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Measurement of single top quark production with CMS

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Single top quark production with the CMS experiment at the LHC

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Abstract

Results of several single top physics measurements that the CMS Collaboration has produced in proton-proton collisions at the LHC at centre-of-mass energies of 7, 8 and 13 TeV, are presented. Separate investigations of the inclusive, fiducial, and differential cross section measurements in the t-channel, the production of top via the s-channel, and the measurements of standard model parameters and rare processes involving a top quark are discussed.

1. Introduction

Studies of top quarks have been of great interest since their discovery by the CDF/D0 experiments at the Tevatron in 1995 [1, 2]. Top quarks are mainly produced through pair-production at Hadron colliders, but are also produced singly through weak interactions, with first observations of singly produced top quarks being made in 2009 by the CDF [3] and D0 [4] experiments and in 2011 by the ATLAS [5] and CMS [6] experiments.

Being the heaviest particle in the Standard Model (SM), the top quark is expected to play an important role in the electroweak symmetry breaking and Beyond the Standard Model (BSM) physics [7]. Single top quark production is a powerful probe between the top quark and electroweak sector, allowing for precision measurements of SM parameters whilst being sensitive to new physics, such as anomalous couplings. Measuring single top quark processes is also important as such processes are backgrounds for Higgs and BSM physics searches and can be used to constrain Parton Distribution Functions (PDFs).

The main SM single top production processes are categorised by the virtuality of the W boson involved in the interaction (see Fig. 1).

Figure 1: Leading order diagrams for single top quark production channels via weak processes: (a) s-channel, (b) t-channel and (c) tW.

Measurements of single top quark production mechanisms, SM parameters and constraints on anomalous couplings have been made with proton-proton (p-p) collision data collected by the CMS experiment [8] from Run-1 of the LHC and the first Run-2 results are discussed. The Run-1 tW result can be found here [9].

A number of the measurements discussed make use of multivariate analysis techniques, such as Boosted Decision Trees (BDTs) and Neural Networks (NNs), to enhance signal/background separation in order to measure the signal with the highest possible significance. Algo-

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rithm training was done using variables with high separating powers between the signal and dominant background(s) and for being well modelled in simulation.

2. t-channel

The t-channel is the single top production mechanism with the largest cross-section at the LHC. A number of different measurements have been performed, including the first measurements at $\sqrt{s} = 13$ TeV with data collected during 2015. The event selections require a single isolated high p_T lepton (an electron or muon), missing transverse energy (E_T^{miss}) from the W boson decay and at least two high p_T jets. Events where there are two jets, one being b-tagged, (i.e. 2-jets 1-tag) are defined as the Signal Region (SR). Where used, the W+jets background Control Region (CR) is defined as 2-jets 0-tags and the $t\bar{t}$ background CR is defined as 3-jets 1-tag or 2-tags. In CRs with more than one b-jet, the hardest b-jet is associated to the top decay. The top mass (m_{top}) is reconstructed from the invariant mass of the lepton, the b-jet from the top quark decay and the E_T^{miss} , with a constraint on the invariant mass of the lepton and E_T^{miss} to be consistent with the W boson mass.

2.1. Inclusive Cross Section

A measurement of the inclusive cross section has been made using 2.2 fb^{-1} of data at $\sqrt{s} = 13$ TeV collected 2015 [10]. Only muons, either from the W boson directly or via an intermediary tau, are considered. The W+jets and $t\bar{t}$ background CRs, as described above 2, were used for validation of the W+jets background simulation and to constrain the $t\bar{t}$ contribution. The multijet background is suppressed as much as possible through the event selection due to poor modelling in simulation, with the remaining events estimated through fitting the transverse W boson mass (m_T^W) distribution using a maximum likelihood fit. A more in depth explanation of the data-driven estimate is detailed in [10].

Further signal/background separation was achieved through the use of a NN and a binned maximum likelihood fit on the discriminator distribution was used to extract the cross section.

The total cross section was measured to be $\sigma = 232 \pm 13$ (stat) ± 12 (theory) ± 9 (lumi) pb and the top to anti-top quark cross section ratio was measured to be $R_t = \frac{\sigma(t)}{\sigma(\bar{t})} = 1.81 \pm 0.18$ (stat) ± 0.15 (syst). Given the charge asymmetry of the p-p initial state resulting in more top quarks being produced than anti-top quarks, R_t is sensitive to the PDF of the up- and down-type quarks. R_t is also directly sensitive to BSM physics, such as anomalous couplings.

Figure 2: Summary of the most precise CMS total single top t-channel inclusive cross section measurements, and the Tevatron combination measurement in comparison with NLO+NNLL QCD calculations [10].

