PROCEEDINGS OF SCIENCE

Measurement of single top production in pp collisions at 7 TeV with the CMS detector

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Alberto Orso Maria Iorio, on behalf of the CMS Collaboration[*]
INFN
E-mail: oiorio@cern.ch

We report on the first measurement of the single top $t-$channel production cross section in proton-proton collisions at center of mass energy $\sqrt{s} = 7$ TeV with the Compact Muon Solenoid (CMS) detector at the Large Hadron Collider (LHC), performed with an integrated luminosity of 36 pb^{-1}. Final states where the top decays leptonically through the chains $t \rightarrow Wb \rightarrow l\nu b$ are considered, and the full four momentum of the top quark is reconstructed from its decay products. Two complementary analyses are performed: a robust template fit analysis aiming to be model-independent based on the fit to a two variables distribution, and a multivariate analysis aiming to maximize the sensitivity of the measurement using a boosted decision tree discriminant. The measurements of the two analyses are then combined, and a lower bound on the Cabibbo Kobayashi Maskawa matrix element $|V_{tb}|$is extracted. The measured cross section is 83.6 ± 29.8 pb and it is consistent with the standard model expectations, resulting in a lower bound of $|V_{tb}| > 0.68$ at 95% confidence level.

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[*] Speaker.

1. Introduction

The Standard Model (SM) predicts the production of tops through three electroweak mechanisms in the LHC energy reach, namely the s,t, and tW channels. Those processes are named single top processes as counterpart to the more abundant $t\bar{t}$ pair production which happens mostly through strong interactions. Amongst the three processes the $t-$channel has the highest cross section and has the most striking final state topology. The SM prediction for $t-$channel cross section at NNLO is $64.6\,^{(+2.09)(+1.51)}_{(-0.71)(-1.74)}$ [1]. Figure 1 shows the Feynman diagrams at Leading Order (LO) and Next to Leading Order (NLO) for $t-$channel production. We report on the first evidence of single top $t-$channel production at the LHC obtained with the CMS experiment [2] , resulting in the first measurement of the $t-$channel cross section, as well as in the extraction of a lower limit on $|V_{tb}|$at 95% confidence level with an integrated luminosity of 36 pb^{-1}collected over the 2010 data taking period. The measurement is the result of the combination of two complementary analyses. The first analysis, called "2D", is based on the template maximum likelihood fit on two angular properties of single top, which is meant to be more model-independent. The second analysis, called "BDT" is a multivariate analysis designed to maximize significance, which is based on a boosted decision tree discriminant using the 37 variables that best exploit our knowledge of the SM single top topology. The t-channel events are simulated with Madgraph [3], and a matching procedure based on Ref [4] is applied to reproduce the NLO features of the signal. Several SM background sources which mimic $t-$channel topology are taken into account: s, and tW channels, the $t\bar{t}$ pair production, production of W/Z+jets, the diboson processes (WW, WZ, and ZZ), and multi-jet QCD processes.

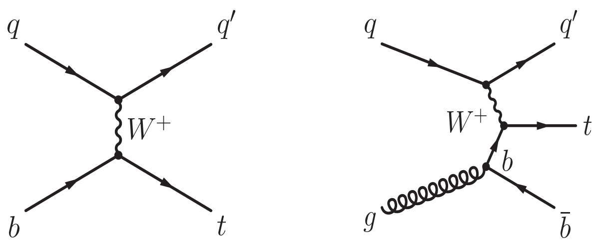

Figure 1: Leading order Feynman diagrams for single top quark production in t channel: $2 \to 2$ (left) and $2 \to 3$ (right).

