PROCEEDINGS OF SCIENCE

Single-top-quark production with CMS

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Measurements of single-top-quark production are presented, performed using CMS data collected in 2011 and 2012 at centre-of-mass energies of 7 and 8 TeV. The cross sections for the electroweak production of single top-quarks in the t-channel and in association with W-bosons are measured and the results are used to place constraints on the CKM matrix element V_{tb}. In the t-channel the ratio of top-quark and top-anti-quark production cross sections is determined and compared with predictions from different parton density distribution functions. Measurements of top-quark properties in single-top-quark production are also presented. The results include the W-helicity in top-quark decay, top-quark polarisation and the searches for s-channel production.

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1. Introduction

Top quarks can be singly produced in proton-proton (pp) collisions via charged-current electroweak interactions. In the standard model (SM), three mechanisms contribute to single-top-quark production: the *t*-channel, the *s*-channel, and the W-associated, or tW, production. In proton-proton collisions at the Large Hadron Collider the *t*-channel mode is by far the most abundant of the three, while on the other hand the tW production could not be observed before the LHC era. The study of single-top-quark production provides a unique possibility to investigate many aspects of top-quark physics that can not be easily probed top quark and top anti-quark pair production via strong interactions: one can investigate the Wtb vertex structure looking for anomalous couplings [1] and flavour-changing neutral current (FCNC) contributions [2] in the production. Moreover, the production cross sections of all single-top-quark processes are directly related to the modulus squared of the Cabibbo Kobayashi Maskawa matrix element V_{tb}. The Wtb vertex can be studied both in production and in decay by measuring the angular distributions of the top-quark and its decay products, that in the standard model directly stem from the V-A structure of the electroweak interaction. An additional feature of the *t*- and *s*-channels in pp collisions is the difference in the production cross section of top quarks with respect to top anti-quarks due to the different parton distribution functions (PDFs) of the quarks in the initial state. Feynman diagrams for the three single-top-quark processes are shown in Fig. 1.

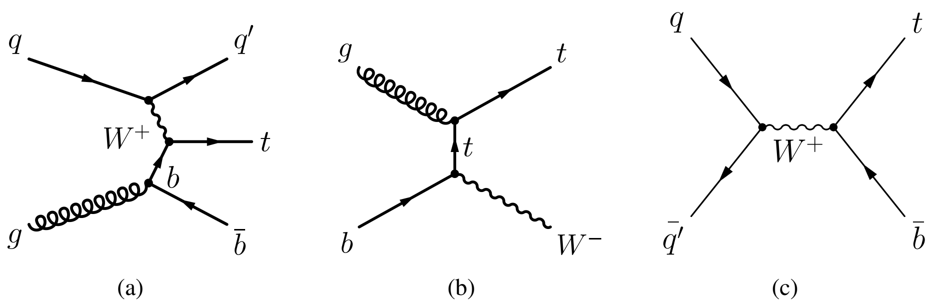


Figure 1: Leading order Feynman diagrams for single-top-quark *t*-channel (a) tW (b), and *s*-channel production.

2. Cross section measurements

2.1 Precision single-top-quark *t*-channel measurements

The *t*-channel is the most abundant of the three single-top-quark production mechanisms at the LHC, as standard model predictions based on approximate next-to-next-to-leading-order (NNLO) from next-to-next-to-leading-logarithm (NNLL) calculations yield an expected total inclusive cross section of $\sigma^{\text{th}}_{t\text{-ch.},\,7\,\text{TeV}} = 64.6^{+2.1}_{-0.7}\,(\text{scale})^{+1.5}_{-1.7}\,(\text{PDF})\,\text{pb}$ at 7 TeV [3], and $\sigma^{\text{th}}_{t\text{-ch.},\,8\,\text{TeV}} = 87.2^{+2.8}_{-1.0}\,(\text{scale})^{+2.0}_{-2.2}\,(\text{PDF})\,\text{pb}$ at 8 TeV [4] where the two contributions to the uncertainty are due to the variation of factorisation and renormalisation scales and to PDFs.

