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Measurements of single top quark cross sections in pp collisions at 8 TeV with the CMS detector

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Abstract

Measurements are presented of the single top quark production in proton-proton collisions at the LHC at a centre-of-mass energy of 8 TeV, using data collected with the CMS experiment during 2012. The first analysis, in the t-channel single top production mode, considers decay channels where the W comes from the top decays into electron-neutrino or muon-neutrino. It makes use of a template fit exploiting the pseudorapidity distribution of the recoil jet and the reconstructed top quark mass, using background estimates determined from control samples in data. The measurement of top/antitop cross section ratio is also presented.

The second analysis, measuring the associated production cross section of single top quark and W boson, considers final states in which the associated W boson, as well as the one originating from the top quark, decay leptonically. Multivariate methods are used to separate the signal from the topologically similar top pair production background. Multivariate techniques are also adopted in the search for *s*-channel single top quark production finally reported, in order to discriminate the very small signal from the huge background processes.

Keywords: single top, CMS, cross section

1. Introduction

The top quark, 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. Three are the different single top production modes, the *t* channel, the *s* channel and the tW production. In Figure 1 the Feynman diagrams for the three processes are shown. In addition to testing the SM prediction at the electroweak scale, the single top production allows to probe directly the Wtb vertex, potentially detecting non-SM couplings (*t* and tW channels) and is sensitive to models of new physics involving non-SM mediators (*s* channel).

In this contribution the precision measurement of the *t*-channel inclusive cross section and top over anti-top production charge ratio, the first observation of the tW associated production and the search for the *s*-channel single top production are presented.

2. Single top production in the *t* channel

The *t* channel is the single top production mode with the highest cross section at the LHC, $\sigma^{\mathrm{th}}_{t\mathrm{-ch.}} = 87.2^{+2.8}_{-1.0}(\mathrm{scale})\,^{+2.0}_{-2.2}(\mathrm{PDF})$ pb [3, 4] at a centre-of-mass energy of 8 TeV, and which presents the most clear final state topology. For this reason it was the first single top process observed and up to now the one which permits the most precise determination of the CKM matrix element $|V_{\mathrm{tb}}|$. Besides, the top over anti-top charge ratio provides a useful information on the PDFs inside the protons.

In this contribution the cross section and the charge ratio measurements using data collected with the CMS detector [5] at a centre-of-mass energy $\sqrt{s}$=8 TeV, corresponding to 19.7 fb^{-1} are described [6]. The typical signature expected comprises one forward jet recoiling against the heavy top quark and one central b jet coming from top decay. Only the leptonic decays of the

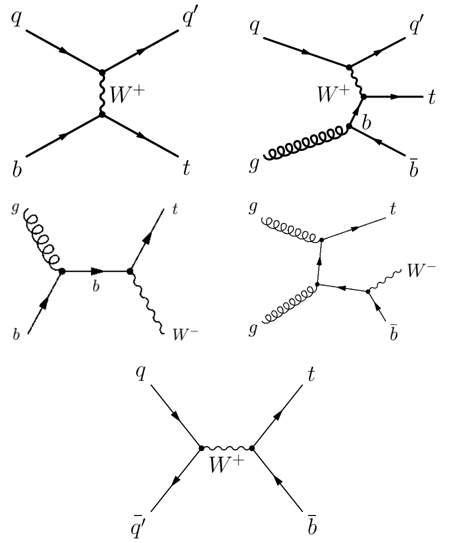

Figure 1: Leading order (LO) Feynman diagrams in the five- (left) and four-flavour (right) schemes for single top production in the t-channel (top) in the tW channel (middle) and in the s-channel (bottom).

W boson are considered, so one isolated charged lepton and missing energy ($\not{E}_{\mathrm{T}}$ is its transverse component) are present as well in the final state. The most important backgrounds, processes whose final states fake our signal, are the top pair production $\mathrm{t\bar{t}}$, W+jets, in particular W+heavy flavoured jets, Z+jets, QCD multijets.

