Observation of associated production of a single top quark and W boson at 8 TeV

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Electroweak production of single top quarks has been observed by the D0 [1] and CDF [2] experiments at the Tevatron. There are three main processes that can produce a single top quark in the Standard Model: the t-channel exchange of a virtual W boson, the s-channel production and then decay of a virtual W boson, and the associated production of a top quark with a W boson (tW). Associated tW production had a negligible cross-section at the Tevatron and so was not previously accessible. At the Large Hadron Collider (LHC), it has a higher cross-section than the s-channel and as such represents a significant contribution to single top quark production.

Associated tW production is an interesting production mechanism for several reasons: its interference with top quark pair production [3], its sensitivity to new physics [4] and its role as a background to several SUSY and Higgs searches. Evidence for tW associated production has been previously presented by ATLAS [5] and CMS [6], and we present here the first observation of tW production at the CMS experiment in pp collisions at $\sqrt{s} = 8$ TeV.

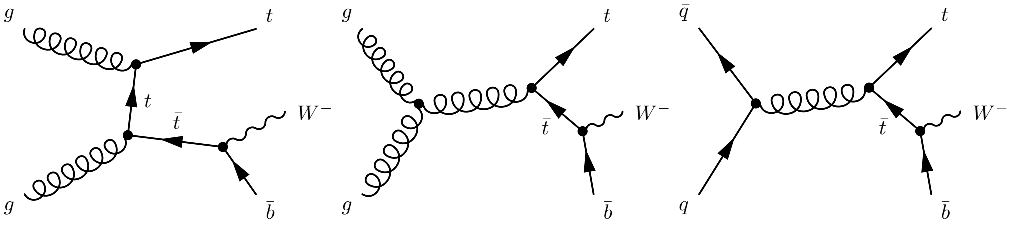

Figure 1: Feynman diagrams for tW single-top-quark production at next-to-leading order that are removed from the signal definition in the DR scheme, the charge-conjugate modes are implicitly included.

The next-to-leading order (NLO) Feynman diagrams for tW production, shown in Fig. 1, present a conceptual problem due to their mixing with perturbative QCD top quark pair ($t\bar{t}$) production. Two methods have been proposed for describing the tW signal: “Diagram Removal” (DR) [3], where the doubly resonant diagrams are excluded from the signal definition; and “Diagram Subtraction” (DS) [3], in which the differential cross section is modified by a gauge-invariant subtraction term, which locally cancels the contribution of the $t\bar{t}$ diagrams. The DR scheme is chosen for this analysis, but the difference between the two schemes is observed to be consistent within statistical uncertainties and is accounted for as a systematic uncertainty.

The analysis presented here investigates the channels in which both W bosons (from the associated production and the top decay) decay leptonically into a muon or electron and the corresponding neutrino. Tau decays are modelled, but not considered in the signal definition. The leptonic final states of the tW process are characterised by two isolated, oppositely charged leptons, a jet from the hadronisation of the b quark, and a substantial amount of missing transverse energy (E_T^{miss}) due to the neutrinos. The primary source of background is $t\bar{t}$ production, with $Z/\gamma*$ +jets processes also contributing strongly in the ee and $\mu\mu$ channels.

The analysis uses fits to a discriminant variable built from kinematic quantities combined using a boosted decision tree (BDT). Two further analyses, intended as cross-checks of the robustness of the multivariate approach, are performed using event counts and kinematic variables as the basis of a fit. For all of the analyses, a sample corresponding to an integrated luminosity of 12.2 fb^{-1} of pp collisions at $\sqrt{s} = 8$ TeV collected by the CMS detector was used. A full description of the CMS detector can be found in [7].

All objects used for selection are reconstructed using the particle flow (PF) algorithm [8, 9]. Data samples are chosen by requiring two leptons (muons or electrons) in the trigger for the event. All events are required to have at least one well reconstructed primary vertex; fake vertices (where a vertex is reconstructed in a location where no interaction occurred) are suppressed by requiring the vertex to have more than 4 associated tracks, $|z| < 24$ cm and $\rho < 2.0$ cm.

