Measurement of the single top quark t-channel cross section with a template fit analysis

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Abstract. We present a measurement of the inclusive single top t-channel production cross section in proton-proton collisions at the LHC, using data collected with the CMS experiment during 2011 and 2012. The analyzed data correspond to an integrated luminosity of 1.17/1.56 fb^{-1} for muon/electron channel respectively at the centre-of-mass energy of 7 TeV, and to 5.0 fb^{-1} at 8 TeV. The analysis exploits the pseudorapidity distribution of the recoil jet and reconstructed top-quark mass using background estimates determined from control samples in data. The measurement is used to determine the CKM matrix element $|V_{\rm tb}|$.

1. Introduction

The top quark, the last of the six quarks discovered at the Tevatron proton anti-proton collider in 1995 [1, 2], can be produced via strong interaction in association with the top anti-quark and via electroweak interaction as single top. Among the three different single top production modes, the t-channel, the s-channel and the tW production, the t-channel is the one with higher production cross section at the LHC, $\sigma_{t-\rm ch.}^{\rm th} = 64.6^{+2.1}_{-0.7}{}^{+1.5}_{-1.7}$ pb [3], at a centre-of-mass energy of 7 TeV and for a top-quark mass of $m_{\rm t} = 172.5$ GeV/c^2. For this reason it was the first single top process observed at the LHC and up to now the one which permits the most precise determination of the CKM matrix element $|V_{\rm tb}|$.

In Figure 1 the leading order Feynman diagrams for the t-channel production are shown. The typical signature expected for such events comprises one forward jet recoiling against the heavy top quark and one central b jet coming from top decay. As in the past analysis [4], only the leptonic decays of the W boson are considered, so one isolated charged lepton and missing energy are present as well in the final state. In addition, a second b jet can be present, coming from gluon splitting and characterized by softer transverse momentum spectrum with respect to the central b jet.

In this contribution the cross section measurements using data collected with the CMS detector [5] at a centre-of-mass energy $\sqrt{s} = 7$ TeV and 8 TeV are described: the first and more sophisticated analysis represents the most precise measurement of t-channel cross section and of $|V_{tb}|$ up to now [6], while the second constitutes the first measurement of single top production cross section at 8 TeV [7].

2. Event Selection and Analysis strategy

The most important backgrounds, processes whose final states fake our signal, are the top pair production $t\bar{t}$ in which one top decays hadronically and the other leptonically, W+jets, in
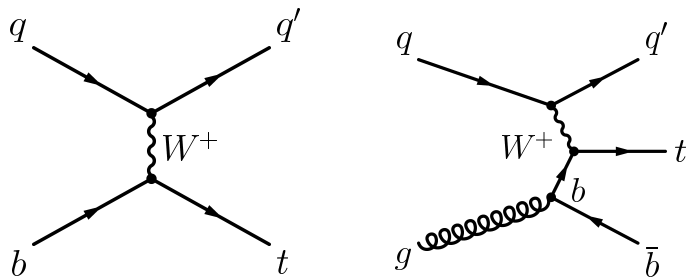
Figure 1. Leading order Feynman diagrams for t-channel single top production in the t-channel: $2 \to 2$ (left) and $2 \to 3$ (right).

particular W+heavy flavoured jets, Z+jets, QCD multijets and minor ones. The event selection is therefore optimized in order to obtain a sub-sample of data enriched in t-channel events, and can be summarized as follows:

- **lepton selection**: exactly one muon or one electron is required to pass tight quality and isolation criteria, and to have a transverse momentum greater than $20\,\mathrm{GeV}/c$ ($26\,\mathrm{GeV}/c$ at $8\,\mathrm{TeV}$) / $30\,\mathrm{GeV}/c$ (muon/electron). This step provides the rejection of most of QCD background;

- **jet selection**: exactly two jets are required to have $p_{\mathrm{T}} > 30\,\mathrm{GeV}/c$ ($> 60\,\mathrm{GeV}/c$ at $8\,\mathrm{TeV}$) for $|\eta| < 4.5$. This allows a tight rejection of W+jets and QCD backgrounds together with $t\bar{t}$ which is characterized by high jet multiplicity;

- **b-tagging**: one and only one jet is required to come from b-quark fragmentation, that is it should pass a tight threshold on the Track Counting High-Purity (TCHP) b-tagging algorithm [8]. This requirement helps reducing W+jets and especially the $t\bar{t}$ background whose final states contain in almost 100% of the cases at least two b jets;