The event selection considers exactly one muon or one electron passing tight quality and isolation criteria, and with a transverse momentum greater than 26 GeV/c / 30 GeV/c (muon / electron). Exactly two jets, reconstructed by clustering particle flow candidates [7] using the anti-k_T algorithm [8], are required to have $p_{\mathrm{T}} >$ 40 GeV/c for $|\eta| < 4.5$, one of which is required to come from b-quark fragmentation. It should pass a tight threshold on the track counting high-purity (TCHP) b-tagging algorithm [9]. These cuts allow a tight rejection of W+jets and multijet QCD backgrounds together with $\mathrm{t\bar{t}}$ which is characterised by high jet multiplicity and presents in almost 100% of the cases at least two b jets in the final state. In order to further reduce the QCD background a cut on the W transverse mass $m_{\mathrm{T}} > 50\,\mathrm{GeV}/c^2$ (muons), or $\not{E}_{\mathrm{T}} > 45$ 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 $\mathrm{t\bar{t}}$ enriched Sideband Region (SB) outside the mass window.

The inclusive 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 ($\mathrm{t\bar{t}}$ + single top s and tW channels), EWK category (W/Z+jets and diboson production) and QCD. For the charge ratio measurement the Signal Region is divided into positively and negatively charged leptons and the two regions are simultaneously fitted (the EWK and signal components are fitted separately). The templates used as models for signal and backgrounds are 1-dimensional histograms either from simulation or from data-driven estimations.

In order to reduce the theoretical uncertainties affecting the W+jets processes, **W/Z+jets $|\eta_{j'}|$ template** and central yield are taken from data: in the Sideband Region subtract from data all the processes except for W/Z+jets, and then take what remains as W/Z+jets data-driven estimation.

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 ($\not{E}_{\mathrm{T}}$) 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 $\mathrm{t\bar{t}}$ **template** is taken from a control sample on data obtained selecting 3 jets with two of them passing b-tagging requirements (henceforth $3j2t$). All the other processes are taken from simulation.

The systematic uncertainties of the measurement (divided into 'instrumental' as jet energy scale and resolution, b-tagging efficiencies, etc., and 'theory' ones, as signal generator, background models and normalisation, renormalisation and factorisation scales, PDFs, etc.) 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/Z+jets and $\mathrm{t\bar{t}}$ data-driven estimates has been also evaluated dicing pseudo-experiments in the Sideband Region and in the $3j2t$ 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.

The uncertainties with highest impact on the inclusive cross section measurement are: signal modelling (5.7%), jet energy scale, resolution, $\not{E}_T$ and pileup (4.3%), statistics (2.7%); while the ones with highest impact on the charge ratio measurement are: PDF uncertainty (6.2%), signal model (6.1%), statistics (5.1%).

In conclusion the analysis reported the following cross section and charge ratio measurements:

$$\sigma_{t\text{-ch.}} = 83.6 \pm 2.3\ (\text{stat.}) \pm 7.4\ (\text{syst.})\ \text{pb}$$
$$R_{t\text{-ch.}} = \sigma_{t\text{-ch.}}(t)/\sigma_{t\text{-ch.}}(\bar{t}) =$$
$$= 1.95 \pm 0.10\ (\text{stat.}) \pm 0.19\ (\text{syst.}).$$

when the Standard Model expectation for the ratio is 1.84 [4]. Figure 2 shows the fit results.

From the cross section a measurement of the CKM element $|V_{tb}|$ can be obtained. Assuming $|V_{td}|$ and $|V_{ts}| << |V_{tb}|$, and allowing for the presence of a possible anomalous form factor f_{L_V} [10] we have $|f_{L_V} V_{tb}| = \sqrt{\sigma_{t\text{-ch.}}/\sigma^{th}_{t\text{-ch.}}}$ and measure

$$|f_{L_V} V_{tb}| = 0.979 \pm 0.045\ (\text{exp.}) \pm 0.016\ (\text{theo.}) \quad (8\ \text{TeV}),$$
$$= 0.998 \pm 0.038\ (\text{exp.}) \pm 0.016\ (\text{theo.}) \quad (7{+}8\ \text{TeV}),$$

where $\sigma^{th}_{t\text{-ch.}}$ is the SM prediction calculated assuming $|V_{tb}| = 1$, and the 7+8 TeV result is obtained combining with BLUE [11] the results of the present analysis and the ones of the previous measurement [12].