Exactly two oppositely charged, isolated leptons are required in the event. Muons are required to be reconstructed by both the tracking and muon systems. They are selected if they have a transverse momentum (p_T) greater than 20 GeV and fall within the pseudorapidity (η) range $|\eta| < 2.4$. Additionally, there is a requirement on the relative isolation of the muon, $I_{rel} < 0.2$ where I_{rel} is defined as the sum of the p_T of all neutral and charged particles within a cone of $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.4$ divided by the p_T of the lepton.

Electrons are reconstructed from energy deposits in the electromagnetic calorimeter and matched to hits in the silicon tracker. They are required to have a $p_T > 20$ GeV and $|\eta| < 2.5$. The electron must have a transverse impact parameter (IP) with respect to the beam spot of less than 0.04 cm. Additionally, electrons are required to have $I_{rel} < 0.15$ within a cone $\Delta R < 0.3$.

The signal region contains exactly two leptons, so events with additional muons or electrons passing a looser selection of $p_T > 10$ GeV are vetoed to suppress background processes. To remove low-mass $Z/\gamma*$ events, the invariant mass of the leptons, m_{ll}, is required to be greater than 20 GeV. In order to further reduce the contribution from $Z/\gamma*$ +jets and other background processes such as WZ and ZZ, events in the ee and $\mu\mu$ final states are rejected if m_{ll} is within the Z mass window of 81 to 101 GeV. The ee and $\mu\mu$ channels are required to have $E_T^{miss} > 50$ GeV, to further suppress the $Z/\gamma*$ +jets backgrounds.

Events failing the Z mass veto are used to reweight the Drell-Yan background Monte Carlo. Using the distribution of E_T^{miss} in the control region additional scale factors are derived that account for the difference between data and simulation based on the amount of missing energy in the event.

PF jets are reconstructed using the anti-k_T algorithm [10] with a resolution parameter of 0.5. Jets are required to have $p_T > 30$ GeV and $|\eta| < 2.4$. A multivariate b-tagging algorithm is used to determine whether a jet came from a b-quark decay, combining tracking information to determine a discriminant. Loose jets are defined in this analysis as any jet failing the above requirements, but passing a selection of $p_T > 20$ GeV and $|\eta| < 4.9$.

In order to constrain the dominant $t\bar{t}$ background, three regions are defined; one signal region and two $t\bar{t}$ enriched control regions. The signal region is defined as containing exactly one b-tagged jet (1j1t), whilst the control regions contain exactly two jets, with one and two b-tags respectively (2j1t and 2j2t).

After the selection is applied, a multivariate analysis is applied in order to discriminate between the tW signal and dominant $t\bar{t}$ background. A boosted decision tree (BDT) is trained using the "Toolkit for Multivariate Data Analysis" (TMVA) [11]. The training is carried out using simulated events for tW and $t\bar{t}$ passing the 1j1t signal region event selection. The thirteen variables combined in the BDT are chosen on the basis of their separation power between the tW signal and $t\bar{t}$ background, and their consistency between data and simulation is confirmed using the control regions. A fit is then performed to the shape of the BDT discriminant over all regions and channels in order to extract the significance and cross-section of the tW signal.