The *t*-channel event signature typically comprises one forward jet scattered off a top quark, and a spectator b-jet from gluon splitting. The decay products of the top quark mainly appear in the central region of the detector. For the 7 TeV CMS measurement [6], a dedicated event selection requiring one lepton, at least two jets, one of which b-tagged, is applied, and then measurements with two complementary approaches are performed. The first approach exploits the reconstructed top-quark mass and the pseudorapidity of the light jet $\eta_{j'}$ recoiling against the top quark. For this analysis the top-quark mass is reconstructed from the top-quark decay products and is required to be inside a window around the nominal the top-quark mass value [7]. A fit to the $|\eta_{j'}|$ distribution is performed on the surviving events. The second approach exploits, via multivariate discriminators, the compatibility of the signal candidates with the event characteristics predicted by the SM for electroweak top-quark production. Panels in Fig. 2 show the distributions of the discriminating

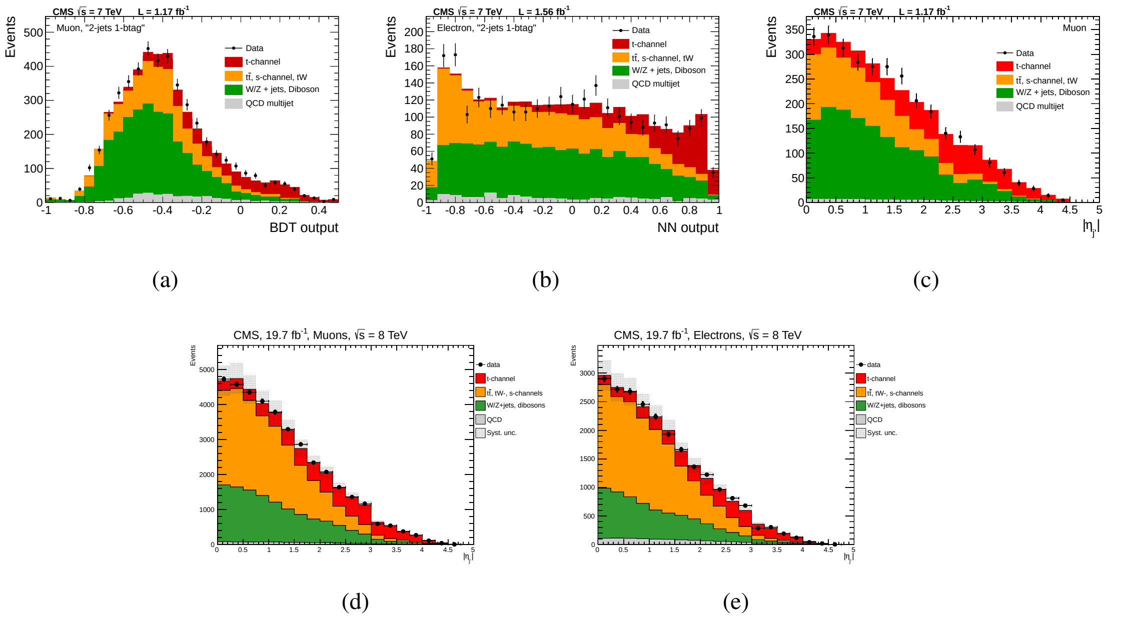


Figure 2: Discriminating variables in a sample with 2-jets, 1 of which b-tagged for the BDT analysis (a), the NN analysis(b), and the $\eta_{j'}$ analysis (c) at 7 TeV, and the $\eta_{j'}$ analysis at 8 TeV (d,e).

variables for each analysis normalised to the result of the signal extraction for 7 and 8 TeV. The three analyses results are combined using the Best Linear Unbiased estimator (BLUE) [8]. The $\eta_{j'}$ analysis is performed on the 8 TeV data as well [9].The measured cross section values for 7 and 8 TeV are:

$$\sigma_{\text{t-ch., 7 TeV}} = 67.2 \pm 3.7\,(\text{stat.}) \pm 4.6(\text{syst.}) \pm 1.5(\text{lumi.}) \qquad (\text{ 7 TeV}). \tag{2.1}$$

$$\sigma_{\text{t-ch., 8 TeV}} = 83.6 \pm 2.3\,(\text{stat.}) \pm 7.1(\text{syst.}) \pm 2.2(\text{lumi.}) \qquad (\text{ 8 TeV}). \tag{2.2}$$

