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Single Top Quark Production Measurements in CMS

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The CMS experiment has measured the electroweak production of top quark in different singly production modes: t-, tW- and s-channel. Recent results on inclusive and differential cross section measurements of t-channel at 13 TeV and of the fiducial cross section at 8 TeV are shown. The search for single top quark production in s-channel at 7 and 8 TeV as well as the search for associated production of Z boson and single top are presented. All measurements are in agreement with the Standard Model prediction and no sign of new physics is observed.

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1 Introduction

Top quark at the LHC is produced mainly in pairs through the strong interaction, however it can be produced singly via the electroweak interaction. Based on the W boson virtuality, single top production is categorized into t-, tW- and s-channel in the descending order in terms of SM prediction for their cross section. In the SM, the associated production of a Z boson and top quark is expected to happen at a low rate, however, it can be enhanced by BSM effects. In this document, the latest results of single top quark production measurements in the CMS experiment[1] at 7, 8 and 13 TeV center-of-mass energy are reported.

2 Single top t-channel cross section measurement

Single top quark production in the t-channel has the highest predicted cross section amongst the foreseen production mechanisms. In the following, recent measurements on inclusive, differential and fiducial cross section of t-channel are reviewed.

2.1 Inclusive cross section at 13 TeV

The measurement of inclusive t-channel cross section at 13 TeV is performed using 2.3 fb^{-1} data collected in 2015 by CMS[2]. This analysis is performed in the muonic decay channel when the W boson from the top quark decay, further decays to a muon and a neutrino. Therefore, the final state is characterized by the presence of exactly one isolated muon, missing energy, one b jet from the top quark decay, and a light-flavour jet in the forward region. Events that contain exactly one muon candidate with transverse momentum $p_T > 22\text{ GeV}$, pseudorapidity $|\eta| < 2.1$, and relative isolation $I_{rel} < 0.06$ are selected, where I_{rel} is defined as the ratio of transverse energy sum deposited in a cone with a size of $\sqrt{\delta\phi^2 + \delta\eta^2} = 0.4$ around muon direction and its transverse momentum. Events with additional muon or electron candidates are rejected. Reconstructed jets are required to have $p_T > 40\text{ GeV}$ within $|\eta| < 4.7$. Selected jets can be further categorized using a b-tagging discrimination algorithm in order to distinguish jets stemming from the hadronization of a b quark. Events are divided in categories named N-jet(s) M-tag(s) where N and M refer to the jet and b jet multiplicities. The category enriched in t-channel signal events is the 2-jets 1-tag, while the 3-jets 1-tag and 3-jets 2-tags categories are used to constrain the $t\bar{t}$ contribution. In order to reduce the QCD contamination, a cut on transverse mass of reconstructed W boson (m_T) at 50 GeV is applied. The QCD contribution is extracted directly from data by a fit to the whole range of m_T distribution and then extrapolation to $m_T > 50\text{ GeV}$. In this fit, the non-QCD (QCD) template is taken from MC simulation(data with inverse muon relative isolation ($I_{rel} > 0.12$)). After the dedicated event selection, a neural network is trained in the 2-jets 1-tag

sample and afterwards applied on all categories which are further separated by the charge of the muon. To determine the signal cross section, a simultaneous binned likelihood fit is performed on the distributions of the multivariate discriminators. The measured cross sections for the top quark and top anti-quark production are $\sigma_{t\text{-ch},t} = 150 \pm 8(\text{stat.}) \pm 9(\text{exp.}) \pm 18(\text{theo.}) \pm 4(\text{lumi.}) \text{ pb}$ and $\sigma_{t\text{-ch},\bar{t}} = 82 \pm 10(\text{stat.}) \pm 4(\text{exp.}) \pm 11(\text{theo.}) \pm 2(\text{lumi.}) \text{ pb}$, respectively. The top quark to top anti-quark cross section ratio $R_{t\text{-ch}}$ is measured in the fit to be $R_{t\text{-ch.}} = 1.81 \pm 0.18(\text{stat.}) \pm 0.15(\text{syst.})$. The inclusive cross section is used to determine the absolute value of the CKM matrix element $|V_{tb}|$. Assuming $|V_{td}|$ and $|V_{ts}|$ to be much smaller than $|V_{tb}|$, the $|f_{LV}V_{tb}|$ is defined as the square root of the ratio of the measured cross section to the SM prediction. It is measured to be $1.03 \pm 0.07(\text{exp.}) \pm 0.02(\text{theo.})$ where f_{LV} is Wtb anomalous coupling form factor.

