Expectations for first single-top studies in CMS in proton-proton collisions

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Abstract. The first long physics run of LHC is taking place at a center-of-mass energy of 7 TeV, and is expected to continue until an integrated luminosity of 1 inverse femtobarn will have been collected. We present an analysis technique to measure the t-channel cross section for single top-quark production in CMS, that can confirm the recent observation of single-top quark production by the Tevatron experiments. Events leading to a signature of exactly one muon and two jets are selected and specific data-driven methods have been developed to reduce the sensitivity to the unknown level of background contamination. Single top quarks provide the possibility to study the polarization of an "isolated quark". This feature is exploited in the presented analysis for the measurement of SM-like single top; with more statistics, the chiral structure of the W-t-b vertex could be probed via the study of the top polarization and any sizable deviation from the Standard Model expectation would be a hint to new physics beyond the Standard Model.

1. Introduction

Top quark is a spin-$\frac{3}{2}$ fermion with electric charge $-\frac{2}{3}e$, the weak isospin partner of the bottom quark, and a color triplet. Even in the Standard Model framework, the top quark is a very special object. The top quark is heaviest particle in the SM and the top Yukawa coupling is surprisingly close to one. The top quark lifetime, $\tau_t = 0.4 \times 10^{-24}$s, is much smaller than the typical time for the formation of QCD bound states. Therefore, the top quark decays long before hadronization.

At the Large hadron Collider (LHC) the top quarks are produced either in pairs through strong interactions or singly via electroweak interactions. Single top production at the LHC can be classified by the virtuality of the involved W-boson: t-channel production ($q^2_W < 0$), s-channel ($q^2_W > 0$) and tW-channel ($q^2_W = M^2_W$). D0 and CDF collaborations reported a $5\sigma$ observation for single top at the Tevatron in proton anti-proton collisions [1],[2].

The largest source of single top at the LHC is the t-channel mode. Therefore, the reobservation of the single top is expected to happen first in the t-channel mode at the LHC. This article proposes a strategy for extraction of t-channel single top signal events and cross section measurement based on the polarization properties of the t-channel single top. The analysis is performed with 200 pb$^{-1}$ recorded by the CMS experiment [3] and at a center-of-mass energy of 10 TeV. The t-channel NLO cross section at 10 TeV center-of-mass energy is 124 pb [4]. This cross section is reduced by about about a factor of two at 7 TeV collisions. The details of signal and backgrounds generation and simulations of the CMS detector response are described in [5].
2. Event selection
This analysis focuses on the $t \to W + b \to \mu + \nu + b$ decay channel. It is required that all events must pass the high-level single-muon trigger conditions which ask for a 15 GeV/c transverse momentum threshold and a pseudorapidity range of $|\eta| < 2.1$. The reconstructed muons with a transverse momentum larger than 20 GeV/c within the trigger acceptance, passing additional quality criteria, are finally selected. Events with more than one muon present and also if an electron candidate is present with tight quality selection and $p_{T,\mu} > 20$ GeV/c (transverse momentum of the muon), $|\eta| < 2.4$ are rejected. The events are accepted only if the reconstructed muon is well isolated. Jets are reconstructed using the iterative cone algorithm with a cone size of 0.5. We consider jets within $|\eta| < 5$ with calibrated transverse momentum larger than 30 GeV/c. The event is accepted only if exactly two such jets were reconstructed. A track-counting (TC) $b$-tagging algorithm is applied which calculates the signed 3D impact parameter significance $(IP/\sigma_{IP})$ of all the tracks passing the quality criteria associated to the jet, orders them by decreasing values of this observable, and defines as jet discriminator the value of $IP/\sigma_{IP}$ for the second (high-efficiency TC) or third (high-purity TC) track. The event is accepted only if exactly one of the selected jets passes a tight threshold on the high-purity TC. Since we expect most of the signal events to have only one $b$-jet inside the tracker acceptance, $|\eta| < 2.5$. The event is rejected if the remaining jet passes a loose threshold on the high-efficiency TC. For more suppression of contributions from processes where the muon does not come from a leptonic decay of a $W$-boson, the events are selected with a transverse $W$-boson mass $M_T > 50$ GeV/c$^2$ where

$$M_T = \sqrt{(p_{T,\mu} + p_{T,\nu})^2 - (p_{x,\mu} + p_{x,\nu})^2 - (p_{y,\mu} + p_{y,\nu})^2}. \quad (1)$$

After application of the above selection cuts, we expect 102 signal events and 229 background events in a data sample of 200 pb$^{-1}$. The main background contribution comes from top pair production (136 events).