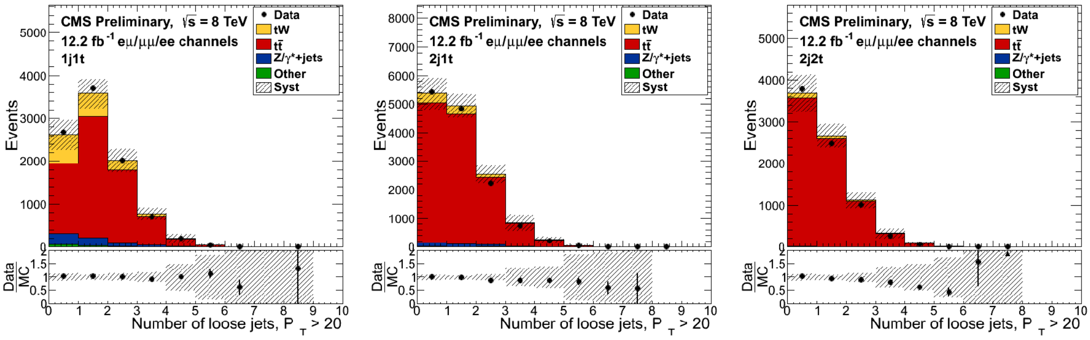

Figure 2: Distribution of the number of loose jets in an event for signal and control regions. This quantity is one of the 13 used as input to the BDT.

The statistical analysis is based on a binned likelihood fit of the BDT distributions. The expected yield for bin i, λ_i, is given by the sum over all considered background processes and the tW signal, scaled with a signal strength modifier μ which is the signal cross sections in units of the Standard Model prediction,

$$\lambda_i = \mu S_i + \sum_k B_{k,i}$$

where k runs over all considered background processes, B_k is the background template for background k, and S is the signal template, scaled according to luminosity measurements and the cross section predicted by the Standard Model.

Nuisance parameters that affect the expected yield, θ_u, are introduced for every source of uncertainty, labelled as u, that affects the predicted event yield. To quantify an excess of events, we use the test statistic q_0, defined as:

$$q_0 = \frac{\delta}{\delta\mu}\mathcal{L}(\mu = 0, \hat{\theta}_0|\text{data})$$

The likelihood is maximised with the signal strength held constant at zero, and the nuisance parameters allowed to float freely, thus finding the maximum likelihood under a background-only hypothesis. The p-value is then defined as the probability to obtain a test statistic value of q_0 as high as, or higher than, the one observed in data under the background-only hypothesis ($\mu = 0$). The distribution of q_0 is determined by generating pseudo-data sets randomly varying the nuisance parameters θ_0. The 68% confidence level interval is evaluated using the profile likelihood method [12].

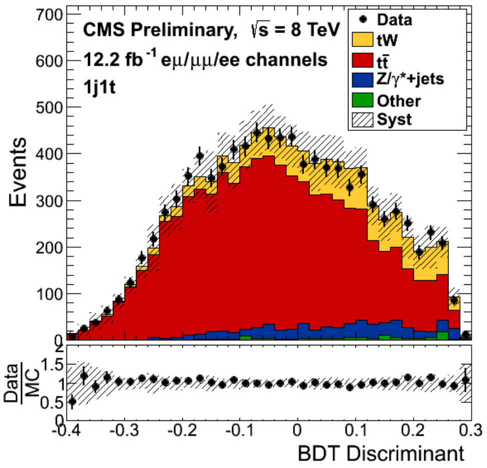

Figure 3: Signal region BDT discriminant for all decay channels, used for fitting.

Systematic uncertainties are treated as nuisance parameters in the fit, and are estimated by their impact on the fitted distributions. A wide range of systematic uncertainties, both theoretical and experimental, are considered. All uncertainties are taken into account by their impact on the shape of the fitted distributions, with the exception of the luminosity, lepton identification and reconstruction efficiencies and $t\bar{t}$ cross section uncertainties which are handled as uncertainties in the production rate.

The effect of each systematic is estimated based on its contribution to the uncertainty on the cross section. The impact of the theory shape uncertainties are estimated by a maximum likelihood fit, setting the nuisance parameters to the $\pm 1\sigma$ levels. For the other uncertainties the cross section is measured with the uncertainty fixed at its central value. The difference in the error on cross-section measurement from the nominal profile likelihood fit is then attributed to that individual uncertainty source.