In order to further reduce the QCD multijet background a cut on the W transverse mass $m_{\mathrm{T}} > 40\,\mathrm{GeV}/c^2$ or $50\,\mathrm{GeV}/c^2$ at $8\,\mathrm{TeV}$ (muons), or $\not{E}_{\mathrm{T}} > 35\,\mathrm{GeV}$ (electrons) is applied. Finally a cut is applied on the reconstructed top-quark mass defining a Signal Region (SR) for $130 < m_{\ell\nu b} < 220\,\mathrm{GeV}/c^2$ and a W+jets and $t\bar{t}$ enriched Sideband Region (SB) outside the mass window.

3. Backgrounds estimation and signal extraction procedure

The cross section measurement is performed with a template fit to the characteristic pseudorapidity of the forward jet, $|\eta_{j'}|$, in the Signal Region. Four are the event yield parameters fitted: signal, top category ($t\bar{t}$ + single top s and tW channels), EWK category (W/Z+jets and diboson production) and QCD. The templates used as models for signal and backgrounds are 1-dimensional histograms either from simulation or from data-driven estimations.

It has been observed, in agreement with other measurements [9, 10], that the Wb+X and Wc+X production is mismodeled in Monte Carlo simulations and a slight excess of such events is present in data. To not rely on simulation, **W+jets $|\eta_{j'}|$ template** and yield are taken from data: in the Sideband Region we subtract from data all the processes except for W/Z+jets, and then take what remains as W/Z+jets data-driven estimation. It has been assumed that Z+jets processes scale as W+jets and have similar $|\eta_{j'}|$ shape. Furthermore it has been proven that the shape of $|\eta_{j'}|$ for this background processes does not change significantly from Sideband to Signal Region.

The **QCD template** is taken from a control region obtained inverting the isolation cut on the selected lepton (for electrons failing identification criteria is also requested). Its yield in the Signal Region is obtained for muons (electrons) performing a fit to the W transverse mass ($\not{E}_{\mathrm{T}}$)
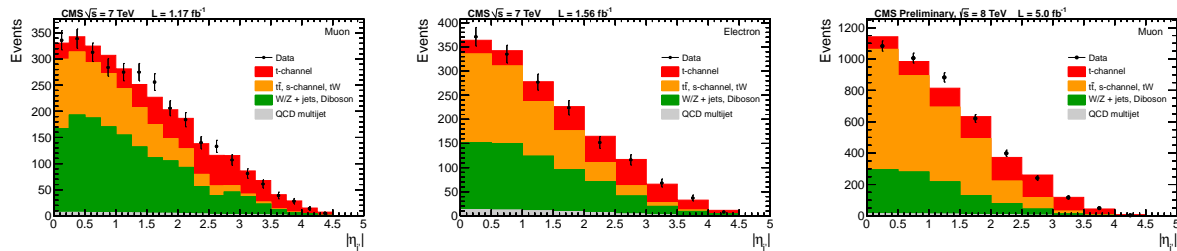
Figure 2. Results of the fit to $|\eta_{j'}|$ for muons and electrons at 7 TeV (left and centre) and for muons only at 8 TeV (right).

distribution and then counting the number of QCD events above the thresholds established in the selection. The QCD yield is considered fixed in the fit to $|\eta_{j'}|$.

Lastly, the $t\bar{t}$ **template** is taken from simulation at 7 TeV and from a control sample on data at 8 TeV (sample obtained selecting 3 jets with two of them passing b-tagging requirements, henceforth '3jets 2tags'). All the other processes are taken from simulation. Figure 2 shows the fit results at 7 and 8 TeV.

4. Systematic uncertainties

The systematic uncertainties of the measurement are determined by use of pseudo-experiments which take into account the effect of the systematic sources on the $|\eta_{j'}|$ distribution and on the event yield of the different processes. For each systematic source the pseudo-experiments are generated with templates varied by $\pm 1\sigma$ of the corresponding uncertainty, and the fit to $|\eta_{j'}|$ is repeated. The mean shift with respect to the nominal measurement is taken as the corresponding systematic error.

