

Rare top quark production and decays at ATLAS and CMS

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The most recent studies in the top quark sector are reviewed with the focus on the rare production mechanisms and suppressed decays. The experimental results obtained with the ATLAS and CMS detectors in proton-proton collisions at the center-of-mass energy of 13 TeV include the measurements of the associated production of top quark pairs with vector bosons ($t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}\gamma$), the first evidence for the $t(\bar{t})\gamma q$ process, the first observation of the $t(\bar{t})Zq$ production, the study of the $t\bar{t} + b\bar{b}$ and $t\bar{t} + t\bar{t}$ processes, as well as searches for lepton flavour violation in top quark decays and effective field theory interpretations. The experimental results show good agreement with the theoretical predictions.

1 Introduction

The top quark takes an important place in the standard model (SM). Its mass and distinctive experimental decay signature in the experiment makes it possible to study a number of very rare production mechanisms, as well as extremely rare decay modes. Top quarks produced in pairs, as well as singly produced particles, were already observed at the LHC. The rare production of top quarks with vector bosons and additional quarks is associated with small cross sections and is also challenging due to complex final states. Study of these rare processes allows us to probe interactions of the top quark with other SM particles and to search for possible anomalous phenomena.

2 Study of associated production of top quark pairs with vector bosons

The study of the top quark pair production ($t\bar{t}$) in association with a W or Z boson is important because these topologies can receive sizeable contributions from new physics, and, in addition, the $t\bar{t}Z$ production represents the main channel to directly measure the top quark couplings to the Z boson. Moreover, the precise measurements of the production cross sections of these processes are essential for the study of the $t\bar{t}H$ production where the $t\bar{t}W$ and $t\bar{t}Z$ events represent one of the dominant backgrounds in the multilepton analysis channels.

The study of the $t\bar{t}W$ production at ATLAS¹ is done in the dilepton same-sign and trilepton channels, while the $t\bar{t}Z$ process is looked for in the dilepton opposite-sign, trilepton and four-lepton final states³. In the analysis of the $t\bar{t}Z$ process using dilepton opposite-sign final states the prompt lepton background originates from Z +jets and $t\bar{t}$ events, while these processes represent a non-prompt lepton background in the other channels, also for the case of $t\bar{t}W$. The prompt lepton background is additionally associated with the diboson production and is one of the dominant backgrounds along with the non-prompt leptons. The analysis proceeds with defining control and signal regions with multiple exclusive event categories based on the number of leptons split into different flavour and sign with an additional selection based on the number of jets and b-tagged jets.

The analysis of the $t\bar{t}Z$ production allows to perform an effective field theory (EFT) study of anomalous contributions to the $t\bar{t}Z$ vertex with obtaining constraints on the Wilson coefficients of the respective dimension-six operators. In such interpretation the $t\bar{t}Z$ event rate can be expressed as a quadratic function of the Wilson coefficients where the linear terms results from the interference between beyond the SM (BSM) and SM operators. The fits to the measured distributions are done to obtain the EFT constrains in the case when both the quadratic and linear terms are kept, as well as when the quadratic terms are omitted. The obtained constraints represent competitive results to the existing direct and indirect limits. The inclusive $t\bar{t}Z$ and $t\bar{t}W$ cross sections are measured with $\simeq 10\%$ and $\simeq 20\%$ precision, respectively, and are comparable to next-to-leading order (NLO) theoretical uncertainties, as shown in Fig. 1.

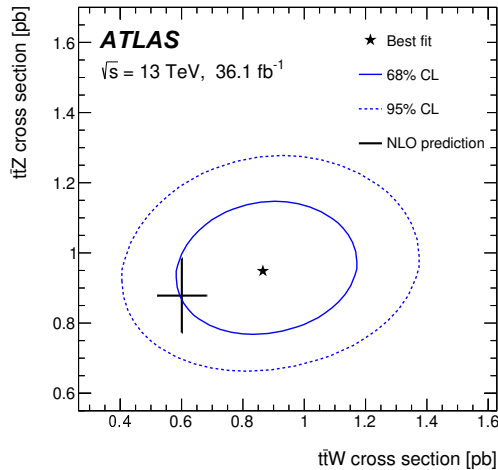


Figure 1 – The results of the simultaneous fit to the $t\bar{t}Z$ and $t\bar{t}W$ cross sections with the 68% and 95% confidence level contours compared to the NLO theoretical predictions³.