2. Selection and reconstruction

Only leptonic decay modes $t \to Wb \to l\nu b$ are considered for this measurement. The peculiar single top event topology is exploited to select signal events: $t-$channel events are characterized by a lepton, a jet stemming from the b quark from the top decay, an extra jet from hadronization of the light quark recoiling against the top and missing energy $\not{E}_T$due to the neutrino escaping the detector, which can be inferred assuming kinematic closure in the transverse plane. A top-quark candidate is reconstructed in each event by pairing the b-tagged jet with a W-boson candidate. The latter is reconstructed by imposing the W-boson mass as a kinematic constraint, leading to a quadratic equation in the longitudinal neutrino momentum, $p_{z,\nu}$. When two real solutions are found the smallest $|p_{z,\nu}|$ is taken, and for complex solutions the imaginary component is eliminated by modifying $E_{\mathrm{T,x}}^{\mathrm{miss}}$ and $E_{\mathrm{T,y}}^{\mathrm{miss}}$ independently, such as to give $M_T = M_{\mathrm{W}}$, where M_T is the transverse mass of the W boson defined as $M_T = \sqrt{(p_{T,l}+p_{T,\nu})^2 - (p_{x,l}+p_{x,\nu})^2 - (p_{y,l}+p_{y,\nu})^2}$. We chose events which are triggered from either a muon or electron with a threshold which is optimized as a function of the data taking period. At least one primary vertex is required to be reconstructed from at least 4 tracks, with longitudinal (radial) distance of less than 24 (2) cm from the center of the detector. We reject events with very high energy noise in the CMS Hadronic Calorimeter (HCAL) barrel or endcaps. The 2D analysis adopts the same definitions of the basic physics objects (leptons, jets, $\not{E}_T$, b tagging) as the CMS $t\bar{t} \to \ell + X$ analyses in order to rely on a robust and already validated object selection. The BDT aims to optimize also the selection of the physics objects, therefore applying a more refined reconstruction tool named particle flow [5] : charged particles associated to non-leading primary vertices are removed and muons, electrons, photons are identified in sequence. The remaining particles are clustered into jets. The requirements on the physics objects are the following for the two analyses:

Tight leptons: One isolated μ (e) in the final state is required with transverse momentum $p_T$of 20 GeV/c ($T_T > 30$ GeV) a pseudorapidity $|\eta| < 2.1$ ($|\eta| < 2.5$). An isolation variable I is defined for the 2D as as the sum of the $p_T$of tracks above 1 GeV/c and of the transverse energies of calorimeter deposits above 1 GeV in a cone $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$ around the lepton direction divided by the lepton p_T. For the BDT, I is defined as he sum of the $p_T$of the identified particles in the $\Delta R < 0.3$ cone around the lepton direction divided by the lepton p_T. I< 0.05 (0.10) is required.
Loose leptons vetoes: A veto is applied on events with a second μ (e) with p_T> 10 (15) GeV/c, $|\eta| < 2.5$, $I < 0.20$ and, for the 2D electron channel, on events with a second electron with$p_T >$ 20 GeV/c, $|\eta| < 2.5$, $I < 1.0$, loose quality cuts, and mass of the dielectron pair $m_{ee} > 106$ or $m_{ee} < 76$.
Jets and b-tagging: Two jets with p_T> 30 GeV/c are required. One jet is required to pass a tight threshold on a b-tagging algorithm (track counting) which orders the tracks forming the jet by their impact parameters significance IP/σ_{IP} and takes the third in decreasing order as discriminator.
Analysis-specific: The 2D analysis vetoes events where the second jet passes a loose threshold on a looser version of the track counting algorithm (taking the second track IP/σ_{IP}). BDT, applies a cut on $\Delta\phi(j_1, j_2) < 3.0$ to remove the kinematic region where the two jets are back-to-back, which is found to be poorly reproduced in MC, affecting some of the BDT variables.
M_T **cut:** To further suppress contributions from processes where the muon (electron) does not come from the decay of a W boson, $M_T > 40$ (50) GeV/c^2 is required. The 2D analysis selects 112 (72) events in the muon (electron) decay channel, while the BDT analysis selects 139 (82). A data-driven estimate of the QCD background is obtained performing a template fit the variable M_T, where the QCD templates are extracted from orthogonal control samples obtained inverting the cut on I.