2.2 Differential cross section at 13 TeV

A differential cross section measurements of t-channel is performed using 2.3 fb^{-1} collision data at 13 TeV, collected during 2015 by the CMS experiment[3]. Very close event selection to the inclusive measurement is exploited to enhance signal to background ratio. To further discriminate the main backgrounds from the signal events, a Boosted Decision Trees(BDT) is trained in 2-jets 1-tag and applied on all categories (2-jets 1-tag and the 3-jets 1-tag and 3-jets 2-tags). Results are obtained using binned maximum likelihood fits separately in each bin of the measurement. The likelihood is defined by taking the m_T distribution for the events with $m_T < 50 \text{ GeV}$, and the BDT discriminant otherwise. In this analysis, the estimation of QCD backgrounds is performed simultaneously in the final fit as the m_T used in likelihood definition is a powerful handle on the QCD estimation. To achieve the differential cross section as a function of the parton-level single top quark transverse momentum and rapidity (y), an unfolding procedure is applied using the TUNFOLD algorithm [4].

The measured unfolded distributions of the top quark p_T and $|y|$ normalized to the measured inclusive cross section of t-channel, are shown in Figure 1 for data and simulation. The large uncertainty for the first p_T bin is due to low acceptance for signal events and the large sensitivity to the systematic uncertainties.

2.3 Fiducial cross section at 8 TeV

A fiducial cross section measurement of single top in t mode is performed using 19.7 fb^{-1} data collected at 8 TeV [5]. In this analysis leptonic decays of top to an electron or muon are studied. Events with exactly one lepton are selected. Muons (electrons) are required to have $p_T > 26(30) \text{ GeV}$ within $|\eta| < 2.1(2.4)$, and to be isolated with $I_{rel} < 0.12(0.1)$. Jets with $p_T > 40 \text{ GeV}$ and $|\eta| < 4.7$ are selected. Events with two jets where one of them passes the b-tagging criteria are used to

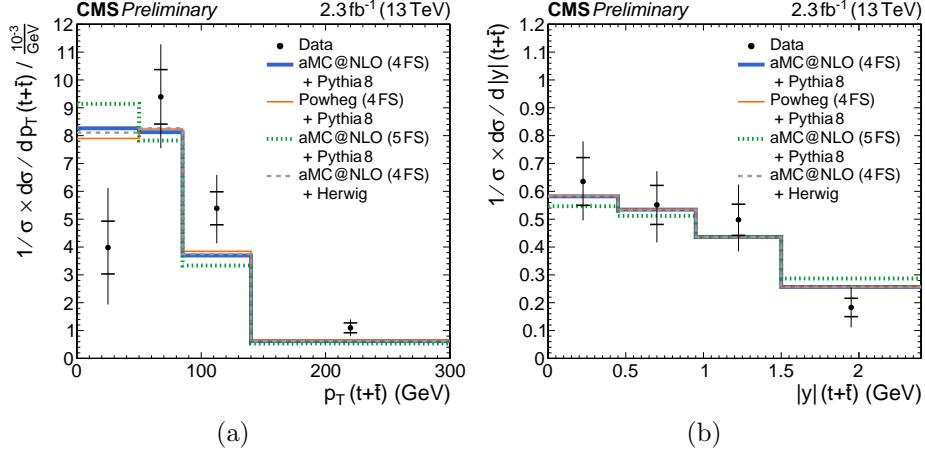


Figure 1: Measured differential cross section of t-channel as a function of the top quark transverse momentum (a) and rapidity(b). The total uncertainty per bin is shown with vertical bar.