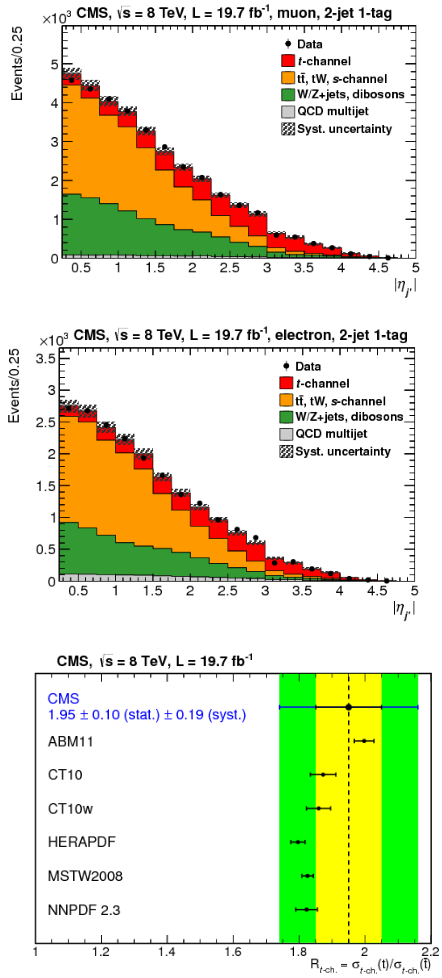

Figure 2: Results of the fit to $|\eta_{j'}|$ for muons and electrons, and the measured top anti-top charge ratio compared to the prediction obtained with several PDF sets.

3. Single top production in association with W boson

The first observation within CMS of tW production analysing data corresponding to an integrated luminosity of 12.2 fb^{-1} collected at a centre-of-mass energy of 8 TeV is described [13]. The theoretical prediction for the production cross section of this process is $\sigma^{th}_{tW\text{-ch.}} = 22.2 \pm 0.6(\text{scale}) \pm 1.4(\text{PDF})$ pb [14]. Since at the NLO the definition of tW production mixes with top quark pair production, the 'diagram removal' scheme, in which all doubly resonant NLO tW diagrams are removed, has been adopted to define the signal.

The analysis considers the dilepton decay channels, so the final state is composed of two oppositely charged muons or electrons, a b-jet and two neutrinos. The primary background comes from $t\bar{t}$ production and $Z/\gamma^\star$ events. Electrons and muons are required to have $p_T >$ 20 GeV/c and $|\eta| < 2.5$ (electrons), < 2.4 (muons) and the dilepton invariant mass, m_{ll}, is required to be greater than 20 GeV/c^2. In addition, for same flavour leptons events are rejected if $81 < m_{ll} < 101$ GeV/c^2 and $\not{E}_T < 50$ GeV. Selected jets must be within $|\eta| < 2.4$ and have $p_T > 30$ GeV/c. Jets coming from hadronization of b quarks are tagged based on the Combined Secondary Vertex algorithm [15]. The signal region is identified requiring exactly 1 jet being b tagged ($1j1t$), while two control regions enriched in $t\bar{t}$ background are defined as well, as $2j1t$ and $2j2t$.

The analysis makes use of a multivariate technique, based on boosted decision trees (BDT) [16], in order to distinguish the tW signal from the dominant $t\bar{t}$ background. The BDT analyzer is trained using 13 variables among which the ones related to the loose jets (jets with loose p_T and $|\eta|$ requirements) have the highest discrim-

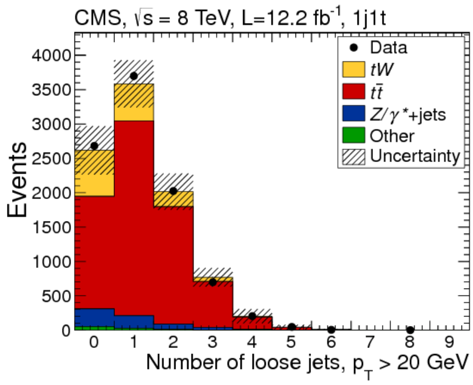

Figure 3: Number of loose jets in the event in the signal region for all final states combined.