3. Signal extraction and systematics

In the 2D analysis a two-dimensional maximum likelihood fit is performed on two angular variables. The first is the cosine of the angle θ^* between the direction of the outgoing lepton and the spin axis, approximated by the direction of the untagged jet, in the top-quark rest frame [6, 7]. Signal events are distributed as $\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{1}{2}(1 + A\cos\theta^*)$ due to the $V - A$ structure of the electroweak interaction [8]. The other variable is the pseudorapidity of the untagged jet, η_{lj}, interpreted as the light quark jet recoiling against the top, and has the highest discriminating power out of the two. The distributions in $\cos\theta^*_{lj}$ and η_{lj} are shown in Fig. 2 for events passing the 2D selection. The BDT analysis combines a set of 37 observables into one single classifier variable *bdt*. The most discriminant ones are the lepton p_T, the mass of the system formed by the reconstructed W boson and the two jets, the p_T of the system formed by the two jets, the p_T of the b-tagged jet, and the reconstructed top-quark mass. The validity of the description of all the input variables in the simulation has been checked using a Kolmogorov-Smirnov test in a W-enriched control sample with no b-tagged jet, shown in Fig. 3 (left). The signal is extracted using a Bayesian approach where the signal has an uniformly distributed positive prior, the background normalizations and the other systematics uncertainties are treated as nuisance parameters and integrated over to get the signal yield posterior. The distribution of the signal and the backgrounds *bdt* discriminant normalized to the median of the posterior is shown in Fig. 3 (right).

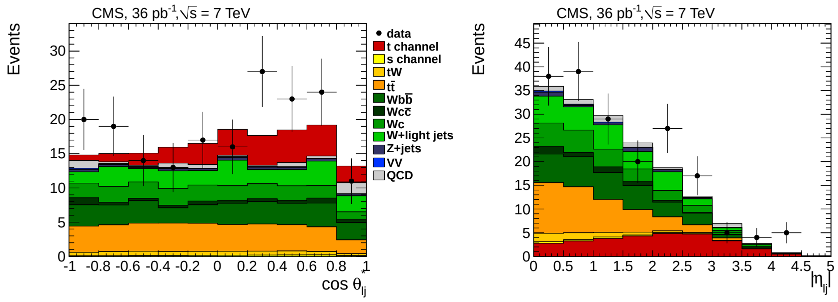

Figure 2: Cosine of the angle between charged lepton and untagged jet ($\cos\theta^*_{lj}$, left panel) and pseudorapidity of the untagged jet (η_{lj}, right panel) after the 2D selection, for both electron and muon decay channels. *QCD* and W + light-partons events are normalized to data, $t\bar{t}$, $VQ\bar{Q}$ (V=W,Z and Q=b,c), and Wc are normalized to the result of a dedicated measurement, all other processes are normalized to theoretical expectations.

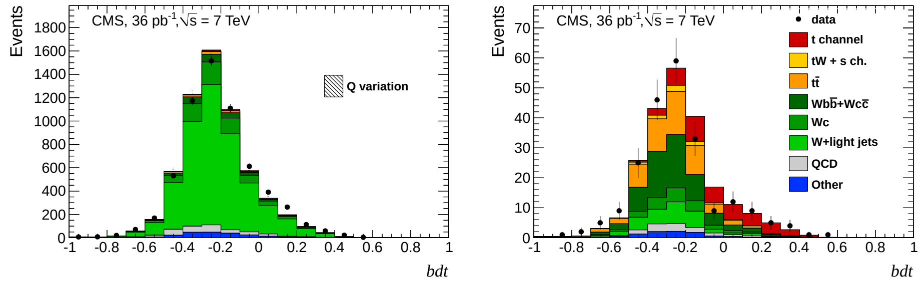

Figure 3: Boosted decision tree discriminant (*bdt*) for both electron and muon decay channels in the W-enriched control sample (left), with simulation normalized to data, also shown for W + jets samples with doubled and halved renormalization and factorization scale (Q). Same observable after the complete BDT selection (right), with signal scaled to the measured cross section and all systematic uncertainties and backgrounds scaled to the medians of their posterior distributions.

