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Measurements of single-top-quark production at the LHC

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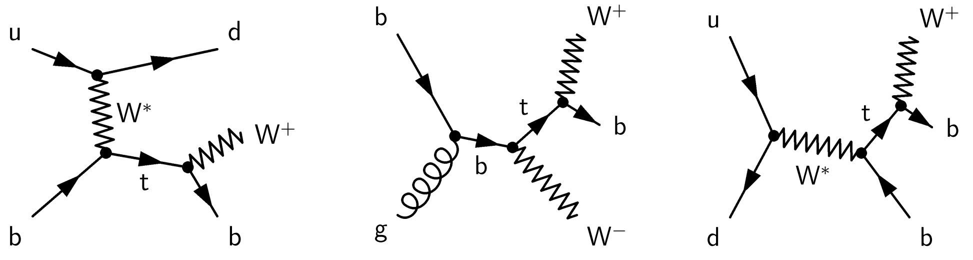
Summary. — This article summarizes the status of measurements of single-top-quark production at the LHC operating at a center-of-mass energy of 7 TeV. As of Summer 2011, the highlights in single-top physics at CERN have been the observation of the t-channel production mode by the ATLAS collaboration with a significance of 7.6 standard deviations and first indications of Wt associated production by CMS with 2.7 standard deviations. The measured cross sections are in good agreement with the predictions by the standard model.

PACS `14.65.Ha` – Top quarks.
PACS `12.15.Hh` – Determination of Cabibbo-Kobayashi-Maskawa matrix elements.
PACS `13.85.Lg` – Total cross sections.

1. – Introduction

At a hadron collider top-quarks or antitop-quarks can be produced singly via the weak interaction involving a W-t-b vertex. There are three relevant subprocesses at the LHC: the t-channel and the s-channel exchange of a virtual W boson and the associated production of an on-shell W boson and a top quark. The corresponding Feynman diagrams including the top-quark decay are shown in fig. 1.

The t-channel mode is by far the dominating subprocess. However, the cross section for Wt production is also of considerable size at the LHC, contrary to the situation at the Tevatron where the Wt mode is negligible compared to the other two channels. Theoretically, the cross sections of the single-top-quark production processes are currently known at next-to-leading order (NLO) in perturbation theory including the resummation of logarithms due to soft gluon contributions [1]. The predictions are summarized in table I, providing the sum of single top-quark and single antitop-quark production. It is worthwhile to note that, at the LHC, the cross sections for t and $\bar{t}$ production are different in the t-channel and in the s-channel, the ratio being approximately equal to 2. The reason for this asymmetry is that the up-quark appears twice as a valence quark in the proton, while there is only one down valence quark. Up-quarks in the initial state lead to t production, while down-quarks initiate $\bar{t}$ production. This cross section asymmetry



(a) (b) (c)

Fig. 1. – Feynman diagrams of t-channel, Wt, and s-channel single-top-quark production.

is not present at the Tevatron because of the $p\bar{p}$ initial state that is symmetric with respect to the quark-antiquark content.

The main objectives of the measurements in the single-top sector at the LHC are the following:

- Observe all three production modes separately.
- Measure the cross sections as precisely as possible to extract the CKM matrix element $|V_{tb}|$.
- Give input to the determination of parton distribution functions (PDF). The t-channel is particularly interesting in this respect. The measurement of the cross section ratio $R_t \equiv \sigma(t)/\sigma(\bar{t})$ gives access to the ratio of the up-quark to the down-quark PDF in an important range of momentum transfer. The t-channel cross section measurement itself provides information on the b-quark PDF.
- Single top-quark final states provide an important window for physics beyond the standard model (BSM) [2], for example, for new gauge bosons (W') that decay preferentially to quarks and would not be detected in lepton final states, charged Higgs bosons, flavour-changing neutral current interactions, or quarks of a fourth generation. It is important to note that the different standard model (SM) single-top-quark channels exhibit complementary sensitivity to particular BSM models, which underlines the necessity to separate them.

