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Observation of W associated single top (tW) production and search for FCNC in tZ events in proton-proton collisions

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The first observation of the associated production of a single top quark and a W boson in proton-proton collisions at $\sqrt{s}$ = 8 TeV with the CMS experiment at the LHC is presented. The data correspond to an integrated luminosity of 12.2 fb^{-1}. The measurement is performed using events with two leptons and a jet originated from a b quark. A multivariate analysis based on kinematic properties is used to separate the signal from the $t\bar{t}$ background. The signal is observed with a 6.0 standard deviation excess above a background only hypothesis. A production cross section of $23.4^{+5.5}_{-5.4}$ pb is measured, in agreement with the standard model expectation of 22.2 ± 1.5 pb.
A study of top-quark anomalous couplings is performed through the search for a single top-quark produced in association with a Z boson. The event selection requires the presence of three isolated leptons, electrons or muons, and of at least one jet. The signal extraction is done using kinematic variables and information related to b-tagging, combined using a Boosted Decision Tree. The search is performed in a data sample corresponding to about 5 fb^{-1} of proton-proton collisions at $\sqrt{s} = 7$ TeV recorded with the CMS detector. No evidence of flavor-changing neutral currents is observed and upper limits at 95% confidence level are determined. The corresponding upper limits on the coupling strengths of an effective model are found to be $\kappa_{gut}/\Lambda < 0.10$ TeV^{-1}, $\kappa_{gct}/\Lambda < 0.35$ TeV^{-1}, $\kappa_{Zut}/\Lambda < 0.45$ TeV^{-1} and $\kappa_{Zct}/\Lambda < 2.27$ TeV^{-1}, where Λ is the expected scale at which new physics could appear. The equivalent top-quark-decay branching fractions are found to be $\mathscr{B}(t \to gu) \leq 0.56\%$, $\mathscr{B}(t \to gc) \leq 7.12\%$, $\mathscr{B}(t \to Zu) \leq 0.51\%$ and $\mathscr{B}(t \to Zc) \leq 11.40\%$.

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This document reports two results involving single top production in association with vector bosons: the first observation of the single top W associated (tW) production [1] in proton-proton (pp) collisions at 8 TeV and the results of a search for flavor changing neutral currents (FCNC) in tZ events [2] in pp collisions at 7 TeV, both performed with the Compact Muon Solenoid (CMS) [3].

1. Observation of W associated single top production

1.1 Introduction

While top quarks are predominantly produced in pairs via the strong interactions in pp collisions, they can also be produced singly via electroweak interactions, involving a Wtb vertex. Single-top-quark production proceeds mainly via three processes: the t-channel exchange of a virtual W boson (tq), the s-channel production and decay of a virtual W boson (tb), and the associated production of a top quark and a W boson (tW).

Because of its interference with top quark pair production [4, 5, 6], its sensitivity to new physics [7, 8, 9] and its role as a background to several SUSY and Higgs searches, W associated single top production is a particularly interesting mechanism. Its production cross section at previous colliders is negligible, while it is experimentally accessible at the LHC, representing a significant contribution to single-top-quark production at the LHC energies.

Evidence for tW associated production has been presented by the ATLAS [10] and CMS [11] experiments. This analysis presents the first observation of tW production at a significance of at least 5 σ above the background-only hypothesis in pp collisions at $\sqrt{s} = 8$ TeV.

The theoretical prediction of the next-to-next leading order (NNLO) cross section for tW in pp collisions at $\sqrt{s}$ = 8 TeV is σ_{tW}^{th}=22.2 $\pm$ 0.6 $\pm$ 1.4 pb [12], where the first uncertainty corresponds to factorization and renormalization scale variation and the second to parton distribution function (PDF) sets.

1.2 Analysis Strategy

The analysis is performed using the dilepton final states, in which both W bosons (the one produced in association with the top quark, and the one from the decay of the top quark) decay leptonically into a muon or an electron, and a neutrino. This leads to a final state composed of two oppositely charged isolated leptons, a jet resulting from the fragmentation of a b quark, and missing transverse energy (E_T^{miss}) due to the two escaping neutrinos. The primary background to tWproduction in this final state comes from $t\bar{t}$ production, with very few Z/γ^*events being the next most significant.

