

The search for the single top at the LHC

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(ricevuto il 20 Luglio 2010; approvato il 20 Luglio 2010; pubblicato online l'11 Ottobre 2010)

Summary. — We report on the predictions of the Standard Model for the single top-quark production at LHC and on the analysis strategies adopted by CMS and ATLAS for the single top-quark search. The Standard Model predicts the production of single top quark through three electroweak processes in the LHC energy reach, referred to as *t*, *s* and *tW* channels, resulting in distinct topologies and backgrounds. Different analysis strategies to search for the single top have been developed by CMS and ATLAS experiments. For the 14 TeV center-of-mass energy scenario all the channels have been considered, while for the 10 TeV scenario a specific strategy has been developed only for the t-channel and has been applied on Monte Carlo samples assuming an integrated luminosity of 200 pb^{-1} .

PACS 14.65.Ha – Top quarks.

1. – Introduction

We report on a study of the Standard Model predictions for the single top quark production at the LHC and the analysis strategies adopted by ATLAS and CMS experiments aiming to single top observation.

Section 2 describes the Standard Model production mechanism of the single top, the motivation for single top studies and provides the cross section of the different single top production channels calculated at the Next to Leading Order.

Sections 3 and 4 describe the analysis strategy adopted, respectively, by Atlas and CMS for the single top search at LHC for the 10 TeV center-of-mass energy scenario.

Section 5 gives an overview of the single top search at the LHC in the 14 and 10 TeV scenario and reports the expectations for single top search at 7 TeV center-of-mass energy scenario.

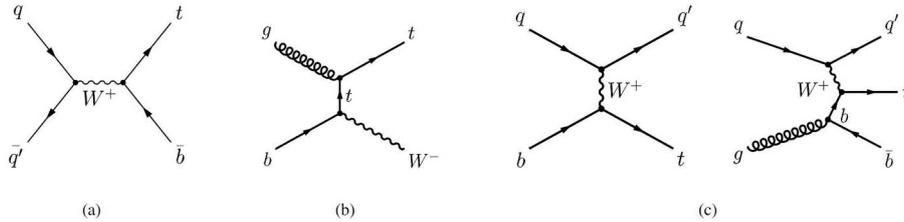


Fig. 1. – Single top quark production channels. a) *s*-channel; b) *tW*-channel; c) *t*-channel.

2. – Standard Model prediction for single top-quark production at LHC

The Standard Model predicts the production of single top through three different mechanisms [1-4] in hadron-hadron interactions. Those three processes involve an electroweak charged current and are classified as: the *s*-channel which is mediated by a W boson with 4-momentum squared $q^2 > m_W^2$, fig. 1(a); the *tW*-channel which involves the production of a W boson with $q^2 = m_W^2$, fig. 1(b); the *t*-channel, mediated by a W boson with $q^2 < 0$, fig. 1(c).

Figure 1(c) shows the Feynman diagrams that contribute to the *t*-channel process. In order to give a fair approximation of the full next-to-leading order (NLO) properties of the signal, the $2 \rightarrow 3$ diagram, fig. 1(c, right), corresponding to the dominant NLO contribution to the *t*-channel, has to be combined with the leading order (LO) $2 \rightarrow 2$ process, fig. 1(c, left), with a matching procedure that must also avoid double counting. The matching procedure adopted in ATLAS introduces a subtraction term into the matrix elements following the ACOT formalism [5]. The matching procedure adopted in CMS assumes that the $2 \rightarrow 2$ diagram gives a better description of the events where the *b* quark has a low transverse momentum p_T , while the $2 \rightarrow 3$ diagram is better for the events of high- p_T *b* quarks. The events are merged with an appropriate p_T threshold and in such way to give a smooth p_T threshold (more details in [6]).