The analysis at CMS² studies final states with two same-sign leptons for the $t\bar{t}W$ process, while the $t\bar{t}Z$ production is looked for in the trilepton and four lepton final states⁴. The prompt and non-prompt lepton backgrounds are validated in control regions in data. The analysis uses an improved multivariate-analysis-based (MVA) lepton identification with respect to the previous iterations of these studies. The $t\bar{t}W$ and $t\bar{t}Z$ cross sections are extracted from combined fit over several exclusive event categories defined by the final MVA-based discriminant and the total number of jets and b-tagged jets. The measured inclusive cross sections show good agreement with NLO predictions.

By including more data it becomes possible to probe differential cross sections of the $t\bar{t}Z$ production. The study done at CMS measures differential distributions of the $t\bar{t}Z$ cross section using kinematic variables sensitive to $t - Z$ anomalous interactions⁵. The measured cross sections are interpreted in two frameworks. The first approach uses an anomalous-coupling Lagrangian based on the neutral vector and axial vector current couplings, as well as the weak magnetic and electric dipole interaction couplings. The second interpretation is EFT-based which considers four dimension-six operators which induce electroweak dipole moments and anomalous neutral-current interactions. The $t\bar{t}Z$ inclusive cross section in this recent analysis is now measured with an improved precision of $\simeq 10\%$. Some measured differential cross sections are presented in Fig. 2.

The analysis of the $t\bar{t}\gamma$ production represents an important study of the top-photon electroweak couplings where the kinematic distributions of the radiated photon, such as transverse momentum, are especially sensitive to new physics contributions. The measurement of the $t\bar{t}\gamma$ differential cross section also provides an important information on the $t\bar{t}$ spin correlations and

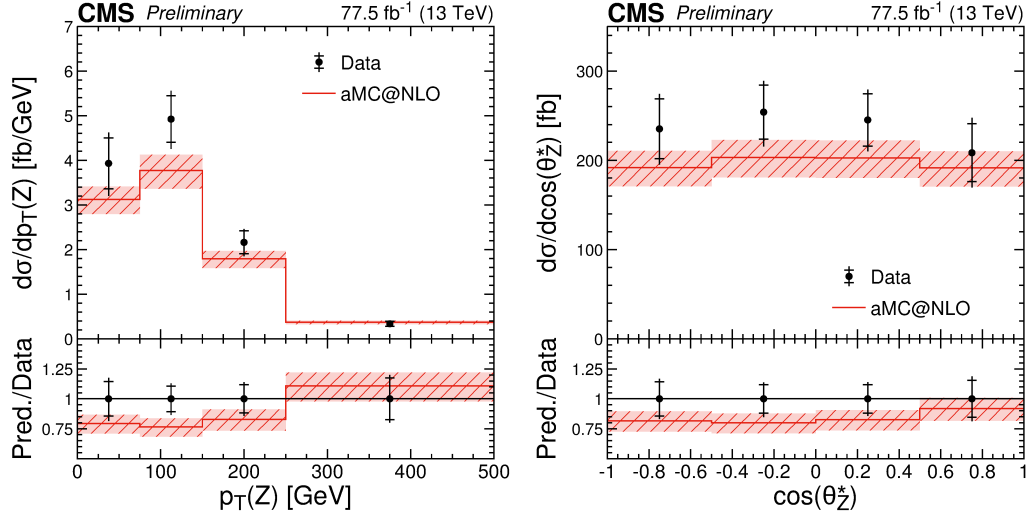


Figure 2 – Comparison between data and MC prediction for differential $t\bar{t}Z$ cross sections as a function of the transverse momentum of the Z boson (left) and the cosine of the angle between the Z boson and the negatively charged lepton from the Z boson decay in the Z boson rest frame (right)⁵. The hatched band includes the theory uncertainties in the prediction.

charge asymmetry, and is complementary to the other $t\bar{t}$ measurements. The $t\bar{t}\gamma$ process is studied at ATLAS in the channels with one or two leptons and the results of the differential measurements are compared to leading-order and NLO predictions⁶. The previously observed disagreements in the large values in the distribution of the azimuthal angular difference between the two leptons are now significantly mitigated with moving to the NLO event generation.

3 Study of single top quark associated production with vector bosons

The associated production of a top quark with a photon ($t(\bar{t})\gamma q$) is an important process which is sensitive to the charge, as well as the electric and magnetic moments of the top quark. The search for this process is done at CMS in the t-channel considering the final state with one muon, one photon, one b-tagged jet and one forward jet⁷.