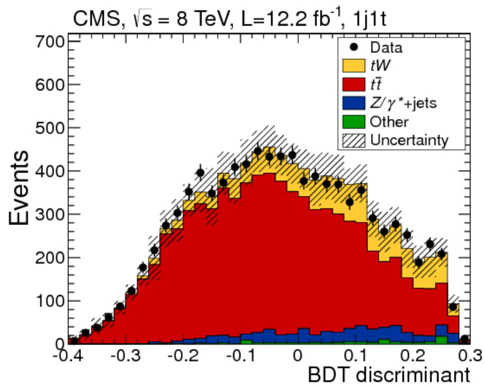

Figure 4: BDT discriminant in the signal region for all final states combined.

ination power (see Figure 3).

The signal extraction is performed with a simultaneous binned likelihood fit of the BDT discriminant in the three regions, where the signal and backgrounds distributions are taken from simulation and their rates are allowed to vary in the fit, constrained in the likelihood function by the systematic uncertainties (affecting both normalisation and shape of the BDT discriminant).

The analysis measures a cross section of 23.4 ± 5.4 pb, where the main contributions to the uncertainty come from the choice of the thresholds for the matrix element and parton showering matching in simulation of $t\bar{t}$ production (14%) and the renormalisation and factorisation scales (12%). The significance of the events is found to be 6.1σ away from the background-only hypothesis corresponding to a p value of 5×10^{-10}.

In Figure 4 the BDT discriminant distribution in the signal region normalised to the fit results is shown.

The cross section measurement is used to determine the absolute value of the CKM matrix, $|V_{\rm tb}|$, as in the t-channel analysis. Under the same assumptions described above the measurement leads to $|V_{\rm tb}| = 1.03 \pm 0.12$ (exp.) ± 0.04 (th.).

Furthermore, to test the robustness and stability of the present result, two cross-check analyses are performed as well. The first one involves a single variable fit rather than the BDT discriminant while the second is based only on event counts after selection. Both analyses measure a cross section in agreement with the BDT analysis, but with larger uncertainties.

4. Search for single top production in the s channel

The single top production in the s channel at the LHC is unfavoured with respect to the other two production modes, involving a quark and an anti-quark in the initial state. The SM prediction at NNLL order for this process at the LHC and at 8 TeV is $\sigma^{\rm th}_{s\text{-ch.}} = 5.55 \pm 0.08(\text{scale}) \pm 0.21(\text{PDF})$ pb [3]. Nonetheless the interest in this channel is focused on possible enhancement of its production due to new physics involving non-SM mediators, like W′ or charged Higgs boson [17]. The study presented here [18] analyses 19.3 fb^{-1} of data collected by CMS in 2012 at a centre-of-mass energy $\sqrt{s}$=8 TeV.

The final state topology is characterized by the presence of one muon or electron and two b quarks, one coming from the top-quark decay and one recoiling against the top quark. The event selection considers exactly one isolated muon or one electron with $p_{\rm T} > 26\,{\rm GeV}/c$, $|\eta| < 2.1$ and $p_{\rm T} > 30\,{\rm GeV}/c$, $|\eta| < 2.5$, respectively. Exactly two jets are required to have $p_{\rm T} > 40\,{\rm GeV}/c$ for $|\eta| < 4.5$ and events with additional jets with $p_{\rm T} > 30\,{\rm GeV}/c$ are rejected. The two selected jets are also required to be originated from b quarks, adopting the track counting algorithm with high purity requirement. Due to the ambiguity in the reconstruction of the top quark hypothesis from b jet, lepton and $\not\!\!E_{\rm T}$, two top mass hypotheses are defined and the correct b jet-to-top assignment is taken based on the one which gives the closer invariant top mass to the value 172.5 GeV/c^2.

