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Search for an excited quark decaying in semi-leptonic channel

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Abstract. A search is performed for a pair-produced excited top quark, t^*, that decays to a top quark and a gluon using data collected by the CMS detector from pp collisions at $\sqrt{s}$ = 8 TeV. The search is performed using events that have a single isolated muon or electron, missing transverse momentum, and at least six jets, one of which must be identified as originating from the fragmentation of a b quark. The data analyzed correspond to an integrated luminosity of 19.6 fb^{-1}. No significant excess is observed and we set a lower limit on the t^*-quark mass of 790 GeV/c^2 at 95% confidence level.

1 Introduction

The top quark, discovered in 1995, with its large mass of $173.5 \pm 0.6 \pm 0.8\,\mathrm{GeV}/c^2$ [1], is unique among the fundamental particles. Many theories have emerged surmising that it may be a composite particle rather than an elementary particle. A direct test of this possibility would be to show the existence of an excited top quark (t^*).

In this analysis, we adopt a model in which the t^* quark has spin 3/2 and decays predominantly to a top quark via the emission of a gluon [2, 3]. Such a heavy spin-3/2 excitation of a heavy spin-1/2 quark is governed by the Rarita-Schwinger [4] vector spinor Lagrangian and the rate of production for such a spin-3/2 quark is higher than for a similarly massive spin-1/2 quark.

In string realizations of the Randall-Sundrum (RS) model, the right-handed t^* quark is expected to be the lightest spin-3/2 Regge excitation [2]. The pair-production cross section at $\sqrt{s}$ = 8 TeV has been calculated to be of the order of a few pb for $m_{t^*} = 500\,\mathrm{GeV}/c^2$ [3].

For this analysis, we assume a 100% branching fraction for $t^* \to$ tg, since this decay channel dominates over others. Since mixing between spin-1/2 and spin-3/2 states is suppressed, we consider only pair production of the t^* quark and its antiparticle in this analysis. We consider decay channels having a single lepton in the final state, either a muon or an electron.

2 CMS Detector and Data Samples

The central feature of the Compact Muon Solenoid (CMS) apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass/scintillator hadron calorimeter (HCAL). Muons are measured in gas-ionization detectors embedded in the steel return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. A more detailed description can be found in [5].

The data used in this analysis were recorded during 2012 by the CMS detector at the LHC, utilizing pp collisions at $\sqrt{s}$ = 8 TeV. The data analyzed correspond to an integrated luminosity of 19.6 fb^{-1} and were acquired using triggers that require at least one lepton candidate and at least three central jets

Simulated $t^*\overline{t^*}$ signal events, including up to two additional hard partons, are generated for t^* using the MadGraph 5 [6] event generator with CTEQ6l1 [7] parton distribution functions (PDFs). Generated events are processed through the CMS detector simulation based on Geant4 4.3.1 [8].

3 Event Selection

The selection for the μ+jets channel requires exactly one muon with $p_T > 26\,\mathrm{GeV}/c$, $|\eta| < 2.1$, relative isolation< 0.12, and a transverse impact parameter (longitudinal distance) with respect to the primary vertex < 2 mm (< 5 mm). The e+jets selection requires exactly one electron having $p_T > 30\,\mathrm{GeV}/c$, $|\eta| < 1.5$, relative isolation< 0.1, and an impact parameter with respect to the primary vertex transverse to the beam direction < 0.2 mm. The trigger requirements described in Sec. 2 define the thresholds for the lepton p_T.

Events with exactly one isolated lepton and at least six jets with $p_T > 30\,\mathrm{GeV}/c$ and $|\eta| < 2.5$ are selected. To meet trigger requirements, the leading three jets are required to have transverse momenta of $p_T > 45\,\mathrm{GeV}/c$ in the early data taking period and $p_T > 55\,\mathrm{GeV}/c$, $p_T > 45\,\mathrm{GeV}/c$, and $p_T > 35\,\mathrm{GeV}/c$, respectively, at later times. At least one jet must be b-tagged.

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After imposing our event selection we observe a total of 13636 events in the μ+jets channel and 11643 events in the e+jets channel.