Events with exactly two oppositely charged, isolated leptons are selected, rejecting events with additional leptons passing looser criteria. Low mass dilepton resonances and $Z \to \ell\ell$ in the same-flavor final states events are suppressed using selection criteria based on the invariant mass of the dilepton system ($m_{\ell\ell}$) and E_T^{miss}.

For events passing this selection, a region rich in signal (signal region) and two regions dominated by background (control regions) are defined. The signal region contains events with exactly one jet passing the selection requirements, which is b-tagged (1j1t region). Two control regions enriched in $t\bar{t}$ background are defined as having exactly two jets with either one or both b-tagged (2j1t and 2j2t regions, respectively).

After the selection, the simulated samples in the 1j1t signal region contain predominantly tW and $t\bar{t}$ events (comprising 16% and 76% of the events, respectively), with a smaller contribution from Z/γ^{*} events (6%). The two control regions are dominated by top quark pair production events.

In order to separate the tW signal from the $t\bar{t}$ background a multivariate analysis using boosted decision trees (BDT) [13] is used. The BDT analyzer is trained using several kinematic variables, the most powerful are those involving extra jets in the event that fail the jet selection criteria. Other variables with significant separation power are related to the kinematics of the system comprised of the leptons, jets and E_T^{miss}: the scalar sum of their transverse momenta (H_{T}), the magnitude of the vector sum of their transverse momenta ($\mathrm{p}_{\mathrm{T}}^{\mathrm{sys}}$), and invariant mass of the system.

The BDT analyzer provides a single discriminant value for each event. The distributions of the BDT discriminant in data and simulation are shown in Fig. 1 for a combination of all three final states in the 1j1t, 2j1t, and 2j2t regions.

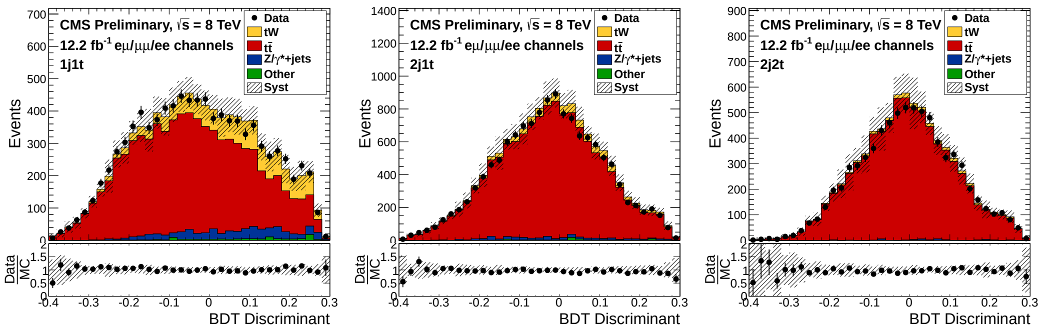

Figure 1: The BDT discriminant, in the signal region (1j1t) and control regions (2j1t and 2j2t) for all final states combined. Shown are data (points) and simulation (histogram). The hatched band represents the combined effect of all sources of systematic uncertainty.

1.3 Results

The uncertainty from all systematic sources is determined by estimating their effect on the normalization and shape of the BDT discriminant for all regions and final states. The dominant systematic uncertainties come from the choice of thresholds for the matrix element and parton showering matching in simulation of $t\bar{t}$ production and the renormalization/factorization scale.

For the significance estimation, a simultaneous binned likelihood fit to the BDT distributions of the three final states in the three regions is performed, including nuisance parameters for all the systematic uncertainty sources. Templates for the shapes of signal and background distributions are taken from simulation. Using four billion pseudo-experiments we observe an excess of events above the expected background with a significance of 6.0 σ, compared to an expected significance from simulation of $5.4^{+1.5}_{-1.4}\,\sigma$.

