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Prospects for the Measurement of the t-channel Single Top-Quark Cross Section in the Muon Channel with 200 pb^{-1} of CMS data at $\sqrt{s} = 10$ TeV

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The first long physics run of LHC is expected to take place at a center-of-mass energy of 10 TeV, and to go on until an integrated luminosity of 200 pb^{-1} has been collected. We present an analysis technique to measure the t-channel single top-quark cross section 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.

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1. Introduction

The theory of electroweak interactions predicts three different production mechanisms for single top-quarks in hadron-hadron collisions, in addition to the more abundant pair production due to the strong interaction: t-channel, s-channel, and associated tW production. Recently, the CDF and DØ experiments reported a $5\,\sigma$ observation of single top-quark production at the Tevatron $p\bar{p}$ collider [1, 2]. At the Large Hadron Collider (LHC) the reobservation is expected to happen first in the t-channel mode, by far the most abundant of the three at LHC energies, and with the most striking final state topology. This article treats this production mode as signal, including the other two in the definition of background, and assumes a data amount of $200\,\mathrm{pb}^{-1}$ recorded by the CMS detector [3] at a center-of-mass energy of $\sqrt{s} = 10\,\mathrm{TeV}$.

2. Selection of Signal Event Candidates

The study focuses on the muonic decay channel, where $t \to bW \to b\mu\nu$. All events must pass the high-level single-muon trigger requirement which includes a $15\,\mathrm{GeV}/c$ transverse momentum threshold and a pseudorapidity range of $|\eta| < 2.1$. Reconstructed muons with a transverse momentum $p_{\mathrm{T},\mu} > 20\,\mathrm{GeV}/c$ within the trigger acceptance, passing additional quality criteria, are selected. The event is rejected if more than one such muon is present and also if an electron candidate is present with tight quality selection and $p_{\mathrm{T},e} > 20\,\mathrm{GeV}/c$, $|\eta| < 2.4$. Events are accepted only if the reconstructed muon object is well isolated. Jets are defined according to the iterative cone algorithm with a cone size of 0.5. We consider jets within $|\eta| < 5$ whose calibrated transverse momentum is greater than $30\,\mathrm{GeV}/c$. The event is accepted only if exactly two such jets were reconstructed. We apply a track-counting (TC) b-tagging algorithm that calculates the signed 3D impact parameter significance ($\mathrm{IP}/\sigma_{\mathrm{IP}}$) 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 $\mathrm{IP}/\sigma_{\mathrm{IP}}$ 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 quark inside the tracker acceptance ($|\eta| < 2.5$), we reject the event if the remaining jet passes a loose threshold on the high-efficiency TC. To further suppress contributions from processes where the muon does not come from a leptonically decaying W boson, we select events with a transverse W-boson mass $M_{\mathrm{T}} > 50\,\mathrm{GeV}/c^2$. Applying this selection, we expect a total of 102 signal events and 229 background events in a data equivalent of $200\,\mathrm{pb}^{-1}$. The dominant background contribution comes from top-quark pair production (42.2 % of all events), followed by W-boson production in association with light (u,d,s) or heavy (c,b) quarks (15.5 % of all events).

Estimations of the QCD multi-jet contamination from the simulated data have to be considered particular unreliable for the purpose of our analysis, because only events from specific kinematical regions pass the selection, and tail effects are the most difficult to properly simulate. These arguments lead to the conclusion that only in-situ data-driven estimations will give the needed confidence on the amount of this background. We extract the size of the QCD multi-jet and signal-like contributions using the M_{T} shape after all other selection criteria have been applied. 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 method, including systematic uncertainty as well as the expected statistical uncertainty.