In the following sections we will discuss the analyses performed by ATLAS and CMS to extract single-top-quark events in the different production channels. Section **2** is devoted to the t-channel measurements and sect. **3** presents the analyses on Wt production, in particular the CMS result based on $2.1\,\mathrm{fb}^{-1}$. Brief accounts on the searches for s-channel production and single-top production via flavour-changing neutral currents (FCNC) are given in sects. **4** and **5**, respectively.

Table I. – *Predicted single top-quark cross sections* [1]. *The quoted numbers are the sum of single-top-quark and single-antitop-quark production in each channel.*

t-channel	Wt production	s-channel
$64.2 \pm 2.6\,\mathrm{pb}$	$15.6 \pm 1.3\,\mathrm{pb}$	$4.6 \pm 0.2\,\mathrm{pb}$

2. – Measurements of the t-channel cross section

In 2011, both the ATLAS and the CMS collaborations have presented measurements of the t-channel single-top-quark cross section at $\sqrt{s} = 7\,\text{TeV}$. The CMS measurement is based on the 2010 data set corresponding to an integrated luminosity of $36\,\text{pb}^{-1}$ [3]. Two independent analyses are performed, one does a maximum likelihood fit to two-dimensional histograms (2D analysis), the other one makes use of many kinematic and event shape variables using a boosted decision tree (BDT). The two results are finally combined using the least squares method with correlations. ATLAS made three preliminary measurements publicly available [4, 5], the latest one being based on 2011 collision data that correspond to an integrated luminosity of $0.70\,\text{fb}^{-1}$. Two independent results are obtained by a cut-based analysis and a multivariate technique based on a neural network (NN).

All these analyses make use of the lepton+jets data set that is defined at trigger level by a single electron or muon trigger. The aim is the selection of signal events in which the W boson originating from the top-quark decays into $e\nu_e$ or $\mu\nu_\mu$. A small additional acceptance is due to the $W \to \tau\nu_\tau$ channel with a subsequent decay of the τ lepton to an electron or muon. The offline selection of events requires a high-p_T electron or muon with $p_T(\ell) > 25\,\text{GeV}$ and $|\eta(\ell)| < 2.5$ in the case of ATLAS and $p_T(\mu) > 20\,\text{GeV}$, $|\eta(\mu)| < 2.1$, or $E_T(e) > 30\,\text{GeV}$, $|\eta(e)| < 2.5$ at CMS. At ATLAS, the presence of a neutrino is reflected in the event selection by requiring $E_{\text{T}}^{\text{miss}} > 25\,\text{GeV}$, while CMS does not cut on the missing transverse momentum. To further reduce generic multijet events produced by QCD processes both collaborations apply a specific veto involving the transverse mass of the W boson: $M_T(W) > 60\,\text{GeV} - E_{\text{T}}^{\text{miss}}$ at ATLAS and $M_T(W \to e\nu) > 50\,\text{GeV}$, $M_T(W \to \mu\nu) > 40\,\text{GeV}$ at CMS.