From the $\sqrt{s} = 13$ TeV measurement of the inclusive cross section in the t-channel, the absolute value of the CKM matrix element V_{tb} was calculated to be $|f_{LV}V_{tb}| = 1.03 \pm 0.07$ (exp) ± 0.02 (theory), where f_{LV} is the anomalous form factor, of 1 for the SM. These results are in good agreement with the SM prediction.

2.2. Differential Cross Section

The cross section for t-channel as functions of the p_T and absolute value of the rapidity ($|y|$) of the top quark have been made using $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 2.3 fb^{-1} [11]. The event selection requires a single muon and a cut on the $m_T^W > 50$ GeV to suppress background multijet events.

A BDT was trained to separate the dominant backgrounds (W+jets and $t\bar{t}$) from the signal events without rejecting events based on their m_T^W . Only variables with a low correlation to the top quark p_T and $|y|$ are used in the training to ensure that the data is not biased towards the signal SM prediction as a SM signal Monte Carlo (MC) simulation sample is used in the training process.

Simultaneous binned maximum-likelihood fits of both the m_T^W distribution and the BDT discriminant are performed, where the former distribution is used for events with $m_T^W < 50$ GeV and the latter distribution otherwise. The two $t\bar{t}$ CRs are also included in the fits and provide a reduction in the correlation between the estimated background yields as well as improving the control of the $t\bar{t}$ yield. The good agreement between data and MC in the depleted SR ($BDT < 0$ and $m_T^W > 50$ GeV) for both the p_T momentum and $|y|$ of the top quark confirmed the validity of the simulated back-

ground processes. In the enhanced SR ($BDT > 0.6$) whilst there is good agreement for the top quark rapidity, the p_T spectrum is harder than expected (see Fig. 3).

As the analysis is measuring the cross section as functions of parton-level variables, unfolding was formed to infer the parton-level distributions from the reconstructed distributions. Signal yields for the unfolding are estimated from maximum-likelihood fits of both the m_T^W distribution and the BDT discriminant with no selection on the BDT discriminant.

Figure 3: The measured differential cross section of single top t-channel production as a function of p_T (left) and $|y|$ (right). Horizontal ticks on the error bars indicate the statistical uncertainty's contribution to the total uncertainty [11].

No significant deviation was observed between experimental measurements and their associated uncertainties and the theoretical predictions based on NLO+PS generators in both the four flavour and five flavour schemes.

2.3. Fiducial Cross Section

A measurement of the cross section in the fiducial volume of the CMS experiment was made using data collected $\sqrt{s} = 8$ TeV corresponding to an integrated luminosity of 19.7 fb^{-1} [12]. Such a measurement, where the phase space is defined so that it closely matches the event selection criteria and detector acceptance, has the advantage of an easier theoretical interpretation and, consequently, reduced generator systematics.

Either an isolated electron or muon are considered and the suppression of the multijet background is achieved by a cut on $E_T^{\text{miss}} > 45$ GeV or $m_T^W > 50$ GeV for electrons and muons respectively. A constraint on the reconstructed m_{top} is applied, where $130 < m_{top} < 220$.

A binned maximum-likelihood fit to the pseudorapidity of the untagged jet is used to extract the signal yield in the SR. Template distributions for $t\bar{t}$, multijet and W+jet backgrounds are obtained through data-driven methods, whilst other background processes are

estimated from simulation. The methodology about the data-driven background is detailed in [12].

The fiducial cross section extracted from the observable phase space to the fiducial phase space, see Fig. 4.

Figure 4: Fiducial cross section measured with the aMC@NLO generator in the 4FS and the POWHEG generator in the 4FS and 5FS compared to the predictions made by the above generators [12]. The inner and outer error bars correspond to experimental uncertainties and the experimental uncertainties with PDF and scale uncertainties, respectively.

From the fiducial cross section measurement, the inclusive cross section was derived, see Fig. 5.

Figure 5: Inclusive cross section measured with the same generators as the fiducial measurement compared to the theoretical predictions [12]. The inner and outer error bars correspond to experimental uncertainties and the total uncertainty, respectively.

Both the fiducial and derived inclusive cross section measurements are consistent with the SM expectations for all the generators considered.

2.4. Top Quark Mass Measurement

Using data collected at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 19.7 fb^{-1} , a measurement of m_{top} was made using the single top t-channel events [13]. Being an almost statistically independent sample with partially uncorrelated systematics from $t\bar{t}$ which occurs at a lower Q^2 than $t\bar{t}$, the result presented will be useful in contributing to the world average of m_{top} (previously only using $t\bar{t}$ based measurements). Only positively charged muons are considered, due to the charge asymmetry of the p-p initial state, and the $|\eta_{lightjet}| > 2.5$, as light jets in the t-channel are produced in a more forward direction than those from $t\bar{t}$.

After the final selection, it is estimated from the MC simulation that 73% of the top quarks reconstructed are from single top production, and of these, 97% are from t-channel production. The W+jets and $t\bar{t}$ backgrounds were studied using the 2-jets 0-tags and 3-jets 2-tags CRs respectively.

