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Measurement of $t\bar{t}$ + X at the CMS experiment

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For the period of 2016 to 2018 (Run-2), data corresponding to an integrated luminosity of around 150 fb^{-1} have been collected at the center of the mass energy of 13 TeV by the CMS experiment at the Large Hadron Collider. The data deluge allows us to perform searches and measurements of the rare processes in the top quark sector. The latest cross section measurements and searches of the rare processes in association with a top quark pair are presented here.

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1. Introduction

For the period of 2016 to 2018 (Run-2), data corresponding to an integrated luminosity of around 150 fb^{-1} has been collected at the center of the mass energy ($\sqrt{s}$) of 13 TeV by the CMS experiment [1] at the Large Hadron Collider. The data deluge allows us to perform searches and measurements of the rare processes in the top quark sector. The latest cross section measurements and searches of the rare processes in association with $t\bar{t}$ such as $t\bar{t}$+W/Z, $t\bar{t}+b\bar{b}$ and $t\bar{t}$ $t\bar{t}$ have been performed with the full Run-2 dataset as well as a partial dataset. An overview of the latest results on these processes by the time of the LHCP2019 conference will be presented.

2. $t\bar{t}$ + W/Z measurements

In the standard model (SM), the $t\bar{t}$ + W/Z processes are among the rare processes with the cross section of the order of 1 pb. However, the sizable contributions can be expected from any possible new physics beyond the SM so they become dominant backgrounds for the other $t\bar{t}$ associated rare processes such as four top quarks and $t\bar{t}$+H searches in the multi-lepton final states. In particular, the $t\bar{t}$ + Z production is the most sensitive process for the coupling of the top quark and the Z boson. Previously the cross sections of these processes were measured using data of 35.9 fb^{-1} at $\sqrt{s}$ = 13 TeV in the same-sign dilepton and multi-lepton channels. The measured cross section of the $t\bar{t}$ + W and $t\bar{t}$ + Z are $0.77^{+0.12}_{-0.11}$(stat) $^{+0.13}_{-0.12}$ (syst) pb with a 4.5 σ significance and $0.99^{+0.09}_{-0.08}$ (stat) $^{+0.12}_{-0.10}$ (syst) pb with a significance above 5 σ, respectively [2]. The measurement of the $t\bar{t}$ + Z cross section has been updated by adding 2017 data summing up to a total of 77.5 fb^{-1} data [3]. A similar strategy to the previous analysis is applied in the final states of exactly three leptons or four leptons. In both cases, exactly one pair of oppositely charged and same flavor leptons with $|m(ll) - M(Z)| < 10$ (20) GeV for three (four)-lepton category is required. Main backgrounds are from at least one top quark in association with a W, Z or Higgs boson. The WZ(ZZ) processes are the second largest backgrounds. Figure 1 shows the comparison between data and predictions in the WZ- and ZZ-enriched data control region.

The measured cross section is $1.00^{+0.06}_{-0.05}$ (stat) $^{+0.07}_{-0.06}$ (syst) pb [3] in the full phase space of $m(ll) > 10$ GeV. This result is more precise than the next-to-leading order theory calculation. Differential cross sections of the $t\bar{t}$ + Z process are also measured for two variables: one is the p_T of the Z candidate and the other is the angle $\cos\theta^*_Z$ between the negative charged lepton and the Z candidate in the Z rest frame. Unfolded distributions for these two variables are shown in Fig. 2.