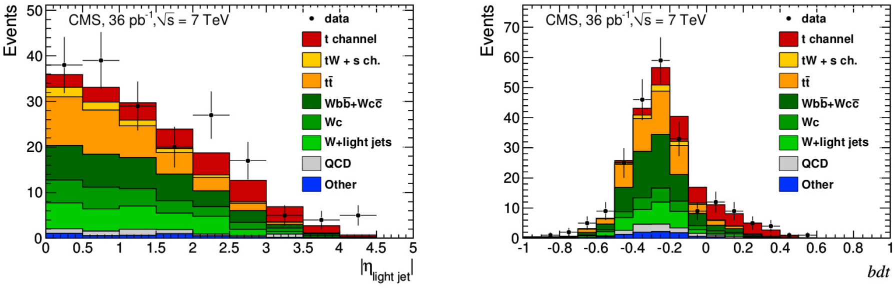
Both collaborations reconstruct jets with the anti-k_T algorithm [6], ATLAS uses $R = 0.4$, CMS $R = 0.5$. The transverse momentum thresholds for counting jets are $p_T > 25\,\text{GeV}$ in the case of ATLAS and $p_T > 30\,\text{GeV}$ at CMS. The pseudorapidity range is extended as far forward as possible to measure the light-quark jet that originates from the upper quark line in the t-channel Feynman diagram as seen in fig. 1(a). ATLAS uses jets in the range $|\eta| < 4.5$, CMS even up to $|\eta| < 5.0$. Both CMS analyses and the ATLAS NN analysis require exactly two jets as defined above. The cut-based analysis at ATLAS uses three-jets events in addition as a separate analysis channel. Since the t-channel signature includes one b-quark jet from the top-quark decay, ATLAS and CMS use b-jet tagging to suppress the dominant W+jets background. ATLAS requires exactly one jet to be tagged by a secondary vertex algorithm. CMS uses slightly different requirements with slight variations among the analyses.

The main backgrounds for single top-quark production are W+jets and QCD multijet production, the later being a difficult instrumental background which is due to the misidentification of a quark jet as a primary electron or muon from the W-boson decay. The misidentification is generally not well modeled in the detector simulation; that is why ATLAS and CMS use collision data to estimate the rate of multijet events and model their kinematics, for example, when looking at distributions of variables. CMS fits the $M_T(W)$ distribution to estimate the multijet background rate. The region below the cut value of 40 or 50 GeV, respectively, is sensitive to the multijet contribution and fixes the rate in the fit. ATLAS uses the $E_{\text{T}}^{\text{miss}}$ distribution in the same manner. Depending on the channel, CMS finds multijet fractions of 1% to 8% after all cuts, while ATLAS operates with fractions of 5% to 10%. Large systematic uncertainties of ±50% are assigned to the rates of the multijet background to cover differences seen when fitting different sensitive variables or altering the modeling of the multijet background. The default model at ATLAS is based on jet-triggered collision events in which one jet is found to have a large electromagnetic energy fraction. At CMS, the multijets background is modeled by events from a sideband region in which the isolation criterium for charged leptons has been inverted.

The event kinematics of the W+jets background is modeled using generated events passed through the full detector simulation. ATLAS uses the Alpgen generator [7], CMS the MadGraph 4.4 generator [8]. In general, the shape of kinematic distributions, including angular variables, is modeled well by the samples of simulated events. Since ATLAS and CMS both use multivariate techniques the background event model is extensively checked in high statistics samples of collision events where all selection cuts have been applied except for the b-tagging requirement. Small differences between the event model and the observed distributions are covered by systematic uncertainties, for example, due to the jet energy scale or the differences due to the choice of the parton shower scheme.

The rate of the W+jets background, however, is not well predicted by used event generators. In particular, the rate of W+heavy flavour jet events shows large differences between the LO prediction and the observation. ATLAS and CMS therefore apply a mixture of simulation and data-based methods to predict the rate of W+heavy flavour events. At CMS, a scale factor of $k_{\mathrm{HF}} = 2 \pm 1$ is determined to correct the LO prediction of $W + c\bar{c}$ and $W + b\bar{b}$ events [9]. The BDT analysis at CMS scales the W+light jets contribution to the cross section predicted by NNLO calculations [10], while the 2D analysis uses a data-driven normalization based on control samples with and without a relaxed (“loose”) b-tagging requirement. The two analyses at ATLAS use different approaches as well. The cut-based analysis applies an algebraic method accounting for the observed event rates in the $W + 1$ jet tagged data set, the $W + 2$ jets pretag data set and the $W + 2$ jets tagged sideband region, that is orthogonal to the data set of the signal selection. The ATLAS NN analysis fits the backgrounds simultaneously with the t-channel signal.