extract the cross section. To reject QCD events with no genuine neutrino, a cut on m_T at $50(\cancel{E}_T$ at 45) in muon(electron) channel is applied. The missing energy \cancel{E}_T is defined as the magnitude of the vector sum of all particles momenta in the final state. Finally, the reconstructed top quark mass is required to be $130 < m_t < 220$. In a fiducial measurement, simulated events in 'generator' level are required to lie in the fiducial volume defined in the event selection in 'reconstruction' level. In this analysis, the fiducial volume is defined with exactly one dressed lepton* in $|\eta| < 2.4$ with $p_T > 30 \text{ GeV}$ and two jets with $p_T > 40 \text{ GeV}$, one identified as b jet in presence of a b hadron in $|\eta| < 2.4$ and the other in $|\eta| < 5.0$. The fiducial cross section is measured using number of observed events (N_{obs}):

$$\sigma_{\text{t-ch.}}^{\text{fid}} = \frac{N_{\text{obs}}}{\epsilon^{\text{fid}} \mathcal{L}},$$

where \mathcal{L} is integrated luminosity, $\epsilon^{\text{fid}} = N_{\text{rec}}^{\text{MC}}/N_{\text{fid}}^{\text{MC}}$, $N_{\text{rec}}^{\text{MC}}$ is number of events after full selection and $N_{\text{fid}}^{\text{MC}}$ is number of events in the fiducial phase space. The Fiducial cross section can be translated to total cross section by $\sigma_{\text{t-ch.}} = \sigma_{\text{t-ch.}}^{\text{fid}} / \text{Acc}^{\text{fid}}$ where $\text{Acc}^{\text{fid}} = \sigma_{\text{t-ch.}}^{\text{fid}, \text{MC}} / \sigma_{\text{t-ch.}}^{\text{MC}}$ is the acceptance of the fiducial volume. The measured fiducial and total cross section in presence of experimental and theoretical uncertainties are:

$$\begin{aligned} \sigma_{\text{t-ch.}}^{\text{fid, obs}} &= 3.38 \pm 0.25(\text{exp.}) \pm 0.06(\text{scale}) \pm 0.08(\text{PDF}) \pm 0.17(\text{NLO - subtr.}) \text{ pb}, \\ \sigma_{\text{t-ch.}}^{\text{obs}} &= 87.2 \pm 6.5(\text{exp.})^{+0.2}_{-1.1}(\text{scale}) \pm 1.9(\text{PDF}) \pm 0.7(\text{NLO - subtr.}) \text{ pb}. \end{aligned}$$

*lepton and its associated clustered radiations together

3 Single top s-channel cross section measurement

Despite its very small cross section among single top at the LHC, s-channel is of special interest. Beside validation of SM, it is sensitive to physics beyond the SM, e.g. models predicting W' boson or charged Higgs as mediator can enhance the cross section. A search for s-channel is performed in CMS using collision data corresponding to the integrated luminosities of 5.1 and 19.7 fb^{-1} at centre-of-mass energies of 7 and 8 TeV, respectively [6]. In this measurement, the leptonic decay of top quark is considered; at 7 TeV only muon channel is studied while at 8 TeV both the muon and electron channels are included. Reconstructed muons with $p_T > 20(26)\text{ GeV}$ at 7(8) TeV within the trigger acceptance ($|\eta| < 2.1$) are selected. Muons should be isolated with $I_{rel} < 0.12$ measured in a cone of size $\Delta R = 0.4$. Isolated electrons with $I_{rel} < 0.1$ in a cone of size $\Delta R = 0.3$, with $p_T > 30\text{ GeV}$ in $|\eta| < 2.5$ are selected. Jets within $|\eta| < 4.5$ and $p_T > 40\text{ GeV}$ are considered and a b-tagging algorithm identify the b jets. Three statistically independent event categories are defined: 2-jets 2-tags as the s-channel enriched sample, 2-jets 1-tag category for controlling the t-channel and $W + jets$ backgrounds and 3-jets 2-tags category to constrain $t\bar{t}$ as the dominant background. In 2-jets 2-tags another selection is applied on number of jets with $20 < p_T < 40\text{ GeV}$ to further reject $t\bar{t}$ background. In the 7 TeV analysis, the m_T distribution is used to estimate QCD multijet contribution. But in the 8 TeV analysis, BDT discriminants are used to estimate and reject multijet events. The BDT distribution is used to define a QCD enriched region. Maximum likelihood fits are performed in QCD enriched regions and results are extrapolated outside. The QCD template is taken from data with non-isolated lepton.