The uncertainty related to W+jets and $t\bar{t}$ data-driven estimates has been also evaluated dicing pseudo-experiments in the Sideband Region and in the '3jets 2tags' sample, repeating the extraction procedure and repeating the fit to $|\eta_{j'}|$. The corresponding uncertainty is taken as the root mean square of the distribution of the fit results. It is worth noticing that the procedure adopted for data-driven background estimation, although sensitive to the available statistics in the control regions, nonetheless makes the measurement less dependent on the theoretical uncertainties involving W+jets and $t\bar{t}$ processes.

For the 7 TeV analysis the uncertainties with higher impact on the cross section measurement are: W+jets rate (5.9%), jet energy scale (4.0%), $t\bar{t}$ rate (3.3%) and b-tagging (3.1%). For the 8 TeV analysis they are: jet energy scale (6.8%), signal model (5.5%), muon trigger and reconstruction (5.1%), b-tagging (4.6%).

5. Results and Conclusions

In conclusion the analyses reported the following cross section measurements, analyzing 1.17/1.56 fb^{-1} for muon/electron channel respectively at 7 TeV, and 5.0 fb^{-1} at 8 TeV:

$$\sigma_{t-\mathrm{ch.}} = 70.0 \pm 6.0 \text{ (stat.)} \pm 7.4 \text{ (syst.)} \pm 1.5 \text{ (lum.) pb} \quad (7\,\text{TeV}),$$
$$\sigma_{t-\mathrm{ch.}} = 80.1 \pm 5.7 \text{ (stat.)} \pm 11.0 \text{ (syst.)} \pm 4.0 \text{ (lum.) pb} \quad (8\,\text{TeV}).$$

when the Standard Model expectation is 64.6 pb at 7 TeV and 87.1 pb at 8 TeV [3, 11]. The main differences between the 7 TeV and the 8 TeV analyses are due to the different pileup conditions (increased number of multiple interactions in the same event) and to the increased contribution
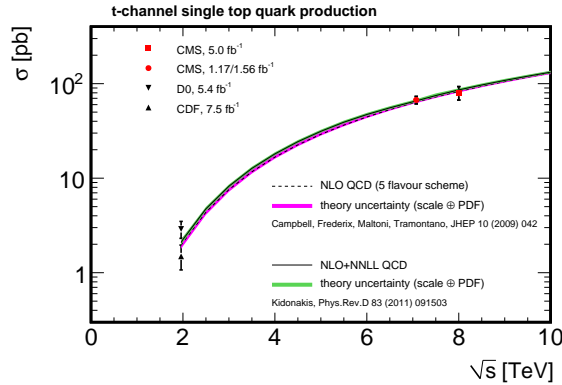
Figure 3. Single top t-channel cross section as function of the centre-of-mass energy. The error band (width of the curve) is obtained by varying the top mass within its current uncertainty [13], estimating the PDF uncertainty according to the HEPDATA recommendations [14], and varying the factorization and renormalization scales coherently by a factor two up and down.

of the $t\bar{t}$ background with respect to W+jets. Moreover, in the 7 TeV analysis both muons and electrons are considered in the final states instead of muons only at 8 TeV.

In addition, the measurement at 7 TeV has been combined using BLUE method [12] with two multivariate analyses (Neural Network and Boosted Decision Trees) measuring the single top t-channel production cross section [6]. The result obtained is:

$$\sigma_{t-\text{ch.}} = 67.2 \pm 6.1 \text{ pb} = 67.2 \pm 3.7 \text{ (stat.)} \pm 4.6 \text{ (syst.)} \pm 1.5 \text{ (lum.) pb}$$

All the results are summarized in Figure 3 where the measurements are compared with the theoretical prediction.

From the cross section a measurement of the CKM element $|V_{\text{tb}}|$ can be obtained. Assuming $|V_{\text{td}}|$ and $|V_{\text{ts}}| << |V_{\text{tb}}|$, and allowing for the presence of a possible anomalous form factor f_{L_V} [15] we have $|f_{L_V} V_{\text{tb}}| = \sqrt{\sigma_{t-\text{ch.}}/\sigma_{t-\text{ch.}}^{\text{th}}}$ and measure

$$|f_{L_V} V_{\text{tb}}| = 1.020 \pm 0.046 \text{ (meas.)} \pm 0.017 \text{ (theor.)} \quad (7\,\text{TeV}),$$
$$= 0.96 \pm 0.08 \text{ (meas.)} \pm 0.02 \text{ (theor.)} \quad (8\,\text{TeV}),$$

where $\sigma_{t-\text{ch.}}^{\text{th}}$ is the SM prediction calculated assuming $|V_{\text{tb}}| = 1$. The 7 TeV result represents the most precise measurement of $|V_{\text{tb}}|$ currently available.