The single top quark processes allow to investigate the physics of the top quark in areas that are difficult to study in $t\bar{t}$ production. In particular, because of the electroweak nature of the production processes, it allows the study of the flavor sector of top quark physics. All single top-quark channels are related to the Cabibbo-Kobayashi-Masakawa matrix element V_{tb} , allowing a direct measurement of this parameter and a new check of consistency of the Standard Model. It is possible to investigate the tWb vertex structure and FCNC couplings in the production processes, and the single top-quark topologies are also a window for searches for anomalous couplings and *s*-channel resonances like W' bosons.

The dominant process at LHC will be the *t*-channel, followed by the *tW*- and then the *s*-channel. Table I shows the cross section calculations at next-to-leading order.

TABLE I. – *Single top-quark cross-sections (pb). All cross sections are calculated with MCFM [7].*

Channel	t	s	tW
14 TeV	246.8	9.82	66
10 TeV	124.5	6.6	32.7
7 TeV	63	4.6	10.6

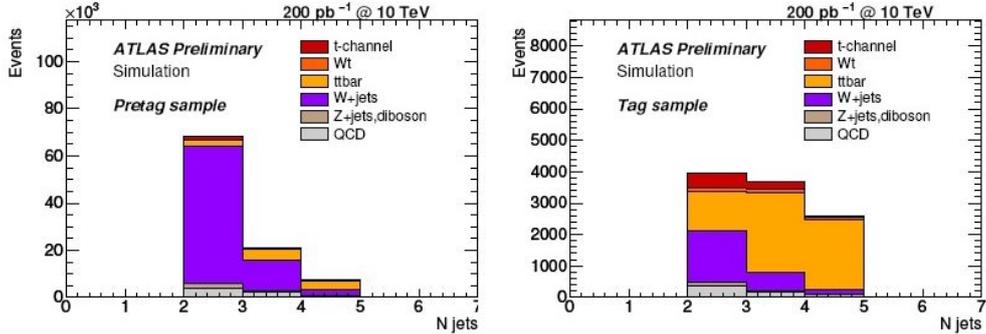


Fig. 2. – Stacked jet multiplicity distribution for preselected events, without b -tagging requirement (left) and with at least one b -tagged jet (right).

3. – Search for single top-quark events at ATLAS

In this section we present a strategy to search for the dominant t-channel single top quark production at ATLAS. The analysis was developed based on simulated events that represent collision data to an integrated luminosity of a few hundred pb⁻¹ at a center-of-mass energy of 10 TeV. The analysis focuses on data-driven techniques to normalize the rates of the main backgrounds. The selection of single top-quark events is optimized for the use of a likelihood method. A detailed description can be found in [8]. At a center-of-mass energy of 14 TeV all three channels have been investigated, a detail description can be found in [9, 10].

3.1. Event preselection. – The event selection is driven by the final state of the t-channel single top-quark process, where the W boson from the top quark decay decays leptonically. Whereas only decays into electron and muon final states are considered. Selected events must have exactly one isolated lepton with $p_T > 20$ GeV/ c . Calibrated jets are reconstructed with a $R = 0.4$ cone algorithm and are required to have $p_T > 30$ GeV/ c and $|\eta| < 5.0$. The identification of jets originating from b -quarks is one of the most important selection criteria for the analysis of events containing top quarks. For the studies described here, we used a jet probability ($JetProb$) tagger [9]. The $JetProb$ tagger is based only on the impact-parameter resolution function of prompt tracks and is expected to be commissioned first with early data. The transverse missing energy is required to be $E_T^{\text{miss}} > 20$ GeV. In order to reduce the QCD-multijet background to a reasonable rate, the transverse mass of the reconstructed W boson has to be greater than 30 GeV/ c^2 . The number of expected events for the different jet multiplicities without and with at least one b -tagged jet can be seen in fig. 2.