An extended unbinned maximum-likelihood fit to the $m_{\mu\nu b}$ distribution is used to measure m_{top} , with the resultant measurement of $m_{top} = 172.95 \pm 0.77 \text{ (stat)}_{-0.93}^{+0.97} \text{ (syst) GeV}$.

Figure 6: The fitted reconstructed $\mu\nu b$ (i.e. m_{top}) mass for simulation (left) and data (right) [13].

This measurement is in good agreement with the current Tevatron + LHC combination result [14] of $m_{top} = 173.34 \pm 0.27 \text{ (stat)} \pm 0.71 \text{ (syst) GeV}$ which uses $t\bar{t}$ events for the measurement.

3. s-channel

A search for the s-channel was made using data collected at $\sqrt{s} = 7$ and 8 TeV corresponding to 5.1 and 19.7 fb^{-1} respectively [15]. The s-channel, whilst being theoretically well described, is the least dominant single top process at the LHC. Only the leptonic decays of the W boson into an electron ($\sqrt{s} = 8$ TeV) or a muon ($\sqrt{s} = 7$ and 8 TeV), either directly or via an intermediate tau, and the corresponding neutrino, are considered.

Events are selected where there is one isolated lepton, E_T^{miss} from the neutrino from the W boson decay, and

at least two high p_T jets present, with at least one jet being b-tagged. The reconstruction of the top quark is realised from the lepton, the b-jet from the top quark, and the E_T^{miss} and a constraint on the W boson mass. The b-jet which provides the reconstructed top mass closest to the known value of the top mass is used for the top reconstruction. The efficiency of assigning the correct b-jet to the top quark was measured to be 74% for s-channel events and 70% for $t\bar{t}$ events. Varying the top mass by its uncertainty of ± 1.5 GeV was shown to have less than a 1% difference on the association efficiency.

These selected events are categorised by their number of jets and whether they are b-tagged or not. The s-channel enriched 2-jets 2-tags category was used for signal extraction, and the 2-jets 1-tag and 3-jets 2-tags categories used to constrain the t-channel and W+jets backgrounds and the $t\bar{t}$ background respectively.

BDTs were used to separate the enhance signal extraction and the training and choice of input parameters was individually optimised for each channel and centre of mass energy in order to fully take into account the differing background levels. With the exception of multijet backgrounds, MC simulation of the various processes were used for the training and evaluation of the BDTs. Multijet background processes were extracted from a data control sample and constrained through a maximum likelihood fit to the m_T^W and a BDT for $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV analyses respectively.

A binned maximum likelihood fit on the BDT distributions in the three regions was performed to extract the signal in all three categories simultaneously, with the two CRs constraining the dominant backgrounds whilst taking into account all the possible correlations in the systematic uncertainties of all three categories.

The cross sections in the s-channel were measured to be $\sigma(7 \text{ TeV}) = 7.1 \pm 8.1 \text{ (stat + syst) pb}$ and $\sigma(8 \text{ TeV}) = 13.4 \pm 7.3 \text{ (stat + syst) pb}$, with the observed Upper Limit at 7 TeV and 8 TeV being 31.4 pb and 28.8 pb respectively. The observed (expected) significance of the combined measurements at $\sqrt{s} = 7$ TeV and 8 TeV was 2.5 (1.1) standard deviations. These results are consistent with the SM predictions.

4. Rare and New Single Top Searches

The high integrated luminosity and centre-of-mass energy at the LHC provides the opportunity to search for rare SM single top production mechanisms. Such processes provide precision tests of the SM, allowing for the probing of the top-Z, WZ, and other couplings, are sensitive to Flavour Changing Neutral Currents (FCNC) and other BSM couplings and are backgrounds to other

rare processes. A number of searches for such processes have been made using Run-1 data collected by CMS.

4.1. Top quark polarisation

The parity-violating nature of the V-A structure of the electroweak interaction means that only left handed quarks are expected at the Wtb vertex and that top quarks produced via the t-channel are expected to be highly polarised along the direction of the spectator (or “recoil”) quark. As the top quark decays prior to hadronisation, it can be used to probe the structure of the electroweak process by measuring its spin orientation through the angular distributions of its decay products. Alteration of this structure would imply the existence of anomalous couplings and the new physics associated with them.

Using data corresponding to an integrated luminosity of 19.7 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$, a high purity sample of t-channel events was used to measure the differential cross section of the angle between the muon from the top quark decay and the polarisation axis in the top quark’s rest frame, θ_μ^* [16]. The study focussed on the single muon decay channel as leptons have the highest spin-analysing power and the CMS detector has a very high muon identification efficiency.