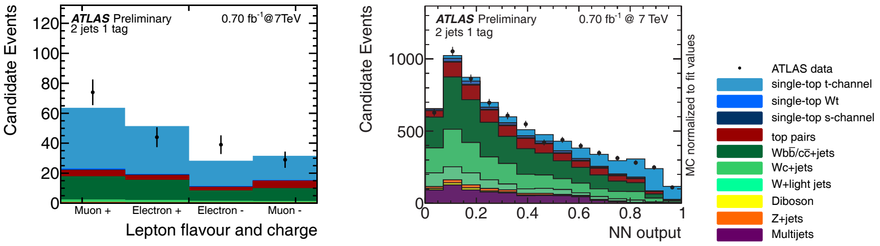
In its final analysis step the CMS 2D analysis contructs two-dimensional histograms with the pseudorapidity of the light-quark jet $|\eta_{\mathrm{lj}}|$, which is the jet that is not identified as a b-quark jet, and the cosine of the so-called polarization angle $\cos\theta(\mathrm{lj}, \ell)$, that is the angle between the light-quark jet and the charged lepton in the top-quark rest frame. This angle discriminates signal from background since single top-quarks are 100% polarized along the direction of the d quark due to the V-A nature of their production vertex. In fig. 2(a) the observed distribution of $|\eta_{\mathrm{lj}}|$ is compared to the expectation obtained from signal and all background processes. The second analysis at CMS uses a BDT that incorporates 37 variables. The t-channel signal is extracted in a Bayesian approach in which all systematic uncertainties are included in the likelihood function and the associated nuisance parameters are integrated out (marginalized). The observed output distribution of the BDT is shown in fig. 2(b). Both CMS analyses observe a t-channel signal with a significance above three standard deviations, the 2D analysis finds $3.7\,\sigma$ ($2.1\,\sigma$ expected), the BDT analyses sees a signal corresponding to $3.5\,\sigma$ ($2.9\,\sigma$ expected). Both analyses' results are combined using a least squares approach taking correlations into account (best linear unbiased estimator). The statistical correlation obtained from pseudo-experiments is 51%, while the systematic uncertainties are assumed to be 100% correlated. The resulting t-channel cross section is found to be $83.6 \pm 29.8(\mathrm{stat.} + \mathrm{syst.}) \pm 3.3(\mathrm{lumi.})\,\mathrm{pb}$ [3]. The most important systematic uncertainty on the cross-section measurement comes from the b-tagging efficiency, that is known within ±15%.



(a) (b)

Fig. 2. – Discriminant distributions of the t-channel single-top-quark analyses at CMS based on an integrated luminosity of $36\,\text{pb}^{-1}$ recorded in 2010. (a) Pseudorapidity distribution of the light-quark jet used as discriminant in the so-called 2D analysis. (b) Discriminant obtained by the boosted decision tree analysis. The displayed distributions include the event of the electron and the muon channels.

The cut-based analysis at ATLAS adds four cuts to the common event pre-selection discussed above: a cut on the sum of the transverse momenta of all objects in the event $H_T > 210\,\text{GeV}$, a cut on the reconstructed top-quark mass $M(\ell\nu b) > 150\,\text{GeV}$ and $M(\ell\nu b) < 190\,\text{GeV}$, $|\eta_{\text{lj}}| > 2.0$, and a cut on the difference in pseudorapidities of the two jets $|\Delta\eta(j_1, j_2)| > 1.0$. The selections were optimized by maximizing a frequentist, binomial significance which takes systematic uncertainties on the background estimate into account. The retained events are separated into 8 different channels according to jet multiplicity (2 or 3), the flavour of the charged lepton (electron or muon), and the sign of its charge (+ or −). The observed event yields and their predictions are displayed in fig. 3(a). A profile likelihood fit is used to determine the cross section: $\sigma_t = 90 \pm 9\,(\text{stat.})^{+31}_{-20}\,(\text{syst.})\,\text{pb}$. The significance of the observed signal corresponds to 7.6 Gaussian standard deviations. The two largest systematic uncertainties of the measurement are the understanding of the b-tagging efficiencies (+18% / −13%) and the modeling of initial-state and final-state radiation (±14%).