3.2. Background normalization. – The strategy presented in this analysis emphasizes the development of techniques to normalize and constrain the main backgrounds using data. This is the case for the dominant W +jets and $t\bar{t}$ production, whose contributions can be fitted from background-enriched samples and propagated to the sample selected for the single top-quark search. This is done using a discriminant in a statistically independent control region. Since our final goal is to measure the t-channel single top-quark production in the 2-jets tagged data set, we investigate the 3-jets pretag data set. The discriminant is built by utilizing an artificial neural network provided by the NeuroBayes

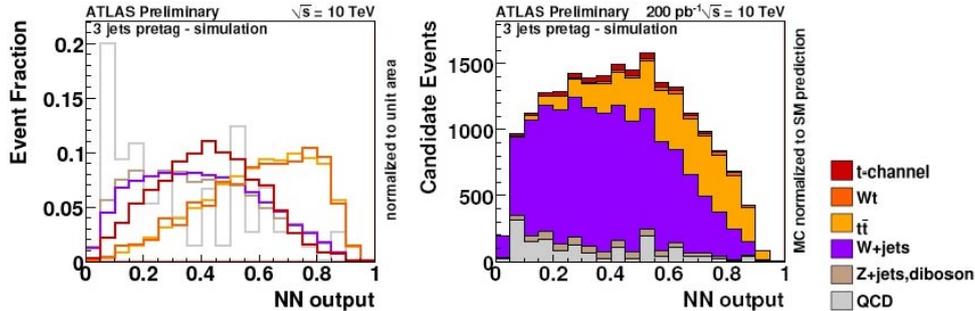


Fig. 3. – Distribution of the NN output normalized to unit area (left) and the expected distribution for an integrated luminosity of 200 pb^{-1} .

package [11]. Bayesian regularization techniques are used for the training process. The network structure contains 11 input nodes corresponding each to one input variable plus one additional bias node. The hidden layer consists of 15 hidden nodes and the single output node gives a continued output in the interval $[0, 1]$. The input variables were chosen in order to limit the effect of the systematic uncertainty due to the jet energy scale. The output distribution of the NN normalized to unit area for the different processes is shown in fig. 3. There is also presented the expected distribution for an integrated luminosity of 200 pb^{-1} . We measure the rate of W +jets and $t\bar{t}$ events using a binned maximum-likelihood fit to the NN output distribution. Gaussian constrains are applied to the expected rates of the other processes. The statistical uncertainties are estimated using ensemble tests to be 2.0% on the W +jets rate and 3.5% on the $t\bar{t}$ rate. When exploiting the shape of a discriminant distribution, one has to account for systematic acceptance as well as shape uncertainties. The following sources are considered: The jet energy scale (JES), altering the JES by $\pm 5\%$, the parton distribution functions by re-evaluation of the acceptance for $t\bar{t}$ events using a re-weighting of events based on the eigenvector method applied to the CETQ66 and MRST2006nnlo PDF sets, and the single top contamination. The total expected uncertainty for the measurement of W +jets rate is estimated to be $\pm 14.1\%$ and for the rate of $t\bar{t}$ events to be $\pm 6.9\%$.

3.3. Search strategy and expected uncertainty. – The search for t-channel single top-quark events is performed in two different approaches. The first approach is based on the use of a set of sequential cuts taking advantage of the characteristics of the t-channel process producing a boosted top quark and a very energetic forward light quark jet. The main backgrounds, W +jet and $t\bar{t}$ events are reduced by requiring $p_T > 50 \text{ GeV}$ of the tagged jet and $|\eta| > 2.5$ for the untagged jet. Applying these cuts the obtained S/B is 0.64.