Both these measurements are in good agreement with the standard model predictions. It is also possible to interpret these results in terms of V_{tb}: under the assumption that $|\text{V}_{\text{td}}|, |\text{V}_{\text{ts}}| << |\text{V}_{\text{tb}}|$, it yields $|\text{V}_{\text{tb}}| = \sqrt{\sigma_{meas.}/\sigma_{theory}}$. Combining V_{tb} derived from the two measurements yields:

$$|\text{V}_{\text{tb}}| = 0.998 \pm 0.038\,(\text{meas.}) \pm 0.016(\text{th.}) \qquad (\text{ 7+8 TeV}). \tag{2.3}$$

Assuming $|\text{V}_{\text{tb}}| < 1$ one thus can retrieve a lower limit using the Feldman-Cousins [10] approach:

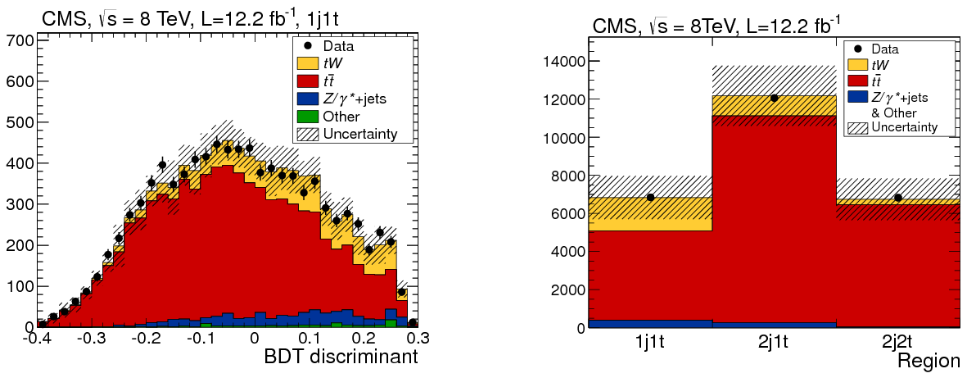
$$0.92 < |\text{V}_{\text{tb}}| < 1 \,@\, 95\%\,\text{confidence level} \qquad (\text{ 7+8 TeV}). \tag{2.4}$$

Finally, it is possible also to extract a ratio between 8 and 7 TeV cross sections, $R_{8/7}$. The measurement yields $R_{8/7} = 1.24 \pm 0.08\,(\text{stat.})\ \pm 0.12(\text{syst.})$. In the ratio part of the uncertainties are reduced or cancel out in the two measurements, thus potentially revealing other deviations from the standard model behavior.

2.2 The tW observation

Single-top-quarks can be produced in association with a W boson in both proton-proton and proton-antiproton collisions, however tW production at the LHC has a cross section much larger than the one at Tevatron [4]. The top-quark and the W-boson can both decay through either leptonic or hadronic chains, where the cleanest signature is provided by the so-called dileptonic channel, i.e. where both decay leptonically.

A measurement at $\sqrt{s} = 8$ TeV was performed on a dataset corresponding to 12.2 fb^{-1}, exploiting a selection with exactly 1 b-jet and two leptons in the final state, and relying on the fit to the distribution of a multivariate discriminant, built with the boosted decision tree technique, to discriminate between the signal and its backgrounds. Control samples with 2 jets and 1-2 b-tags are used to control the $t\bar{t}$ background. Fig. 3 shows the fitted distribution of the multivariate discriminant and the contribution of signal and backgrounds to the jet multiplicity bins considered in the analysis.



(a) (b)

Figure 3: Distribution of the fitted boosted decision tree discriminant in the signal-enriched sample (a), and of the number of events in the tW-enriched region vs control regions (b).

The fit establishes an excess of events compatible with a tW signal above a large background, mostly consisting of $t\bar{t}$ events, with a significance of 6.1 standard deviations (5.4 ± 1.4 being the expected significance). The measured cross section is 23.4 ± 5.4 pb, compatible with the predicted cross section of $\sigma^{\text{th}}_{\text{tW, 8 TeV}} = 22.2 \pm 0.6\ (\text{scale}) \pm 1.4\ (\text{PDF})$ pb.