At the end the signal sample is still dominated by the backgrounds, mainly $t\bar{t}$, W+jets and t channel single top, and so a multivariate analysis using BDT is performed in order to take advantage of the different final state topology of the signal and the backgrounds. Two independent BDT trainings are set up in the signal region (2j2t) and in a $t\bar{t}$ enriched region (3j2t), optimised for electron and muon decay channels. Among the kinematic and angular variables considered, the ones with

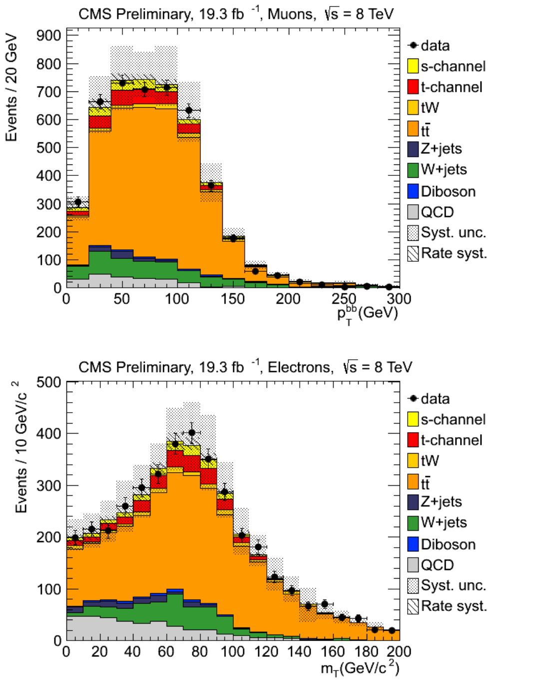

Figure 5: Two of the most discriminating variables used in the BDT for separating signal and backgrounds: vector sum of p_T of the two b-jets system (up) and the W boson transverse mass (bottom).

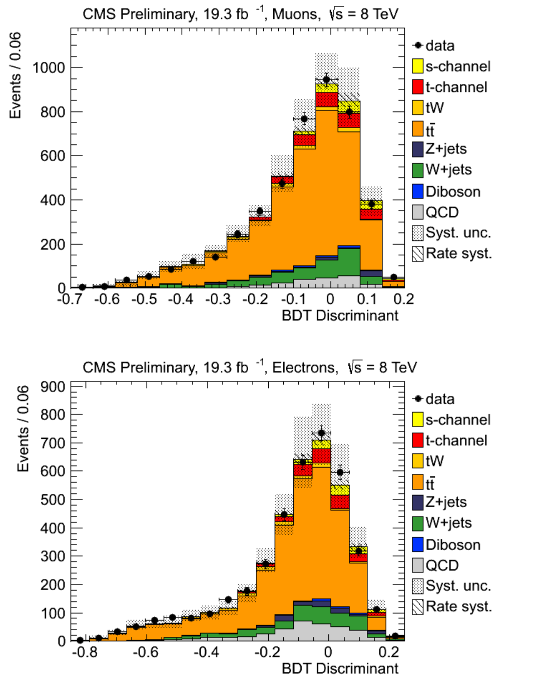

Figure 6: BDT discriminant for the muon (up) and electron (bottom) channels. The simulation is normalised to the fit results.

the highest discriminating power are the vector sum of p_T of the two b-jets system and the W boson transverse mass (Figure 5). For the first variable the signal shows a lower p_T distribution with respect to $t\bar{t}$ since the two b jets carry a larger fraction of the original transverse momentum, peaking around zero. The W transverse mass, reconstructed from the lepton and the $\not\!\!E_T$, shows a clear jacobian peak for lepton-neutrino pairs coming from the same W-boson decay (signal), while presents a broader distribution for events where two W bosons are produced ($t\bar{t}$).