The second approach aiming to improve the signal purity further is based on few variables and a likelihood ratio method. Two likelihood ratio discriminants are constructed, one for the rejection of $t\bar{t}$ events and another for the rejection of W +jets events. The observables entering the likelihood calculations are the pseudorapidity of the highest p_T untagged jet, ΔR between the lepton and the highest p_T b-tagged jet, the ΔR between the highest p_T b-tagged jet and the highest p_T untagged jet and the centrality. The expected distributions for both likelihood ratios are shown in fig. 4. Accepting all events, which have values greater than 0.9 in both discriminants, the S/B is increased

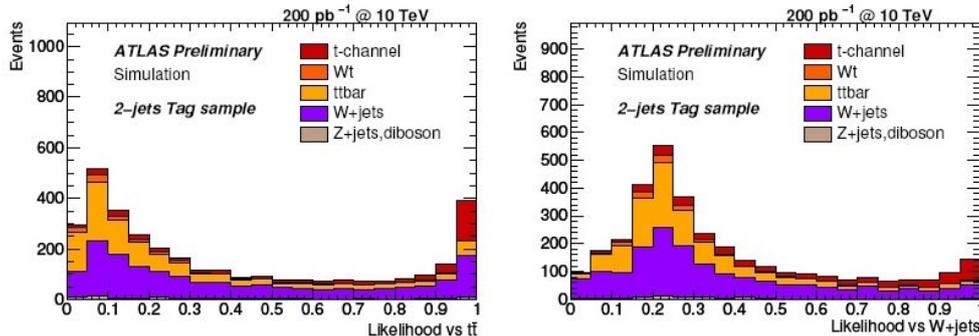


Fig. 4. – Distribution of the likelihood ratio discriminants in 200 pb^{-1} in the 2-jets tagged sample. Two discriminants are constructed, one for the rejection of $t\bar{t}$ events (left) and another for the rejection of W +jets events (right).

by almost 70%. We estimate the sensitivity for the single top-quark t -channel production using both approaches. Only events with exactly two jets are used. The impact of systematic sources of uncertainties on the cross section measurement is determined with ensemble tests. We consider the following sources: Background normalization, uncertainty on the W +heavy flavor cross sections, b -tagging uncertainty, JES, initial and final state radiation, PDF, generator dependence, luminosity and lepton identification and reconstruction uncertainty. The uncertainty expected for the cut-based and likelihood analyses are 45% and 40%, respectively. The largest source of error comes from the uncertainty on the b -tagging performance.

4. – Search for single top at CMS

In this section we describe the strategy for the search of the single top in the dominant t -channel process at CMS, since it also has the most potential for early rediscovery. The reported analysis has been developed studying a Monte Carlo sample corresponding to an integrated luminosity of 200 pb^{-1} and a center-of-mass energy of 10 TeV (see also [12]). The analysis at 14 TeV refers to all the single top channels and is reported in detail in [13]. For this study the s and tW channels are considered as background.

4.1. Event selection. – The event selection takes only into account the final states where the top decays through: $t \rightarrow W\bar{b} \rightarrow \bar{b}\mu\nu$. The topology of the selected events therefore consists of a single μ coming from the W decay, a b jet coming from the top decay and a light flavour jet. The main background contributions to this topology of events come from the W + jets, $t\bar{t}$.

Events triggered by a reconstructed muon with transverse momentum $p_T > 15 \text{ GeV}/c$ and within $|\eta| < 2.1$ are selected. Exactly one muon is required with transverse momentum $p_T > 20 \text{ GeV}/c$, $|\eta| < 2.1$ reconstructed in both the CMS Tracker and the CMS Muon Detector. Defining $\Delta R = \sqrt{(\eta)^2 + (\phi)^2} < 0.3$, muons within $\Delta R < 0.3$ from the jets defined above are discarded. To reject QCD background we also apply the cut on $relIso = \frac{p_T}{trackIso + caloIso + p_T} > 0.95$, where $trackIso$ and $caloIso$ are, respectively, the sum of the p_T of the tracks in the CMS Tracker and the sum of the energy releases in the CMS Calorimeters in a $\Delta R < 0.3$ cone centered on the muon momentum direction.

We require $relIso > 0.95$. We veto events where an electron is present with the following criteria: $p_T > 20 \text{ GeV}/c$, $|\eta| < 2.4$ in order to reject $t\bar{t}$ di-leptonic decay channels.