2.3 The *s*-channel search

The *s*-channel single-top-quark production mode has the smallest cross section of all three in proton-proton collisions, with a predicted value of $\sigma^{\text{th}}_{s\text{-ch. 8 TeV}} = 5.55 \pm 0.08\ (\text{scale}) \pm 0.21\ (\text{PDF})$ pb at $\sqrt{s} = 8$ TeV, however it provides a complementary search avenue for deviations from the standard model with respect to other single-top-quark processes. The standard model *s*-channel topology composes of the decay products of the top quark and a recoiling b-jet.

An analysis selecting events with 2 b-tagged jets and a lepton is performed on the full $\sqrt{s} =$ 8 TeV dataset, performing a profile likelihood fit to a multivariate discriminant built to separate the *s*-channel events from its backgrounds, mainly $t\bar{t}$, multijet QCD and W bosons produced in association with jets. A limit to the *s*-channel production cross section is extracted, measuring $\sigma_{s\text{-ch.,8TeV}} < 11.4(17.0, 9.0)$ pb at 95% confidence level, and yielding a measured cross section of $6.2^{+8.0}_{-5.1}$ pb, obtained evaluating the 68% CL interval with the Feldman-Cousins [10] approach in the presence of a physical boundary of a non-negative *s*-channel cross section.

3. Properties measurements in the *t*-channel

3.1 Probing the Wtb vertex structure: W-helicity fractions and top-quark polarisation

All single-top-quark processes feature a Wtb vertex both in the production and in the decay of the top-quark. In the standard model the top-quark is produced with a well defined polarisation due to the V-A nature of the interaction. For the same reason, a precise mixing of the fraction of left (F_L), right (F_L), and longitudinally polarised (F_0) W-bosons from top-quark decay is predicted in the SM. Precise measurements of the top-quark polarisation and of the W-helicity fractions allow to spot eventual deviaitons due to anomalous couplings in the Wtb vertex which would modify the $V-A$ nature of the standard model coupling.

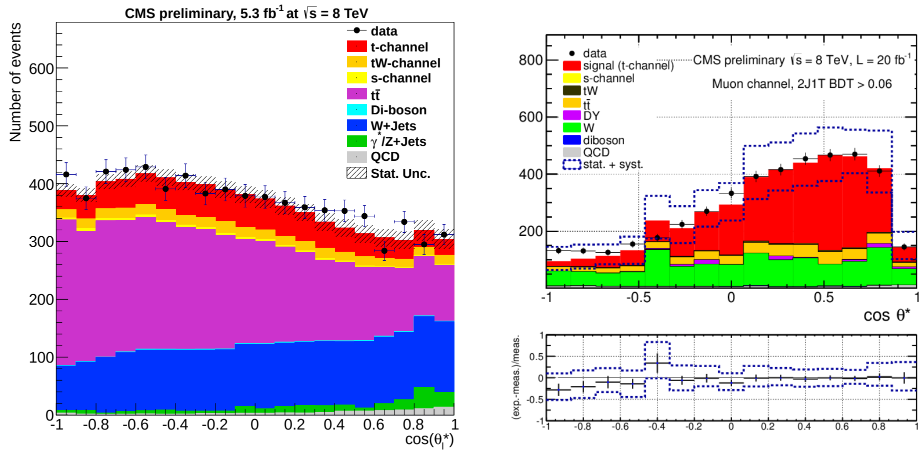
The variable $\cos(\theta_l^*)$ is defined in the top-quark rest frame as the cosinus of the angle between the lepton 3-momentum in the W-boson rest-frame and the 3-momentum of W-boson, and its distribution is a function of the polarisation fractions. The cosinus of the angle between the lepton from top-quark deacy and the recoil jet $\cos(\theta^*)$ depends on the top-quark polarisation. A measurement the W-helicity fractions is performed by CMS on 7 and 8 TeV data [11]. After applying the same selection as for the cross section measurements in Sec. 2, a fit to the $\cos(\theta_l^*)$ distribution is performed on both 7 and 8 TeV data. In addition, a measurement of the top-quark polarisation is performed using the full 8 TeV dataset [12]. Fig. 4(a) shows the distribution of $\cos(\theta_l^*)$ after the fit on the 8 TeV data. Fig. 4(b) shows the distribution of $\cos(\theta^*)$ with $\sqrt{s} = 8$ TeV TeV data.