The signal extraction consists in a binned maximum likelihood fit to the BDT distributions on data in the $2j2t$ and $3j2t$ categories simultaneously (Figure 6). The inclusion of the $3j2t$ category allows to constrain the $t\bar{t}$ and W+jets backgrounds while taking into account all possible correlations in the systematics uncertainties between the two regions. The signal and all the background models are taken from simulation except for the multijet QCD background, for which a dedicated treatment has been adopted. The QCD model is taken from a control region in data defined inverting the lepton isolation for muons and requiring that either the isolation cut or identification criteria fail for electrons. The QCD normalisation is estimated by a fit to the m_T (muons) or $\not\!\!E_T$ (electrons) and its uncertainty is conservatively assigned by repeating the same fit in a QCD-enriched region and varying the non-QCD contributions by 20%.

The likelihood model includes the background rates as nuisance parameters with a coefficient for each background template with a log-normal prior. The prior uncertainties on the background normalisation have been taken from the recent measurements of the corresponding processes, i.e. 10% for $t\bar{t}$, 30% for W+jets, 10-30% for QCD (in the different event categories), 15% for single top in the *t* channel. The impact of the background rates uncertainties on the *s*-channel cross section measurement is evaluated removing one uncertainty at a time from the likelihood model and measuring the corresponding variation in the profile likelihood. The other instrumental and theoretical uncertainties (listed in Section 2) are evaluated performing two fits to the pseudodatasets generated with the up/down variations of the systematic source of interest (with other sources fixed to zero), and taking the difference in the fitted signal yield between these fits and the nominal fit as the corresponding up/down uncertainties.

The systematic uncertainties with the highest impact on the measurement have been found to be the factorisation and renormalisation scales (~80%), jet energy scales (~50%), and matching thresholds (~30%). The single top-quark *s*-channel inclusive production cross section has been measured to be $\sigma_{s\text{−ch.}} = 6.2 \pm 5.4$ (exp.) $\pm$ 5.9 (th.) pb. Using the Feldman-Cousins unified approach [19] the 68% confidence level (CL) intervals which do not reach negative cross section values are reported as well: $\sigma_{s\text{−ch.}} = 6.2^{+8.0}_{-5.1}$ pb. Finally, the measurement leads to an upper limit evaluated using a Bayesian approach of 11.5 (17.0, 9.0) pb at 95% CL, where the numbers in parenthesis refer to the expected limits in presence of SM signal and in the background-only hypothesis.

Future extensions of this analysis will include the whole 7+8 TeV datasets to increase the sensitivity of the measurement and will exploit the reduced factorisation/renormalisation scale uncertainties from the NLO $t\bar{t}$ generators.

5. Conclusions

In this paper the results of the most recent studies on single top production at CMS have been described. The first analysis, a precision measurement of the *t*-channel inclusive cross section and of the top over anti-top charge ratio, leads to the most precise $|V_{\text{tb}}|$ determination in single top sector and opens the way to discriminate among the different PDF sets, should a better precision be achieved. The second one, the tW inclusive cross section measurement, with its signal significance of 6.1σ represents the first observation of this production mechanism at the LHC. Finally, the search for the single top production in the *s* channel has been presented, reporting an upper limit at 95% CL of 11.5 pb.

All the results are summarised in Figure 7 where the measurements are compared with the theoretical prediction.

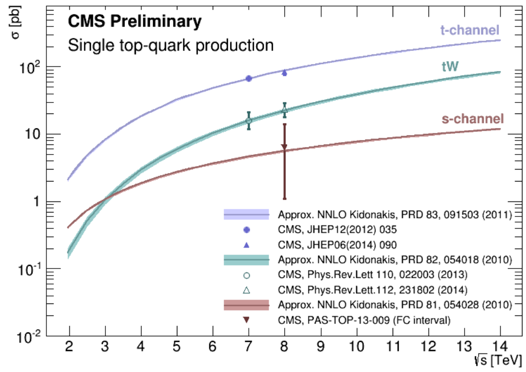

Figure 7: Summary of single top cross section measurements by CMS, as function of centre-of-mass energy.

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