The presence of exactly two jets with transverse momentum $p_T > 30 \text{ GeV}/c$ is required.

Exactly one jet identified as b jet is required, according to the algorithm TrackCounting [14], while a b -jet veto is applied on the second in order to identify it as the light quark jet. The jet stemming from the b quark in fig. 1(c, right) is more likely to be produced at very high pseudorapidity $|\eta|$ in module. Since the b -tagging algorithm requires the jet to be in the acceptance region of the CMS Tracker ($|\eta| < 2.5$), the contribution of signal events where there are 2 jets identified as b -jets is strongly suppressed.

The transverse mass of the W boson $m_{T,w}$ is reconstructed from the muon momentum and the missing transverse energy E_T^{miss} . To reject QCD we require $m_{T,W} > 50 \text{ GeV}/c^2$.

4.2. QCD background estimation. – In order to extract the fraction of QCD that survives the $m_{T,W}$ cut, a data-driven method is applied. A QCD-enriched control sample is defined inverting the cut on $relIso$, then the shape of QCD $m_{T,W}$ is extracted from the control sample and used in the fit to the QCD contribution of the $m_{T,W}$ of the sample surviving the other cuts. The $m_{T,W}$ of other channels where a W boson is present is obtained either from W -boson-enriched control samples, from Monte Carlo or from a $Z \rightarrow \mu\bar{\mu}$ boson-enriched samples where one of the muons is taken as the neutrino and the mass of the Z boson is rescaled to the W boson mass.

4.3. Template fit. – The variable $\cos\theta_{lj}$ is then defined as the angle between the light quark jet and the muon in the top quark rest frame. This variable exploits the completely left-handed polarization of the top quark [15]. The angular distribution of the top quark decay products with respect to its spin axis, taken as the direction of the light quark jet, is

$$(1) \quad \frac{d\Gamma}{\Gamma d\cos\theta} = \frac{1}{2} \cdot (1 + A \cdot \cos\theta).$$

With $A = 1$ for the lepton, -0.4 for the b quark, and -0.33 for the ν . To define the top quark rest frame, the top quark momentum is reconstructed as the sum of the 4-momenta of the muon, the b -tagged jet and the neutrino. The neutrinos $p_{x,\nu}$ and $p_{y,\nu}$ are taken from E_T^{miss} . The neutrino $p_{z,\nu}$ is obtained constraining the invariant mass of the $\mu\nu$ pair to the W boson mass m_W . Imaginary solutions arise due to the finite E_T^{miss} resolution when the W boson transverse mass $m_{T,W}$ is greater than m_W . In this case we constrain m_{TW} to m_W and choose the $p_{x,\nu}$, $p_{y,\nu}$ that minimize the distance from the E_T^{miss} in the (p_x, p_y) -plane. Figure 5(left) shows the reconstructed top quark mass. Figure 5(right) shows the distribution of $\cos\theta_{lj}$ for simulated events assuming an integrated luminosity of 200 pb^{-1} .

To extract the signal from data a binned maximum likelihood template fit is performed on $\cos\theta_{lj}$ in a region where the background distribution of $\cos\theta_{lj}$ is assumed to be flat. In order to check this flatness hypothesis, background-enriched control samples are defined, fig. 6 (left), for the different contributions. The shape of the signal distribution is taken as the shape of the Monte Carlo distribution of $\cos\theta_{lj}$ at high statistics.