The main sources of uncertainty are found to be the theoretical uncertainties. The largest uncertainty comes from varying the Matrix Element/Parton Shower (ME/PS) matching thresholds on the $t\bar{t}$ MC samples, giving an uncertainty of 14% on the measured cross section. Choosing different renormalisation/factorisation (Q^2) scales for the tW and $t\bar{t}$ samples leads to an uncertainty on the cross section of 11%. Varying the top-quark mass around the measured values gives an uncertainty on the cross section of 10%.

Two additional analyses were carried out as tests of the robustness of the BDT analysis: the first used a fit directly on the event counts and the second on the transverse momentum of the system (p_T^{syst}), defined as the vector sum of the transverse momentum of the leptons, b-tagged jet and missing transverse energy of the event. Both analyses use the same event selection as the BDT with additional cuts. First, events with any loose b-jets (loose jets as defined above passing the b-tagging criteria) were vetoed. Secondly, an additional requirement that the scalar sum of the transverse momentum of the two leptons, jet and E_T^{miss} (H_T) be greater than 160 GeV was applied in the $e\mu$ channel. The fit was performed in the same way as described for the BDT.

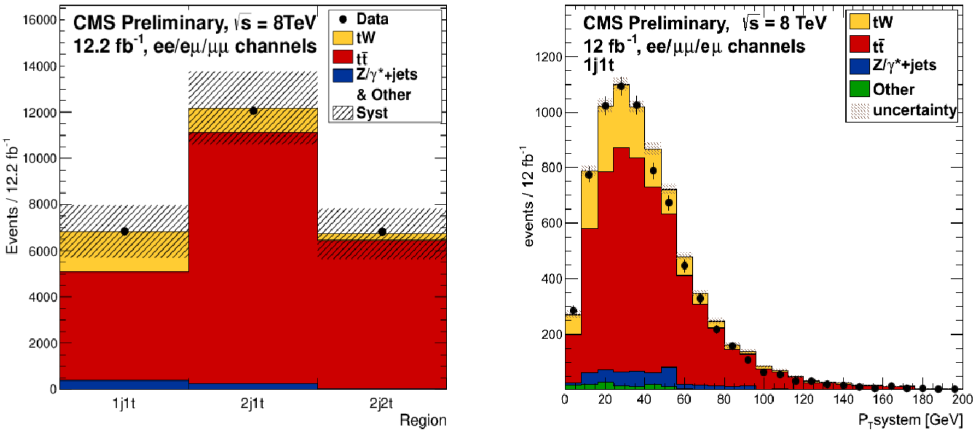

Figure 4: Distributions fitted in the cross check analyses. The event counts for all channels and regions (left), and the transverse momentum of the system for all channels in the signal region (right).

For the BDT analysis, an excess of events compared to a background-only hypothesis of 6.0σ is observed, compared to an expected significance, extracted from simulation, of $5.4^{+1.5}_{-1.4}\sigma$. The measured cross section, including both statistical and systematic uncertainties, is found to be $23.4^{+5.5}_{-5.4}$ pb, in agreement with the Standard Model. This compares favourably to the Standard Model cross section value of $22.2 \pm 0.6 \pm 1.4$ pb at $\sqrt{s} = 8$ TeV, assuming a top-quark mass of 172.5 GeV [13].

The event count based analysis observes a signal excess of 3.6σ, with an expected significance of $2.8^{+0.9}_{-0.8}$, and measures a cross section of $33.9^{+8.6}_{-8.6}$ pb. The p_T^{syst} fit analysis observes an excess of 4.0σ against an expected significance of $3.2^{+0.4}_{-0.9}$, and measures a cross section of $24.3^{+8.6}_{-8.8}$ pb. All the results are consistent with each other and the Standard Model.

The production of a single top quark in association with a W boson is observed in the dilepton decay channel in pp collisions at $\sqrt{s} = 8$ TeV in the CMS experiment at the LHC. A multivariate analysis is used to extract the tW signal from the dominant $t\bar{t}$ background, and an excess of events over a background-only hypothesis is observed with a significance of 6.0σ. The cross section is measured to be $23.4^{+5.5}_{-5.4}$ pb, in agreement with the Standard Model.

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