3. $t\bar{t}+b\bar{b}$ measurements

The process of $t\bar{t}+b\bar{b}$ includes the additional $b\bar{b}$ production which mainly originates from gluon splitting. This process is rare and amounts to around 2% of the $t\bar{t}$+jj process [4]. However, this process is the main background to the $t\bar{t}$+H and four top quark production searches. It is challenging to identify two additional jets since there are four b jets in the final state. At CMS, the cross section of the $t\bar{t}+b\bar{b}$ process has been measured for the first time in the hadronic channel with an integrated luminosity of 35.9 fb^{-1}. In this analysis, to reduce the possible permutations among the b jets, the χ^2 fitting using the top quark mass and the W boson mass in each side of a top quark decay

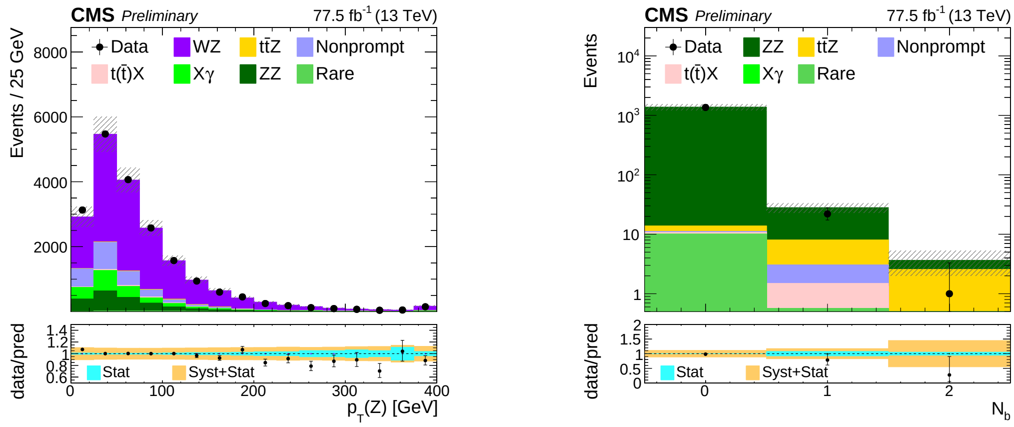

Figure 1: Distributions of the predicted and observed yields for the reconstructed transverse momentum of the Z candidates (left) in the WZ-enriched control region and number of b jets in the ZZ-enriched control region. The shaded band represents the total uncertainty in the prediction. The lower panels show the ratio of the data to the predictions. The inner band gives the statistical uncertainty in the ratio, and the outer band the total uncertainty [3].

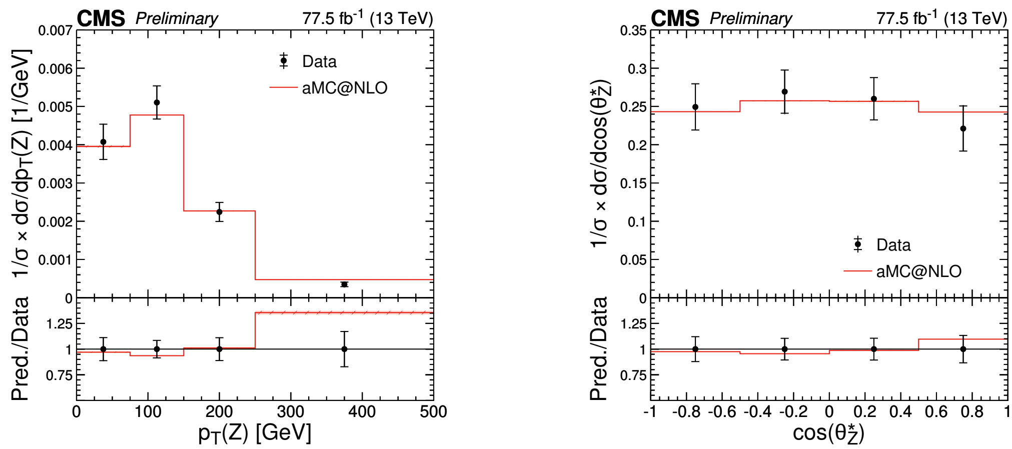

Figure 2: Measured normalized differential $t\bar{t}$+Z production cross sections in the full phase space as a function of the transverse momentum p_T of the Z boson and $\cos\theta_Z^*$ which is the angle between the negative charged lepton and the Z candidate in the Z rest frame [3].

is applied. After requiring $\chi^2 < 33.38$, among the remaining jet combinations, two additional jets are assigned using a Boosted Decision Tree (BDT) with various variables such as b-tagging output, invariant masses of pairs and triplets of jets, angular openings between jets and p_{T} of jets.