4.3.1. Significance and cross section measurement. The statistical significance has been obtained by performing two ensemble tests in the hypotheses of no single top (H_0) and t - and s -channel single top quark production present (H_1). The test was performed on

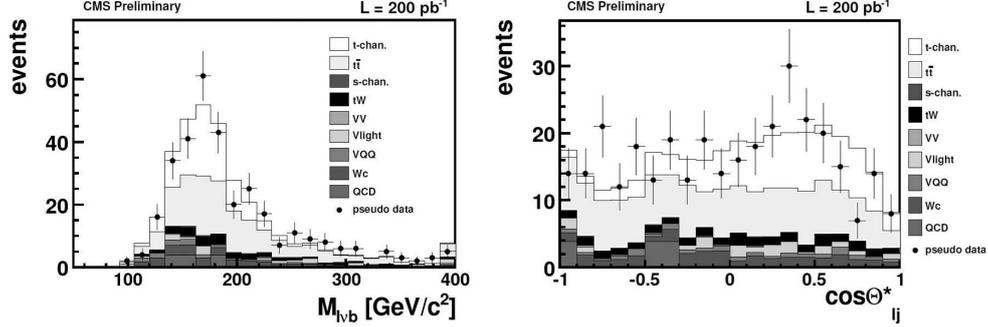


Fig. 5. – Distribution of the reconstructed top quark mass (left) and $\cos \theta_{lj}$ (right) for the signal and background channels after full selection. The dots represent the sum of all channels for the equivalent of an integrated luminosity of 200 pb^{-1} . The histograms lines indicate the single contribution of all channels.

toy Monte Carlo where the systematic uncertainty was drawn randomly from a Gaussian distribution centered at zero and with a width equal to their extreme values. Figure 6 (right) shows the sensitivity as a function of the integrated luminosity. The procedure adopted yields a statistical cross section uncertainty of 35%, which moves to 40.8% and 27.8% when the overall background is rescaled by +50% and -50%, respectively. Systematic uncertainties sum up to 14%, not including the luminosity uncertainty, foreseen to be 10%.

5. – Conclusions

We reported on the expectations for Standard Model single top production at LHC and on the strategies for single top quark search adopted by ATLAS and CMS. Amongst the three Standard Model production mechanisms, the t -channel has the highest cross section and a detailed strategy for single top search in such channel has been reported

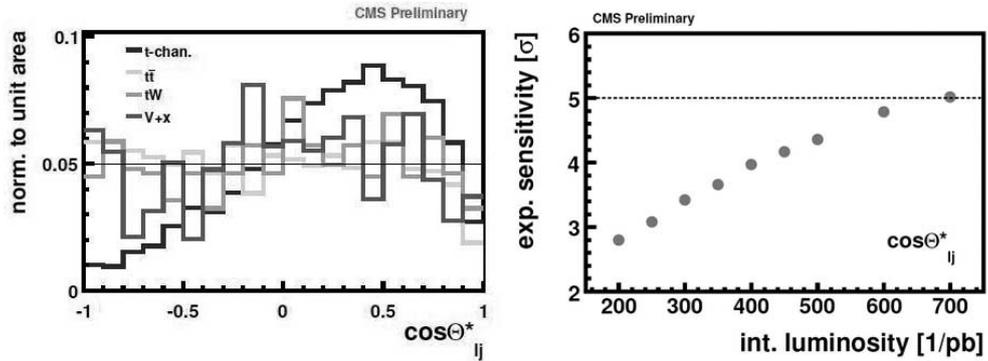


Fig. 6. – Left: control samples to check the shapes of background contributions. The $t\bar{t}$ and tW control samples are taken from simulated events, the $V+x$ sample is taken dropping the requirement for the b -tagged jet. Right: evolution of the sensitivity of the analysis with respect to the luminosity. Systematic uncertainties are not taken into account.

in the 10 TeV collision energy scenario assuming a 200 pb^{-1} integrated luminosity from ATLAS and CMS. The cross section of single top t-channel on such sample was measured with an uncertainty of 40% (ATLAS) and 39% (CMS). The *a priori* significance for a single top measurement on such sample is 2.7σ for both experiments. A rescaling of the signal and background yields according to the cross-section ratio expected for 10 and 7 TeV collision energies, assuming the same selection as in the 10 TeV case shows that to get the same sensitivity as for the 10 TeV samples the integrated luminosity needed at 7 TeV is about double the one at 10 TeV.

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