Table 1: Cross section measurements by channel and by analysis. The first uncertainty is statistical, the second systematic.

Channel	2D analysis	BDT analysis
μ	$104.1 \pm 42.3^{+24.8}_{-28.0}$ pb	$90.4 \pm 35.1^{+16.5}_{-19.7}$ pb
e	$154.2 \pm 56.0^{+40.6}_{-46.6}$ pb	$59.2 \pm 35.1^{+13.1}_{-13.7}$ pb
$\mu + \mathrm{e}$	$124.2 \pm 33.8^{+30.0}_{-33.9}$ pb	$78.7 \pm 25.4^{+13.2}_{-14.6}$ pb
	combined: 83.6 ± 29.8 pb	

Several sources of systematic uncertainty have been considered:
Common systematics: Jet Energy Scale (JES) and correlated $\not\!\!E_T$variation, b-tagging and mistagging efficiencies, unclustered $\not\!\!E_T$calibration, background rates uncertainty, parton fragmentation model (signal,$t\bar{t}$, W/Z+jets), renormalization scale ($t\bar{t}$, W/Z+jets), final state radiation ($t\bar{t}$). Modeling uncertainties have been evaluated with dedicated samples.
Analysis specific systematics: separate *QCD* fit systematics, data driven template shapes (2D only), different W/Z+ jets normalizations. The impact of each individual source of uncertainty on both analyses has been estimated with an ensemble of pseudoexperiments. The dominant systematic uncertainties on the cross section determination come from the b-tagging efficiency, known within ±15% and the renormalization scale variation.

4. Cross section and V_{tb}

Under the assumption that all uncertainties are Gaussian and symmetric, the 2D and BDT cross section measurements are combined with the BLUE technique [9], with a statistical correlation of 51% estimated with pseudoexperiments, and treating all the systematic uncertainties as fully correlated with the exceptions of those coming from estimates based on data. Table 1 shows the results from each analysis and for the combination.

The significance of the measurement is obtained with the CL_b method, yielding a value of 3.7 (3.5) standard deviations for the 2D (BDT). A measurement of $|V_{\mathrm{tb}}| = \sqrt{\frac{\sigma^{\mathrm{exp}}}{\sigma^{\mathrm{th}}}} = 1.14 \pm 0.22(\mathrm{exp}) \pm 0.02(\mathrm{th})$ is derived under the assumption that $|V_{\mathrm{td}}|$ and $|V_{\mathrm{ts}}|$ are much smaller than $|V_{\mathrm{tb}}|$, where σ^{th} is the SM prediction assuming $|V_{\mathrm{tb}}| = 1$. I Under the further hypothesis that $0 \leq |V_{tb}|^2 \leq 1$, the lower bound of $|V_{tb}|$< 0.62 (0.68) is obtained for 2D (BDT) respectively.

5. Conclusions

We reported on the first measurement of the single top $t-$channel cross section in proton proton collisions at 7 TeV, yielding a cross section of: $\sigma^{\mathrm{exp}} = 83.6 \pm 29.8$ $(\mathrm{stat.} + \mathrm{syst.}) \pm 3.3$ (lumi.) pb with a significance of 3.7 (3.5) standard deviations. From measurement it was possible to infer $|V_{\mathrm{tb}}| = 1.14 \pm 0.22(\mathrm{exp}) \pm 0.02(\mathrm{th})$, and to get and a lower bound of $|V_{tb}|$< 0.62 (0.68) in the assumption $0 \leq |V_{tb}|^2 \leq 1$.

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