The resulting values obtained from the combination of the 7+8 TeV fit are $F_L = 0.293 \pm 0.069\,(\text{stat.}) \pm 0.030\,(\text{syst.})$, $F_R = -0.06 \pm 0.057\,(\text{stat.}) \pm 0.027\,(\text{syst.})$, and $F_0 = 0.713 \pm 0.114\,(\text{stat.}) \pm 0.023\,(\text{syst.})$. The polarisation of the top quark can be derived from the top-quark spin asymmetry information that is contained in the $\cos(\theta_l^*)$ unfolded distribution, and yields $P_t = 0.82 \pm 0.12(stat) \pm 0.32(syst)$

These measurements can be used to extract direct limits on anomalous tensor terms in the couplings at the Wtb vertex as well.

3.2 The top-quark charge ratio

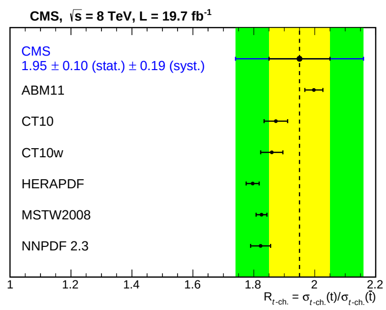
A measurement of the ratio between the production cross sections for single top quark and top anti-quark in the *t*-channel, R_{charge}, can provide a constraint on PDF modeling. R_{charge} is also directly sensitive to physics beyond SM manifested as anomalous couplings in the Wtb vertex,



(a) (b)

Figure 4: Distribution of $\cos(\theta_l^*)$ obtained from the fit (a), results of the fit plus in the $F_R - F_0$ plane versus the standard model prediction (b), and limit on left and right tensor coupling extracted from the W-helicity fractions measurement (c).

or to possible contributions from Flavour Changing Neutral Current processes. The cross section measurement reported in Sec. 2 for 8 TeV has been repeated for events with positively and negatively charged leptons [9], obtaining the following result for the cross sections for top-quark and top-anti-quark production and the respective ratio R_{charge}:



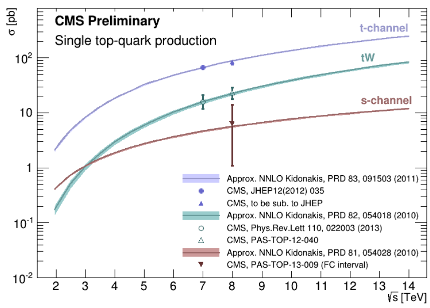
(a)

Figure 5: Ratio of top-quark over top-anti-quark production cross sections in the t-channel compared to predictions from different PDFs.

$$\sigma_{\text{t-ch., t, 8 TeV}} = 49.9 \pm 1.9\,(\text{stat.}) \pm 8.9(\text{syst.} + \text{lumi})\,\text{pb}. \tag{3.1}$$

$$\sigma_{\text{t-ch.}, \bar{t}, \text{ 8 TeV}} = 28.8 \pm 2.4\,(\text{stat.}) \pm 4.9(\text{syst.} + \text{lumi})\,\text{pb} \tag{3.2}$$

$$R_{\text{charge}} = 1.76 \pm 0.15\,(\text{stat.}) \pm 0.022(\text{syst.}). \tag{3.3}$$



(a)

Figure 6: Overview of the single-top-quark processes measured cross sections.

4. Conclusions

The measurements performed by CMS of the three single-top-quark processes and of the t-channel event properties were presented. The t-channel cross section measurements 7 and 8 TeV centre-of-mass energies, both with a relative uncertainty smaller than 10%, were reported, as well as the first observation of the tW process at $\sqrt{s} = 8$ TeV, and the observed limits on the standard model s-channel production. The measured cross sections are shown in Fig. 6. The measurements of top-quark polarisation, W-helicity and of the ratio of top-quark over top-anti-quark production cross sections in the t-channel the were reported. All these measurement are in good agreement with the standard model predictions.

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