(a) (b)

Fig. 3. – Measurement of t-channel candidate events at ATLAS using collision data corresponding to an integrated luminosity of $0.70\,\text{fb}^{-1}$. (a) Observed event yields of the cut-based analysis in the different categories of lepton flavour and lepton charge compared to the prediction. (b) Distribution of the NN output discriminating between signal and background events normalized to the fit result.

The second ATLAS analysis uses a NN to combine 13 kinematic variables to a powerful discriminant. The background rates of the W+jets processes are determined in a simultaneous fit when determining the signal content. A frequentistic method based on pseudo-experiments is employed to estimate the impact of systematic uncertainties on the t-channel cross section which is found to be $\sigma_t = 105 \pm 7\,(\mathrm{stat.})^{+36}_{-30}\,(\mathrm{syst.})\,\mathrm{pb}$. The dominating systematic uncertainty is due to the uncertainty in the jet energy scale (+32% / −20%).

Already these first t-channel measurements are systematically limited and the challenge for the future will be to reduce these uncertainties to obtain precise cross-section determinations to facilitate the extraction of $|V_{tb}|$ or to be used as input to PDF fits.

3. – Search for Wt production

The associated Wt production features two W bosons in its final state and, according to the decay of these bosons, one distinguishes two experimentally relevant channels: the dilepton channel in which both W bosons decay into $e\nu_e$ or $\mu\nu_\mu$, leading to a signature of two charged leptons, large $E_{\mathrm{T}}^{\mathrm{miss}}$ and one b-quark jet; and secondly, the lepton+jets channel in which one W decays leptonically as mentioned above and the second one decays to a quark-antiquark pair resulting in high-p_T hadronic jets. The lepton+jets channel has a signature of one charged lepton, $E_{\mathrm{T}}^{\mathrm{miss}}$, and three jets.

ATLAS has performed searches for Wt production with the 2010 data set ($36\,\mathrm{pb}^{-1}$) and with collision data recorded in 2011 that correspond to an integrated luminosity of $0.70\,\mathrm{fb}^{-1}$ [11]. CMS has performed an analysis in the dilepton channel using 2011 data with an integrated luminosity of $2.1\,\mathrm{fb}^{-1}$ [12].

The object definitions of electron and muon candidates and jets are very similar to the ones used in the t-channel analyses. An important modification is the use of central jets only. ATLAS counts jets with $|\eta| < 2.5$, CMS with $|\eta| < 2.4$. The requirements on missing transverse energy are increased; at ATLAS $E_{\mathrm{T}}^{\mathrm{miss}} > 50\,\mathrm{GeV}$, CMS requires $E_{\mathrm{T}}^{\mathrm{miss}} > 30\,\mathrm{GeV}$, but only if the two charged leptons have the same flavour (ee or $\mu\mu$). ATLAS and CMS apply a veto on events in the ee and $\mu\mu$ final states if the dilepton invariant mass falls into a window around the Z mass. ATLAS also applies a selection to reduce the contributon from $Z \to \tau^+\tau^-$ events: $\Delta\phi(\ell_1, E_{\mathrm{T}}^{\mathrm{miss}}) + \Delta\phi(\ell_2, E_{\mathrm{T}}^{\mathrm{miss}}) > 2.5$.

The dominating background to Wt production is $t\bar{t}$ pair production. In the dilepton channel, where only one b-quark jet is expected for signal events, the $t\bar{t}$ rate is estimated in the 2-jets control region. CMS splits the 2-jets events in the 1-tag and 2-tag channels and determines the $t\bar{t}$ background simultaneously with the signal in one fit. After all cuts CMS expects about 150 Wt signal events summed over all dilepton channels (ee, $\mu\mu$, and $e\mu$), while the expectation value of the number of background events is estimated to be 740 events. The number of observed events is 964 corresponding to a signal significance of $2.7\,\sigma$ ($1.8\,\sigma$ expected). The measured cross section is $\sigma_{Wt} = 22^{+9}_{-7}\,(\mathrm{stat.} + \mathrm{syst.})\,\mathrm{pb}$. ATLAS measures a cross section of $\sigma_{Wt} = 14.4^{+5.3}_{-5.1}(\mathrm{stat.})\,^{+9.7}_{-9.4}(\mathrm{syst.})\,\mathrm{pb}$ with a significance of only $1.2\,\sigma$.