4 Mass Reconstruction

The procedure adopted for reconstructing the mass is described as follows: after assigning the reconstructed objects to the partons from the decays we perform a kinematic fit to improve the resolution of the reconstructed mass of the t^* candidates. In the lepton+jets channel, one W boson decays leptonically, while the other W boson decays hadronically, resulting in the final state:

$$t^*\overline{t^*} \to (\ell\nu b g)(q\bar{q} b g).$$

The momenta of the particles in the final state must satisfy the following constraints:

$$m(\ell\nu) = m(q\bar{q}) = M_W \quad (1)$$
$$m(\ell\nu b) = m(q\bar{q}b) = M_t \quad (2)$$
$$m(\ell\nu b g) = m(q\bar{q}bg) = M_{t+g}, \quad (3)$$

where $M_W = 80.4\,\mathrm{GeV}/c^2$ is the mass of the W boson, $M_t = 173.5\,\mathrm{GeV}/c^2$ is the mass of the top quark, and M_{t+g} is a free parameter that is optimized in the fit.

The reconstructed objects in the event that are assigned to a parton for the fit are the charged lepton, the missing transverse momentum $\not{p}_T$, and the six leading jets. With one unknown and five constraints we perform a kinematic fit by minimizing a χ^2 computed from the difference between the measured momenta of all final-state particles and their fitted values, divided by the measurement uncertainty, subject to the kinematic constraints listed above.

All permutations of jet-quark assignments are considered, subject to the condition that a b-tagged jet must be assigned to one of the b quarks (if multiple jets are tagged, two of them are assigned as b quarks). The jet-quark assignment with the smallest χ^2 value is chosen for reconstructing the event. Figure 1 shows the distribution of the reconstructed top plus gluon mass, M_{t+g} for the μ+jets and e+jets channels.

5 Background Estimation

We use a data-driven method to estimate the background contribution to the signal region. We model the background from standard model sources using a Fermi-like function:

$$f(x) = \frac{a}{1 + e^{\frac{x-b}{c}}}, \quad (4)$$

where x represents the reconstructed mass and a, b, and c are parameters that are determined by a fit to the data. The t^*-signal distribution is modeled using simulated samples. Figure 1 shows the fit to the reconstructed top+gluon mass distribution using Eq. 4.

We fit the background function plus the signal model to the reconstructed mass spectrum observed in data above a mass of $350\,\mathrm{GeV}/c^2$ (the function describes the tail of the background distribution, not the peak at low mass). The three parameters of the background function and the signal cross section are allowed to float during the maximum likelihood fit.

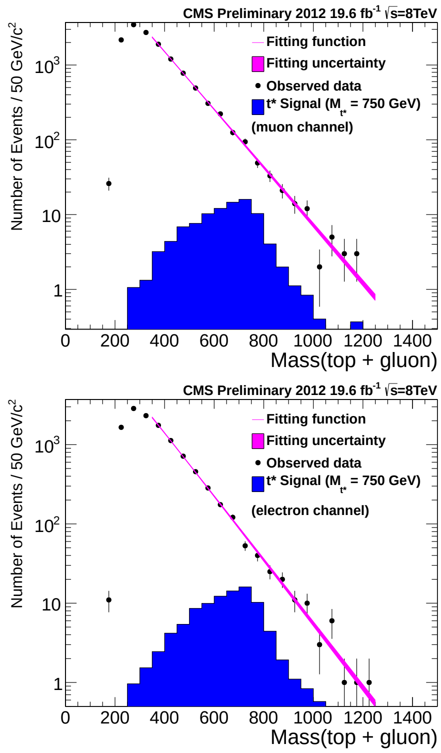

Figure 1. The reconstructed top+gluon mass spectrum for data (points) along with the background fit to the data (curve), and signal distribution (histogram) in the μ+jets (up) and e+jets (down) channels. The reconstructed masses are those of the jet-quark assignment with the smallest χ^2 value for each event.

6 Systematic Uncertainties

Systematic uncertainties influence the signal and background predictions for the M_{t+g} distribution that are used to test whether the observed events are consistent with the signal-plus-background or the background-only hypotheses.

The uncertainty on the background shape is estimated from the uncertainties on the background fit parameters (a, b, c).