A profile likelihood method is used to determine the signal cross section and 68% confidence level interval. The measured cross section is found to be $23.4^{+5.5}_{-5.4}$ pb, in agreement with the predicted SM value of $22.2 \pm 0.6 \pm 1.4$ pb.

The cross section measurement is used to determine the absolute value of the Cabibbo-Kobayashi-Maskawa matrix element $|V_{\mathrm{tb}}|$, assuming $|V_{\mathrm{tb}}| \gg |V_{\mathrm{td}}|$ and $|V_{\mathrm{ts}}|$:

$$|V_{\rm tb}| = \sqrt{\frac{\sigma_{\rm tW}}{\sigma_{\rm tW}^{\rm th}}} = 1.03 \pm 0.12\ ({\rm exp.}) \pm 0.04\ ({\rm th.})$$

where $\sigma_{\rm tW}^{\rm th}$ is the theoretical prediction of the tWcross section assuming $|V_{\rm tb}| = 1$, and the uncertainties are separated into experimental and theoretical values. Using the SM assumption of $0 \leq |V_{\rm tb}|^2 \leq 1$, a lower bound on $|V_{\rm tb}|$ at a 95% CL of $|V_{\rm tb}| > 0.78$ is found using the approach of Feldman and Cousins [14].

Two additional cross-check analyses, based on the event selection above, are conducted: one performing a fit to the ($p_{\rm T}^{\rm sys}$) distribution, the other using a cut and count approach. Both analyses have a loose jet b-tag veto and add a selection requirement on $H_{\rm T}$ for the $e\mu$ final state. The statistical evaluation uses the same method as the BDT analysis and the results from both cross-check analyses are consistent with the multivariate one within uncertainties.

2. Search for Flavor Changing Neutral Currents in tZ events

A novel search for Flavor Changing Neutral Currents (FCNC) in Z associated single-top-quark production in 5 fb^{-1} of proton-proton collisions at 7 TeV is presented. Final states in which both the top quark and the Z boson decay leptonically into electron or muons are investigated, leading to a topology with three leptons, one b jet and $E_T^{miss}$from the top decay. The analysis is sensitive to both production gqt and decay Zqt anomalous couplings. In order to improve statistics the 4 channels (eee, $\mu\mu\mu$, $ee\mu$, $\mu\mu e$) are combined and BDT discriminants are used to disentangle the signal.

The main backgrounds are represented by two categories: events with 3 real leptons (mostly WZ and ZZ plus jets) and events with one fake lepton coming from a mis-reconstructed jet or a non-prompt lepton (mostly Z plus jets). The reconstructed mass of the W (m_T^W) is used both to get a data-driven normalisation of the Z+jets background and to suppress its contribution. In order to discriminate the signal from the main background (diboson plus jets) a multivariate approach based on the variables related to the reconstructed leptons, jets, Z boson and top candidates is used.

Four separate BDTs analyzers, one for each anomalous coupling signal considered, are trained on the respective signal MC and the WZ+jets background. No evidence of signal events is observed so 95%CL exclusion limits on anomalous couplings are calculated from the shapes of the BDT discriminant distributions using a profile likelihood ratio method. Systematic uncertainties are accounted for as nuisance parameters.

The 95% CL exclusion limits, calculated as functions of the κ_{gut}/Λ and κ_{Zqt}/Λ parameters, are shown in Fig. 2. The corresponding limits on the branching fractions $\mathscr{B}(t \to gq)$ and $\mathscr{B}(t \to Zq)$ are computed from the total NNLO top-quark width Γ_{top} [15] and the widths $\Gamma_{t\to gq/t\to Zq}$ of the $t \to gq$ and $t \to Zq$ decays corresponding to values of κ_{gqt}/Λ κ_{Zqt}/Λ at the 95% CL exclusion limits, calculated using MADGRAPH. The branching ratios are then defined as :

$$Br(t \to gq/Zq) = \frac{\Gamma_{t\to gq/t\to Zq}}{\Gamma_{t\to gq/t\to Zq} + \Gamma_{top}}, \tag{2.1}$$

A summary of the expected and observed limits are presented in Table 1.