4. – Search for s-channel production

The production of single-top-quarks via the s-channel exchange of a virtual W boson is the most difficult SM single-top subprocess to observe at the LHC, since it has the lowest cross section and is missing a special characteristic like the forward jet of the t-channel. Analysts at ATLAS have performed a first search [13] for this process at

LHC building largely on the t-channel analysis. The main difference in the event preselection is motivated by the s-channel signature that contains two b-quark jets, see fig. 1(c). Therefore, exactly two b-tagged jets with $|\eta| < 2.5$ are required, leading to an expectation of $S/\sqrt{B} = 0.88$. Analysis level cuts on six kinematic variables are added and lead to a small improvement of $S/\sqrt{B} = 0.98$. At present, only an upper limit on the cross section can be set: $\sigma_s < 26.5\,\text{pb}$ at the 95% C.L., which is about 5 times the standard model value. In the future, the use of multivariate techniques and more collision data may allow the observation of this challenging process.

5. – Search for FCNC induced single top-quark production

In the SM, FCNC are strongly suppressed in the top-quark sector due to a very effective GIM mechanism; decays induced by FCNC have only branching ratios at the level of 10^{-13}. Physics beyond the standard model (BSM) can yield increases of FCNC effects by several orders of magnitude [14]. Any evidence for FCNC in the top-sector would therefore be a clear hint for BSM physics.

ATLAS has searched for single top-quark production by an anomalous coupling of a gluon to an up- or charm-quark: $u\,(c) + g \to t$. The top quark is assumed to decay SM-like according to $t \to b + W$. The analysis strategy is very close to the NN analysis measuring the t-channel cross section, see sect. **2**. However, in the event selection only exactly one central b-tagged jet is required. A NN is used to separate single-top FCNC-like events from background and the SM single-top processes, mainly t-channel events. In collision data corresponding to $36\,\text{pb}^{-1}$ no hints for an FCNC signal are found and a limit of $\sigma_{\text{FCNC}} < 17.3\,\text{pb}$ is set. Using theoretical calculations [15] this cross section limit can be converted into limits on the anomalous coupling constants κ_{tug} and κ_{tcg}.

6. – Summary

The ATLAS and CMS collaborations have done the first measurements of single top-quark cross sections at the LHC operating at $\sqrt{s} = 7\,\text{TeV}$. At CMS, evidence of t-channel production was seen with a significance of $3.7\,\sigma$ yielding a cross section of

$$83.6 \pm 29.8\,(\text{stat.} + \text{syst.} \pm 3.3(\text{lumi.})\,\text{pb} \quad [3].$$

Based on data corresponding to $0.70\,\text{fb}^{-1}$ the ATLAS collaboration has observed a t-channel single-top signal with a significance of $7.6\,\sigma$ using a cut-based technique. The corresponding cross section is

$$\sigma_t = 90 \pm 9\,(\text{stat.})^{+31}_{-20}\,(\text{syst.})\,\text{pb} \quad [5].$$

Both measurements are in agreement with the prediction by the SM: $64.2 \pm 2.6\,\text{pb}$ [1].

An important part of the physics program concerning single-top at the LHC are also the searches for Wt production. While first signals of this process are appearing, the significance is not yet large enough to claim evidence ($3\,\sigma$) or even observation ($5\,\sigma$). This important step will be left to the analysis of the full 2011 data set which will be done in 2012.

ATLAS has also searched for SM s-channel production and for BSM FCNC-induced single top-quark production. No signals were observed and upper limits on the corresponding cross sections have been established.

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