A data driven method is used to estimate the QCD background contamination. The QCD background is extracted using the $M_T$ shape after applying all selection criteria. The distribution is parametrized by the sum of a signal-like and a background-like template. These templates are extracted from high-statistics control samples. For the background-like template the anti-isolated phase space, orthogonal to the standard selection, is exploited, whereas the signal-like template is obtained from a $Z$-boson enriched control sample. We assign a 45% overall uncertainty of the technique, taking into account systematic uncertainties as well as the statistical uncertainty. More details of the technique can be found in [5].

To reconstruct the top quark candidates the precise knowledge of the $W$-boson mass provides a kinematic constraint, which leads to a quadratic equation in the longitudinal component of the neutrino momentum. This equation has, in general, two solutions, which can have an imaginary part (this happens when $M_T$ is larger than the $W$-pole mass used in the constraint). In this analysis the imaginary component is eliminated by modifying the missing transverse energy until it gives $M_T = M_W$, still respecting the $W$-mass constraint. When there are two real solutions, we choose the solution with the smallest absolute value. A similar two-fold ambiguity presents itself when reconstructing a top-quark hypothesis, since two jets are selected. The $b$-tagged jet is assigned to the top-quark decay. Figure 2 shows the mass of the reconstructed top quark for events passing the full selection. The observation of a maximum around the known value of the top mass in real collision data will be a strong indication of the presence of top quarks.

3. Extraction of single top signal
One of the interesting features of the signal is that the top quarks are produced highly polarized with respect to a specific spin axis [6],[7]. The direction of the top-quark spin is visible in the
angular correlations of its decay products, which are distributed according to

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_{lj}^\ast} = \frac{1}{2} (1 + A \cos \theta_{lj}^\ast).
\]

(2)

where \(\theta_{lj}^\ast\) is the angle between the direction of the outgoing lepton and the spin axis, approximated by the direction of the untagged jet, in the top-quark rest frame. \(A\) is the coefficient of spin asymmetry, equal to +1 for charged leptons. Figure 2 shows the distribution of the cosine of this angle, for events passing all event selection cuts. The dip at \(\theta_{lj}^\ast\) near one is due to the muon \(p_T\) and \(M_T\) cuts. In order to extract the signal events, a binned likelihood fit is applied to the \(\cos \theta_{lj}^\ast\) distribution. To be less sensitive to the kinematic effects due to the cuts on muon \(p_T\) and \(M_T\) at \(\cos \theta_{lj}^\ast\) near 1, the fit range is restricted to \([-1,0.75]\). The signal template is taken from simulation, while the overall background is assumed to be flat. This assumption has been verified with background-enriched control samples. Due to the flatness of all background the method is insensitive to the detailed composition of the background. The statistical sensitivity of the signal extraction has been determined by simulating 500,000 pseudo-experiments. This procedure yields a 35% statistical uncertainty on the cross section.
for a data sample equivalent to 200 pb$^{-1}$ at 10 TeV center-of-mass energy. Assuming that the true value is the one predicted by the SM, the expected sensitivity of the method is 2.8$\sigma$. The inclusion of systematic uncertainties coming from Parton Distribution Functions and from detector knowledge contribute an additional 14%, and the expected sensitivity is lowered to 2.7$\sigma$. In Figure 3 the expected sensitivity, only statistical uncertainties, as a function of the integrated luminosity is shown. Naively, it is expected that a factor of two larger data is necessary at 7 TeV collisions to obtain the same expected sensitivity shown in Figure 3.

![Figure 3. Evolution of the expected sensitivity with the integrated luminosity.](image)

4. Conclusions and outlook
In this report, an analysis strategy is proposed to measure the $t$-channel single top quark production cross section. The strategy is based on the use of the polarization of single top quarks ($\cos\theta^*_\ell j$). The $\cos\theta^*_\ell j$ is robust against systematic uncertainties. The evidence of $t$-channel single top quark production in proton-proton collisions with an integrated luminosity of 1 fb$^{-1}$ and at 7 TeV seems to be achievable in particular after including the electron decay mode.

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