To reduce the multi-jet background, the Quark-Gluon Likelihood Ratio (QGLR) algorithm is applied using the fact that the multi-jet process originates mainly from gluon jets while the $t\bar{t}$+$b\bar{b}$ event has four light-quark jets from W bosons in the top quark decays. To further improve the sensitivity, weakly supervised learning called CWoLa (classification without labels) BDT has been developed and applied. In this weakly supervised approach, the classifier is trained using data. Two orthogonal regions are treated as signal and background separately. The signal purity increased by applying QGLR > 0.5 and CWoLa BDT > 0.8 requirements. Multi-jet contribution is estimated from the data. The control region is obtained by inverting QGLR and CWoLa BDT requirements.

Two distributions of QGLR and CWoLa BDT variables are shown in Fig. 3.

Finally, $t\bar{t}$+$b\bar{b}$ signal contribution is extracted by fitting to the 2 dimensions of two largest b-tag output of the selected additional jets. The measured $t\bar{t}$+$b\bar{b}$ cross section is $5.5 \pm 0.3\,^{+1.6}_{-1.3}$ pb in the full phase space where the additional b jets should satisfy $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.4$. The cross sections in the visible phase spaces: one that is based on the stable particle after hadronization (parton-agnostic, PA) requiring only 8 jets, 4 b jets, and one that is based on the parton-level information (parton-based PB) at least two b jets not to originate from top quarks are $1.6 \pm 0.1\,^{+0.5}_{-0.4}$ pb and $1.6 \pm 0.1\,^{+0.5}_{-0.4}$ pb, respectively. These two numbers are the same due to the fact that the two definitions for the visible phases are similar. Predictions from POWHEG + PYTHIA8, POWHEG + HERWIG++ and MG5_aMC@NLO (4FS, 5FS $t\bar{t}$+jets FxFx) are generally lower than the measured value as shown in Fig. 4.

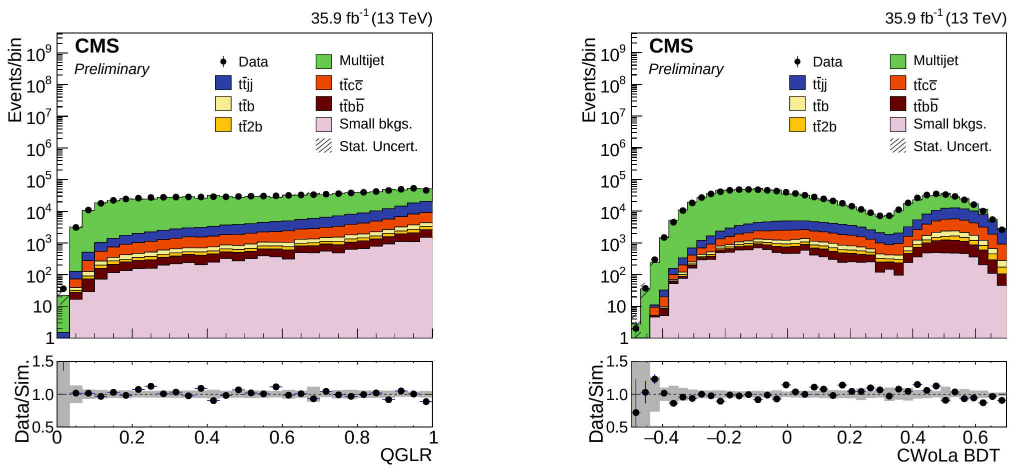

Figure 3: Distributions of the QGLR (left) and the CWoLa BDT (right) [5].