For signal extraction, other BDTs are trained per each category in electron and muon channels at 7 and 8 TeV and maximum likelihood fit is employed to measure the cross section. The cross section is measured to be $7.1 \pm 8.1(\text{stat} + \text{syst})\text{pb}$ at 7 TeV and $13.4 \pm 7.3(\text{stat} + \text{syst})\text{pb}$ at 8 TeV, corresponding to a combined signal rate relative to SM expectations of $2.0 \pm 0.9(\text{stat} + \text{syst})$. The combined signal strength is measured with the observed significance of 2.5 standard deviations with 1.1 standard deviations expected. The observed and expected upper limits at 95% CL on the combined signal strength are found to be 4.7 and 3.1.

4 Associated production of Z boson and single Top at 8 TeV

Having high centre-of-mass energy and luminosity at the LHC enhances the chance for observing rare SM or BSM single top quark production processes. A search for the SM production of a single top quark in association with a Z boson is performed at 8 TeV [7]. In this process, the top quark is produced via the t-channel mechanism and

the Z boson is radiated off one of the initial or final state quarks or from the exchange of W bosons. Therefore, considering leptonic decay of top quark and Z boson, the final state consists of a neutrino, one b quark and three leptons and a quark. Each selected event contain exactly three leptons each with $p_T > 20 \text{ GeV}$ and $|\eta| < 2.5(2.4)$ for electrons(muons). The electrons(muons) should be isolated, $I_{rel} < 0.15(0.12)$ measured in cone of size 0.3(0.4). There are four possible leptonic combinations in the final state: $eee, \mu\mu\mu, \mu\mu e$ and $ee\mu$. To fulfil the criteria of Z boson decay, two same flavour leptons are required to have opposite charges and invariant mass around Z mass ($76 < m_{ll} < 106 \text{ GeV}$). In $eee, \mu\mu\mu$ channels, the pair with closest mass to Z peak mass is selected for Z boson reconstruction. The third lepton is used to reconstruct the W boson. Jets with $p_T > 30 \text{ GeV}$ within $|\eta| < 4.5$ are selected. Event is accepted if it contains two or more jets while one or more pass b-tagging criteria. To further reject backgrounds, a cut on m_T is applied at 10 GeV . In addition to signal region defined by the above criteria a control region enriched with DY and WZ processes is defined with the same selection but vetoing events containing b-tagged jet. A BDT is trained in signal sample to separate signal events from background processes. The signal extraction is performed using a simultaneous likelihood fit on distributions of BDT output in the signal region and m_T in the background-enriched control region in four different leptonic final states. Template for backgrounds with non-prompt leptons ($t\bar{t}$ and DY) is taken from non-isolated sample. The combined measured signal cross section is found to be $\sigma_{tZq \rightarrow \ell\nu b\ell q} = 10^{+8}_{-7} \text{ fb}$ which is in agreement with the SM prediction of $8.2^{+0.59}_{-0.03}(\text{scale}) \text{ fb}$. The signal is measured with the observed and expected significances of 2.4 and 1.8, respectively. An upper limit on the tZq cross section is set at 21 fb at the 95% CL.

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