In Figure 4, for the 8 TeV analysis, the verification of two important features characterizing the t-channel production is shown: the first is the charge asymmetry between top quark and anti-quark production (the first is produced with a cross section double compared to the second), the other is the top quark polarisation due to the V-A nature of the couplings. It can be accessed via $\cos\theta^*$ distribution, where θ^* is the angle, in the top quark rest frame, between the charged lepton and the non-b-tagged jet.

References

[1] Abe F *et al.* (CDF Collaboration) 1995 *Phys. Rev. Lett.* **74**(14) 2626–2631
[2] Abachi S *et al.* (D0 Collaboration) 1995 *Phys. Rev. Lett.* **74**(14) 2632–2637
[3] Kidonakis N 2011 *Phys. Rev.* **D 83** 091503 (*Preprint* 1103.2792 [hep-ph])
[4] Chatrchyan S *et al.* (CMS Collaboration) 2011 *Phys. Rev. Lett.* **107** 091802 (*Preprint* 1106.3052 [hep-ex])
[5] Chatrchyan S *et al.* (CMS Collaboration) 2008 *JINST* **03** S08004
[6] Chatrchyan S *et al.* (CMS Collaboration) 2012 *JHEP* **2012**(12)
[7] CMS Collaboration 2012 Measurement of the single-top-quark t-channel cross section in pp collisions at $\sqrt{s}$ = 8 TeV CMS Physics Analysis Summary CMS-PAS-TOP-12-011 URL https://cds.cern.ch/record/1478935
[8] CMS Collaboration 2011 b-jet identification in the CMS experiment CMS Physics Analysis Summary CMS-PAS-BTV-11-004 URL http://cdsweb.cern.ch/record/1427247
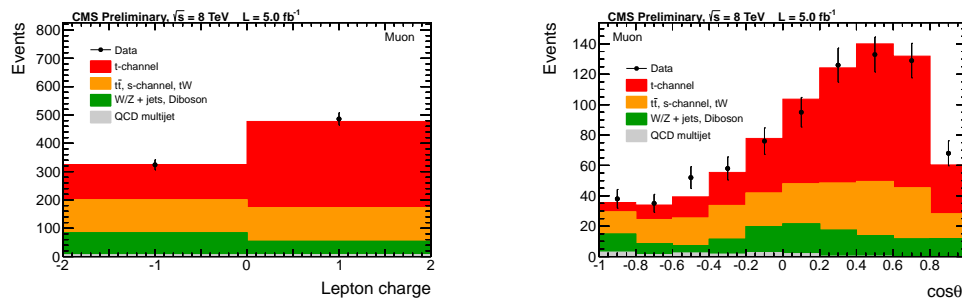
Figure 4. Two characteristic features of the single top t-channel production: charge asymmetry (left) and top quark polarisation (right). Signal and background processes are normalised to the fit results and the cut $|\eta_{j'}| > 2.0$ is applied to highlight the features.

[9] Aad G *et al.* (ATLAS Collaboration) 2012 *Phys.Lett.* **B707** 418–437 (*Preprint* 1109.1470 [hep-ex])

[10] CMS Collaboration 2011 Measurement of associated charm production in W final states at $\sqrt{s} = 7$ TeV CMS Physics Analysis Summary CMS-PAS-EWK-11-013 URL http://cdsweb.cern.ch/record/1369558

[11] Kidonakis N 2012 (*Preprint* 1205.3453 [hep-ph])

[12] Lyons L, Gibaut D and Clifford P 1988 *Nucl. Instr. and Meth. A* **270** 110

[13] Group T E W (CDF and D0 Collaborations) 2009 (*Preprint* 0908.2171 [hep-ex])

[14] Campbell J M, Huston J W and Stirling W J 2007 *Rept. Prog. Phys.* **70** 89 (*Preprint* hep-ph/0611148)

[15] Aguilar-Saavedra J A 2009 *Nucl. Phys. B* **812** 181 (*Preprint* 0811.3842 [hep-ph])