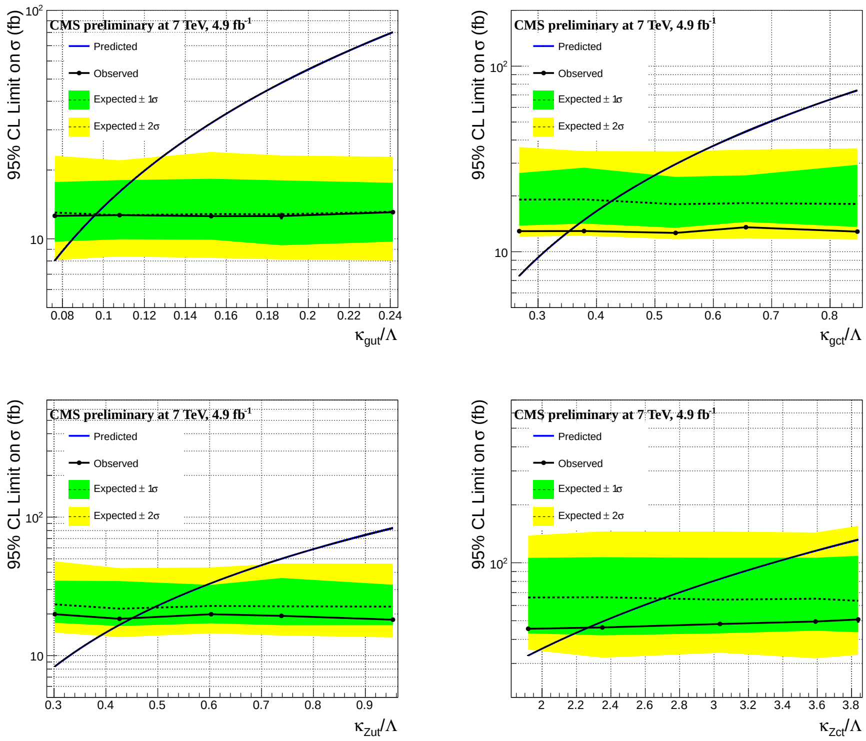

Figure 2: 95% exclusion limit for the *gut* (top left), *gct* (top-right), *Zut* (bottom left) and *Zct* (bottom right) couplings as functions of the κ/Λ parameters. The blue lines shows the predicted cross-section, as calculated by MADGRAPH.

couplings	Expected	Observed	$\mathscr{B}(t \to gq/Zq)$
κ_{gut}/Λ	0.096	0.096	0.56 %
κ_{gct}/Λ	0.427	0.354	7.12 %
κ_{Zut}/Λ	0.492	0.451	0.51 %
κ_{Zct}/Λ	2.701	2.267	11.40 %

Table 1: Expected and observed exclusion limits at 95% CL, and the corresponding limits on the top-quark-decay branching ratios.

3. Conclusions

A search for top-quark anomalous couplings in the FCNC production of a single top-quark in association with a Z-boson, in the tri-leptonic channels was performed using a BDT technique to discriminate between signal and background [2]. No evidence of signal is observed, so 95% CL limits on the parameters of an effective Lagrangian describing in a model-independent way FCN couplings of the top quark to the SM gauge bosons are extracted: $\kappa_{gut}/\Lambda < 0.10$ TeV^{-1}, $\kappa_{gct}/\Lambda < 0.35$ TeV^{-1} , $\kappa_{Zut}/\Lambda < 0.45$ TeV^{-1} and $\kappa_{Zct}/\Lambda < 2.27$ TeV^{-1}. In terms of branching fractions related to rare top decays, these bounds read $\mathscr{B}(t \to gu) \leq 0.56\%$, $\mathscr{B}(t \to gc) \leq 7.12\%$,

$\mathscr{B}(t \to Zu) \leq 0.51\%$ and $\mathscr{B}(t \to Zc) \leq 11.40\%$.

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 [1]. A multivariate analysis is used to discriminate the tW signal from the predominant $t\bar{t}$ background. An excess of events above 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 prediction.

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