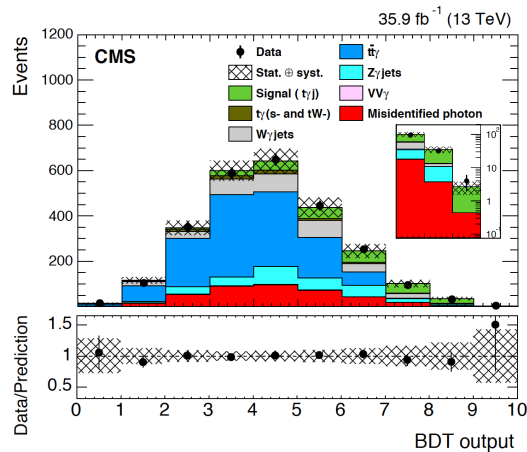


Figure 3 – The boosted decision tree output distribution for data and SM predictions after the fit in the analysis of the $t(\bar{t})\gamma q$ process⁷.

The presence of the forward light flavour energetic jet is a very characteristic signature of the single top quark associated production with vector bosons. The dominant background includes

the $t\bar{t}\gamma$ production, among other contributions. The analysis uses a boosted decision tree-based discriminator to suppress various backgrounds, as shown in Fig. 3. This study resulted in the first evidence for this process at 4.4 (3.0) σ observed (expected).

The production of a top quark in association with a Z boson ($t(\bar{t})Zq$) is sensitive to anomalous WWZ triple-gauge and tZ couplings. The analysis of this production at CMS was done in the final state with three leptons⁸. This study uses an improved lepton identification which allowed to boost the final sensitivity in this search. A simultaneous fit is performed over several event categories to extract the signal with the sensitivity of 8.2 (7.7) σ observed (expected) leading to the first observation of this process. Comparisons after the final event selection criteria between data and predictions are shown in Fig. 4.

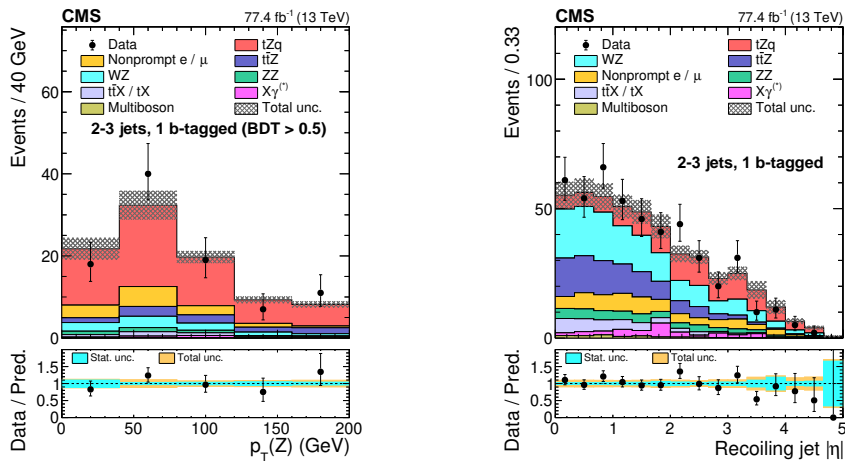


Figure 4 – Comparison between the number of expected and observed events for the distributions of the recoiling jet $|\eta|$ (left) and the transverse momentum of the Z boson after the additional selection on the final discriminant (right)⁸.

4 Study of top quark pair production in association with heavy flavour quarks

The production of $t\bar{t}$ with additional jets is associated with large theoretical uncertainties due to the presence of two different scales of the top quark mass and the jet transverse momentum. The measurements of the associated production of top quark pairs with b quarks ($t\bar{t} + b\bar{b}$) are done at ATLAS in single lepton and dilepton final states⁹. This study is an important test of QCD predictions with providing a better estimation of one of the main backgrounds in the $t\bar{t}H(H \rightarrow b\bar{b})$ analysis. The $t\bar{t} + b\bar{b}$ component is extracted from data using MC templates defined by the flavour of additional quark-jets. The measured inclusive fiducial cross sections generally exceed the $t\bar{t} + b\bar{b}$ NLO predictions but are still compatible within the total uncertainties. The inclusive cross section is measured with precision of $\simeq 20\%$ and is better than in the theoretical calculations. The measured cross sections in fiducial region is presented in Fig. 5.