3. Extraction of the Cross Section

A specific feature of the signal, stemming from the $V-A$ structure of the weak interaction, is the almost 100 % left-handed polarization of the top quark with respect to the spin axis. The direction of the top-quark spin is visible in angular correlations of its decay products, which are distributed according to

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*_{lj}} = \frac{1}{2}(1+\cos\theta^*_{lj}), \tag{3.1}$$

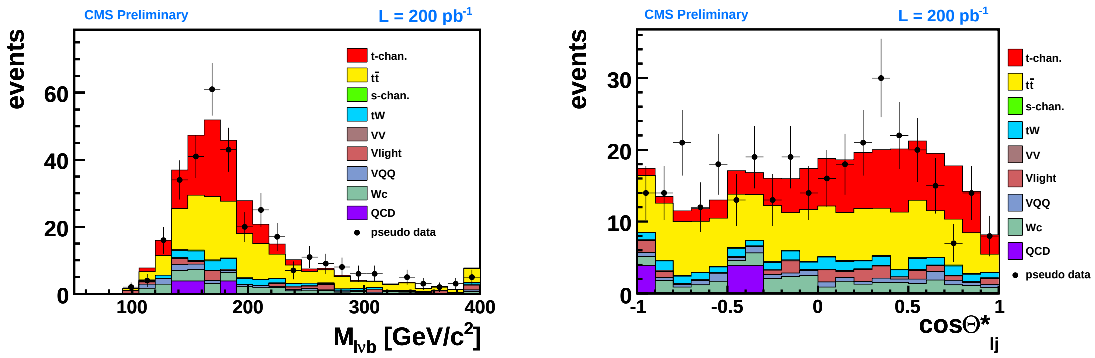
where θ^*_{lj} is the angle between the direction of the outgoing charged lepton and the spin axis, approximated by the direction of the untagged jet, in the top-quark rest-frame [4].

In order to access the top-quark rest-frame, the four vector of the top-quark candidate has to be reconstructed from the measured decay objects. The first step in this reconstruction makes use of the precise knowledge of the W-boson mass to provide a kinematic constraint, which leads to a quadratic equation in the longitudinal neutrino momentum. This equation has, in general, two solutions, which have an imaginary part if M_{T} is larger than the W-boson pole-mass used in the constraint. Here, the imaginary component is eliminated by modifying the missing transverse energy such as to give $M_{\mathrm{T}} = M_W$, still respecting the W-boson mass constraint. When two real solutions are present, we choose the solution with the smallest absolute value. A further 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 3 (a) shows the mass of the reconstructed top quark ($M_{l\nu b}$) 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. Figure 3 (b) shows the distribution of the cosine of the polarization angle θ^*_{lj} for events passing the event selection. The dip at $\cos\theta^*_{lj} \sim 1$ is due to the cut on the transverse momentum of the muon.

The cross section is determined by performing a binned likelihood fit to the $\cos\theta^*_{lj}$ distribution of the selected events. The inputs to the fit are the template distributions for the signal and background. The signal template is taken from simulation, while the overall background is assumed to be flat. This assumption is verified with background-enriched control samples, finding distributions consistent with the flatness hypothesis within the statistical uncertainties. The fit is restricted to the [-1, 0.75] interval in order to minimize the aforementioned kinematic effects due to the muon definition.

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 equivalent of 200 pb^{-1} at 10 TeV center-of-mass energy, assuming that the true value is the one predicted by the standard model, and the expected sensitivity of the method is 2.8 σ. The inclusion of systematic uncertainties coming from PDFs and from detector knowledge contribute an additional 14 %, while the expected sensitivity is lowered to 2.7 σ.



(a) (b)

Figure 1: The mass of the reconstructed top quark (a) and the distribution of the cosine of the polarization angle θ^*_{lj} for events passing the full selection. The pseudo data distribution is obtained from a bin-by-bin smearing of the total event yield based on Poisson statistics.

4. Conclusion

The central result of the analysis presented here [5] is that it is realistic to provide the first evidence of single top-quark production in a pp collider with $200\,\mathrm{pb}^{-1}$ of data at 10 TeV. After applying a selection optimized for t-channel single top-quark events, which leaves $t\bar{t}$ as the dominant background, we achieve the needed separation of the signal from the background by exploiting the polarization of the top quark. Applying this method, we obtain an total uncertainty of 35 % (stat.) $\pm$ 14 % (syst.) $\pm$ 10 % (lumi) and an expected sensitivity of 2.7 σ.

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