CRs were used to validate and, where necessary, correct the backgrounds for this measurement. Only the multijets background required a data-driven estimation. BDTs were used to further enhance the separation between signal and background events. Further details regarding the background modelling and the use of BDTs can be found in [16].

The signal was extracted using a simultaneous maximum-likelihood fit to the BDT distribution for the $t\bar{t}$ and W+jets backgrounds in the 2-jets 1-tag region and the 3-jets 2-tags $t\bar{t}$ CR. Inclusion of the $t\bar{t}$ CR in the fit further constrained the respective background process.

From this measurement, the top quark spin asymmetry (A_μ) was extracted using a χ^2 -fit of the unfolded $\cos(\theta_\mu^*)$. The measurement of $A_\mu = 0.26 \pm 0.03 \text{ (stat)} \pm 0.10 \text{ (syst)} = 0.26 \pm 0.11$ is compatible within 2.0 standard deviations of the SM prediction ($A_\mu = 0.44$).

4.2. Single top quarks in association with a Z boson

A search for the associated production of a Z boson with a single top quark (tZq), for both the expected SM and tZ FCNC processes, has been made using data corresponding to an integrated luminosity of 19.7 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$ [17]. This rare process is sensitive to a number of couplings, namely the top-Z, WZ and anomalous couplings.

Figure 7: A comparison of the normalised differential cross section as a function of the unfolded θ_μ^* for top and anti-top quarks and the theoretical predictions [16].

Both SM and FCNC final states involved three high p_T isolated leptons (electrons or muons) with the former requiring 2-jets 1-tag and E_T^{miss} (from the W boson decay) and the latter requiring either 1-jet 1-tag (tZ-FCNC) or at least 2-jets and least 1-tag ($t\bar{t}$ -FCNC). The pair of oppositely charged same flavour leptons with an invariant mass closest to the Z boson mass are assumed to have originated from the Z boson. The third lepton is assumed to have been produced from the W boson decay. Kinematic requirements in the SR are also made on the E_T^{miss} and m_T^W in order to further reject backgrounds, with optimisation being done separately for the SM and FCNC signals. A CR requiring 1 or 2-jets 0-tags is used by both SM and FCNC searches in order to create background enriched region which is used to help estimate the WZ and nonprompt lepton backgrounds.

Both searches used a BDT in order to enhance signal/background separation, with the BDT distributions in the SR being simultaneously fitted with the m_T^W distribution in the CR using a likelihood-based fit.

An event yield compatible with the tZq SM prediction was observed and the corresponding measured being $\sigma(\text{measured}) = 10_{-7}^{+8} \text{ fb}$ ($\sigma(\text{predicted}) = 8_{-0.03}^{+0.59} \text{ fb}$) with a significance of 2.4 standard deviations.

No evidence for FCNC interactions for either single top or $t\bar{t}$ processes was observed. The limits at the 95% Confidence Level (CL) set on the branching ratio of the top quark into a Z boson and up-type quark are $\mathcal{BR}(t \rightarrow Zu) < 0.022\%$ and $\mathcal{BR}(t \rightarrow Zc) < 0.049\%$. These limits are an improvement on the previous ones set by the CMS collaboration by a factor of two.

4.3. Monotops

Multiple BSM theories posit the existence of massive neutrally charged particles that only weakly interact with matter. Such “invisible” particles, can only be inferred by the presence of a large imbalance in transverse momentum. At tree level a monotop system is produced from either the decay of a heavy bosonic resonance or a Flavour Changing process mediated by an invisible boson. A search based on the latter process was made using data recorded at $\sqrt{s} = 8$ TeV for an integrated luminosity of 19.7 fb^{-1} where the top decays into a bottom quark and a hadronically decaying W boson [18].

The event selection requires 3-jets 1-tag, with the jets’ invariant mass $< 250 \text{ GeV}$ and $E_T^{\text{miss}} > 350 \text{ GeV}$. Events containing isolated electrons or muons are rejected. The dominant backgrounds are W+jets and Z+jets and $t\bar{t}$ events. A CR requiring one or two isolated muons is used to provide a data-driven estimate of the V+jets, detailed in [18]. MC simulation is used to estimate the remaining backgrounds.

Figure 8: The 95% expected CL and observed CL limits for a scalar (left) and vector (right) invisible particle as a function of their mass [18].

Using a likelihood based method to extract the signal and backgrounds, no excesses were observed above the background expectation. Lower limits at the 95% CL on the mass for invisible scalar and vector particles were set at 330 GeV and 650 GeV respectively.

5. Conclusion

An overview of the searches and measurements by the CMS experiment from Run-1 of the LHC and the first Run-2 measurements have been discussed. It is expected that the increased luminosity and cross section during Run-2 will benefit s-channel and rare single top searches. All results have shown good agreement with Standard Model, and whilst there has been no observation of any BSM physics, improved limits have been set on anomalous couplings involving single top quarks.

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