Another rare process that allows to study the QCD predictions is the four top quark production that is also sensitive to the top quark Yukawa coupling. The search for this process at ATLAS is done in single lepton and dilepton opposite-sign channels¹⁰. Events are categorised based on the number of jets and b-tagged jets. There are several validation regions defined to

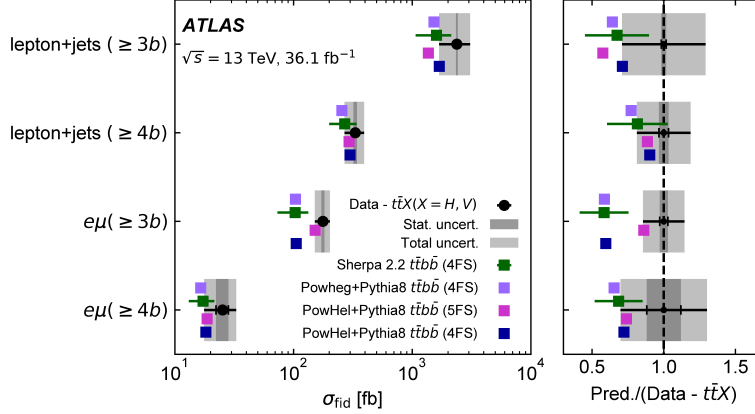


Figure 5 – The measured fiducial cross sections, with $t\bar{t}H$ and $t\bar{t}V(V = W, Z, \gamma)$ contributions subtracted from data, compared with $t\bar{t} + b\bar{b}$ predictions⁹.

perform the measurement of the b tagging efficiencies adapted to the topology of these events and to extrapolate it to the signal regions. The results are combined with the previously published dilepton same-sign and multilepton results. This combination has resulted in the exclusion of the cross section of $t\bar{t} + t\bar{t}$ production down to $\simeq 5\times$ the predicted value at 2.8 (1.0) σ observed (expected), with the final limits presented in Fig. 6. The analysis also includes an EFT interpretation optimised for four-top contact interactions.

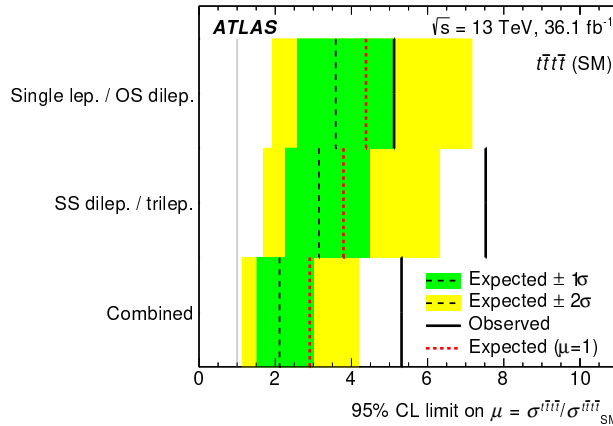


Figure 6 – Summary of the 95% confidence level limits on the $t\bar{t} + t\bar{t}$ production relative to the SM prediction in the individual channels and for the combination¹⁰.

The search for the $t\bar{t} + t\bar{t}$ production in similar final states is also done at CMS¹¹. Several event categories are defined based on the number of reconstructed jets and b -tagged jets used in a simultaneous fit to extract the signal. A combination with dilepton same-sign and trilepton results is also performed. The EFT interpretation was done for four-fermion operators which contribute to the $t\bar{t} + t\bar{t}$ production. The combined sensitivity to the $t\bar{t} + t\bar{t}$ production reaches 1.4 (1.1) σ observed (expected).

5 Effective field theory study in dilepton events

The EFT interpretations are becoming an essential part of many analysis studying top quarks. The full EFT at NLO interpretation is done for the top quark production in the dilepton final state at CMS, which mainly includes top quarks produced in $t\bar{t}$ and $t(\bar{t})W$ processes¹². There

are several types of operators which contribute to the production of these events, including operators associated with the Wtb couplings, chromomagnetic dipole moment, triple gluon field and flavour-changing neutral currents. The interference between the $t\bar{t}$ and $t(\bar{t})W$ processes is removed. The EFT constraints are set through the fit of a Neural Network discriminants trained to distinguish between the EFT contributions and the SM prediction.

6 Search for lepton-flavour violation

In addition to the rare top quark production, one can also search for rare decays of these particles. One such analysis is done at ATLAS to search for the charged lepton-flavour violation (LFV) with the model-independent approach in three-particle decays of top quarks¹³. The LFV decays of top quarks are extremely suppressed in the SM and any deviations from these zero rates would indicate the presence of new physics. The analysis is based on the study of the three-lepton final state to set limits several EFT operators, including the axial-vector, scalar, pseudo-scalar and lepton-quark interactions. The probability of observing LFV top quark decays is excluded down to the $\simeq 10^{-5}$ level and this constraint is more stringent than the current indirect limits set at $\simeq 10^{-3}$.

7 Conclusion

The experiments done with the ATLAS and CMS detectors at the LHC provide us with a great opportunity to study very rare processes with top quarks. Recently, we have observed for the first time the process with the production of single top quarks in association with a Z boson, as well as have obtained the first evidence for the single top quark production with a photon. The study of the underlying physics in these processes and searches for BSM phenomena will proceed with even more data in the coming years.

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