4. Searches for four top quarks

The four top-quark process is a rare process in the standard model and its theoretical cross section of 12 fb has been calculated at the next-to-leading order including electroweak corrections. Measurement of the four top-quarks can constrain the magnitude and CP (Charge-Parity) properties of the top quark Yukawa coupling to the Higgs boson. This process can also be significantly enhanced due to BSM (Beyond Standard Model) particles such as a heavy pseudoscalar or scalar boson in association with a $t\bar{t}$ pair in 2HDM. The search has been performed in the single lepton and the dilepton final states with a branching fraction of 40% of the $t\bar{t}t\bar{t}$ with data of an integrated luminosity of 35.8^{-1} [6]. Two BDTs are used to improve the sensitivity: one for finding a correct jet-combination for the hadronic top quark decay and one for signal and background classification. The analysis has combined previous results [7] in the dilepton same sign and trilepton channels, the latter of which has a branching fraction has the branching fraction of 12%. The combination shows the observed limit of 33 fb (20 fb for expected limit).

Searches for four top quarks have been pursued in the dilepton same sign and trilepton channels with the full Run-2 data corresponding to an integrated luminosity of 137 fb^{-1}. These same sign

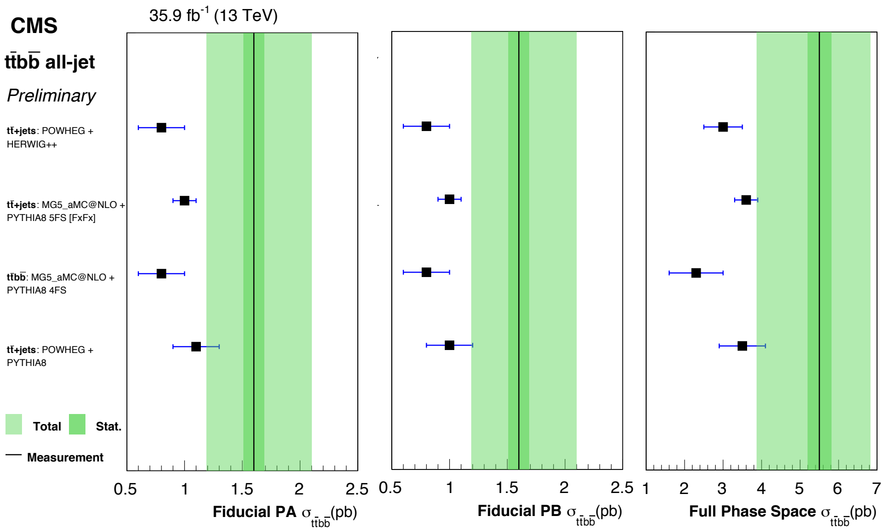

Figure 4: Comparison of the measured tt̄+bb̄ production cross sections with predictions from several Monte Carlo generators for the three definitions of the tt̄+bb̄ phase space. Uncertainty bands include the statistical uncertainty and also theory uncertainty from the PDFs and scale (μ_R and μ_F) variations [5].

and trilepton channels are the most sensitive channels due to low level of backgrounds. The main background is the tt̄ in association with additional bosons and also the dilepton channel in the tt̄ process. The distributions of the jet multiplicity in the tt̄+Z enriched region and the H_T in the signal region are shwon in Fig. 5. Two approaches as the previous search have been used: Following the strategy from the previous search, two approaches have been used in this analysis: one is simple cut-and-count based on number of (b)-jets and the other is multivariate technique with BDT using the lepton and jet kinematic variables 17 signal regions based on the BDT score. The measured cross section in the updated result with full Run 2 data using cut-based analysis is 9.4 fb with a significance of 1.7 σ [8]. At 95% confidence level, the obtained upper limit is 20.0 fb. Using BDT with lepton and jet kinematic variables and categorizing events in 17 signal regions based on the BDT score, the sensitivity is enhanced. The measured cross section is 12 fb with a significance of 2.6 σ. The upper limit is 22.5 fb.