Given that the signal shape is based on simulation, we consider it to be affected by both experimental and theoretical uncertainties.

Experimentally, the signal may be affected by a number of sources. The integrated luminosity is known to a precision of 4.4% [9]. We generate the M_{t+g} distribution for values of the jet energy scaled by ±1 standard deviation of the η- and p_T-dependent scale uncertainties from Ref. [10]. We account for the uncertainty related to energy resolution of jets by generating the M_{t+g} distribution after adjusting the smearing by ±1 standard deviation (6–20% depending on η).

Further sources of experimental uncertainty include trigger efficiencies and lepton identification correction factors that are all obtained from data. The systematic uncertainty in the b-tagging efficiency is estimated by varying, one-by-one, the efficiency of tagging jets (from b- or c-jets) and the mis-tag rate (from light-flavor jets) by ± 1 standard deviation [11, 12]. The systematic uncertainty due to the modeling of pileup events is checked by varying the average number of pile-up events by $\pm 4.4\%$.

We estimate the effect of theoretical uncertainties from the PDFs by varying the CTEQ PDF parameters.

7 Limit Calculation

We examine the top plus jet mass spectrum for signs of a t^* quark resonance and compute an upper bound on the $\mathrm{t}^*\overline{\mathrm{t}^*}$ production cross section using Bayesian statistics [13]. The systematic uncertainties on the signal are modeled by nuisance parameters with log-normal priors. The background function plus signal template are used in a fit to the data using the negative log likelihood as a test statistic. The uncertainty on the background shape is incorporated by marginalizing the background-fit parameters using uniform priors. To combine the results from the μ+jets and e+jets channels, we multiply the likelihoods from the two channels together.

8 Results

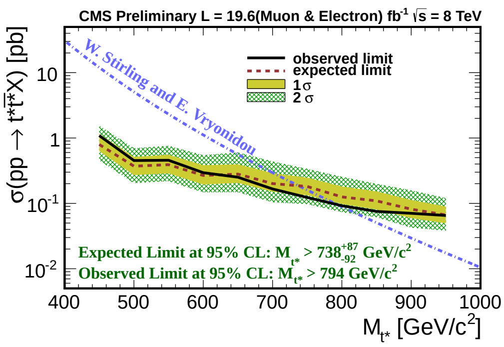

Figure 2. The observed (solid line) and expected (dashed line) 95% CL upper limits for the $\mathrm{t}^*\overline{\mathrm{t}^*}$ production cross section as a function of the t^* mass for combined data. The ± 1 and ± 2 standard deviation ranges for the expected limits are shown by the bands. The theoretical cross section is shown by the dashed-dotted line.

Figure 2 shows the observed and expected upper limits, at 95% CL, for the $\mathrm{t}^*\overline{\mathrm{t}^*}$ production cross section as a function of the t^* mass. The lower limit for the t^* mass is given by the value at which the upper limit curve for the $\mathrm{t}^*\overline{\mathrm{t}^*}$ production cross section intersects the spin-3/2 RS theoretical curve from Ref. [3]. This gives the 95% CL observed (expected) limit for the t^* mass of 790 GeV/c^2 (738^{+87}_{-92} GeV/c^2).

9 Summary

We have conducted a search for excited top quarks that are pair produced in pp interactions and decay exclusively to a standard model top quark and a gluon. Events that have an electron or a muon and at least six jets, one of which is identified as a b-jet, are selected. A kinematic fit assuming $\mathrm{t}^*\overline{\mathrm{t}^*}$ production is performed and a candidate t^* mass is reconstructed for every event. The reconstructed mass has been analyzed in the full $\sqrt{s} = 8$ TeV proton-proton data sample, corresponding to an integrated luminosity of 19.6 fb^{-1}, and no significant deviations from the standard model predictions have been found. In the absence of signs of new physics, upper limits on the production of $\mathrm{t}^*\overline{\mathrm{t}^*}$ are set as a function of the t^* mass. By comparing the results to the predicted cross section for $\mathrm{t}^*\overline{\mathrm{t}^*}$ production in the spin-3/2 RS model, we exclude masses below 790 GeV/c^2 at 95% CL.

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