHEP 08 (2018) 011.

[8] ATLAS Collaboration, ATLAS-CONF-2019-045, http://cdsweb.cern.ch/record/2693930.

[9] CMS Collaboration, Eur. Phys. J. C 81 (2021) 378.

[10] ATLAS Collaboration, Eur. Phys. J. C 80 (2020) 1085.

[11] CMS Collaboration, Phys. Lett. B. 820 (2021) 136565.

[12] CMS Collaboration, JINST 13 (2018) P05011.

[13] ATLAS Collaboration, JHEP 04 (2019) 046.

[14] CMS Collaboration, JHEP 07 (2020) 125.

[15] CMS Collaboration, Phys. Lett. B 803 (2020) 135285.