Four top searches have been also used to constrain the mass parameter space for the scalar and pseudoscalar bosons. Scalar boson masses between 350–470 GeV and pseudoscalar boson masses between 350–550 GeV are excluded (see Figs. 6).

5. Conclusions

Measurements of the tt̄+W/Z processes have been updated with adding more data up to a total of 77.5 fb^{-1} and are getting more precise than the NLO calculation. These rare processes are already measured differentially. The tt̄+bb̄ cross section is measured in the hadronic channel for the first time and shows that predictions are generally lower than the measured cross sections. The searches for four top quark production have been performed with the full Run-2 data in the single and multi-lepton channels. No significant deviation is found from the SM. By the time of the

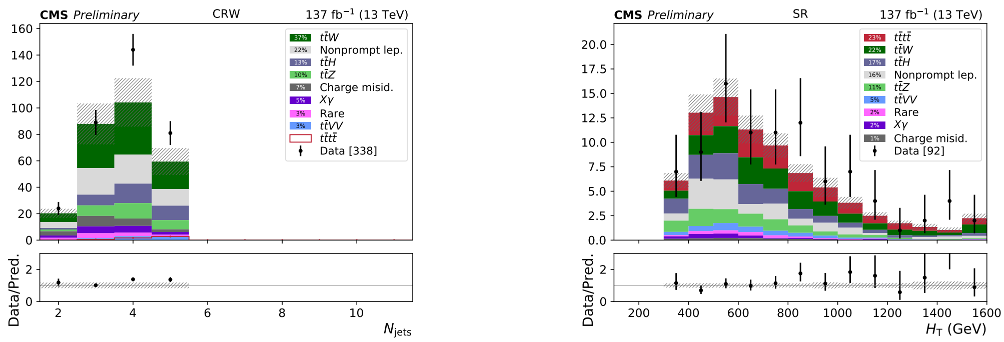

Figure 5: Distributions of the $t\bar{t}$+Z enriched area (left) and the signal area (right) [8].

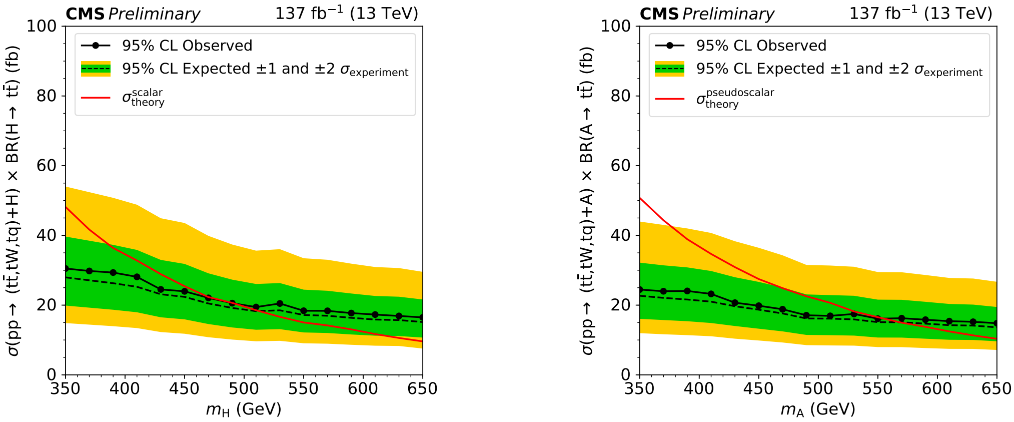

Figure 6: Cross section limits as a function of boson mass for heavy scalar (left) and pseudoscalar (right) [8].

LHCP2019 conference, for most of analyses, only a fraction of the Run-2 data have been analyzed. More measurements will come soon with the full Run 2 data.

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