Search for heavy quarks decaying into a top quark and a W or Z boson using lepton + jets events in pp collisions at s√=7TeV

Citation: Chatrchyan, S., V. Khachatryan, A.M. Sirunyan, A. Tumasyan, et al. "Search for heavy quarks decaying into a top quark and a W or Z boson using lepton + jets events in pp collisions at s√=7 TeV". Journal of High Energy Physics, 154, January 2013, pp. 1-30.

As Published: http://dx.doi.org/10.1007/JHEP01(2013)154

Publisher: Springer-Verlag

Persistent URL: http://hdl.handle.net/1721.1/105126

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: *October 28, 2012*
ACCEPTED: *December 18, 2012*
PUBLISHED: *January 24, 2013*

Search for heavy quarks decaying into a top quark and a W or Z boson using lepton + jets events in pp collisions at $\sqrt{s} = 7$ TeV

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ABSTRACT: Results are presented from a search for the pair-production of heavy quarks, $\mathrm{Q\overline{Q}}$, that decay exclusively into a top quark and a W or Z boson. The search is performed using a sample of proton-proton collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ corresponding to an integrated luminosity of $5.0\,\mathrm{fb}^{-1}$, collected by the Compact Muon Solenoid experiment. The signal region is defined using a sample of events containing one electron or muon, missing transverse momentum, and at least four jets with large transverse momenta, where one jet is likely to originate from the decay of a bottom quark. No significant excess of events is observed with respect to the standard model expectations. Assuming a strong pair-production mechanism, quark masses below 675 (625) GeV decaying into tW (tZ) are excluded at the 95% confidence level.

KEYWORDS: Hadron-Hadron Scattering

ARXIV EPRINT: 1210.7471

doi:10.1007/JHEP01(2013)154

Contents

1 Introduction

New heavy quarks (Q) that decay to top quarks and electroweak bosons (W, Z, or Higgs bosons) appear in many theoretical scenarios, the simplest being the sequential fourth generation model [1]. Experimental constraints on masses of the fourth-generation quarks [2–4] suggest that the dominant decay mode of the down-type fourth-generation quark is to a top quark and a W boson. There are also models [5–7] that include non-chiral heavy quarks with vector-like couplings to bosons. Such quarks cancel quadratically divergent corrections to the Higgs boson mass, and thereby stabilize it at the electroweak symmetry breaking scale. In these models, the new quarks can also decay through flavor-changing neutral-current processes, such as to a top quark and a Z boson, or to a top quark and a Higgs boson.

This Letter presents a search for the pair production of new heavy quarks Q that decay exclusively to a top quark and a W boson, or to a top quark and a Z boson. The current experimental constraints on masses of heavy quarks Q are set by previous LHC searches. If Q exists, its mass must be greater than 480 GeV, assuming the exclusive decay $Q \to tW$ [8], or greater than 475 GeV, assuming the decay $Q \to tZ$ [9]. Given these constraints, the mass splitting between the heavy quark Q and the top quark must be large, so that the decay products can be produced on-shell. For heavy down-type quarks decaying exclusively into a top quark and a W boson, the full decay chain is $Q\overline{Q} \to tW^-\bar{t}W^+ \to bW^+W^-\bar{b}W^-W^+$, and for up-type quarks decaying exclusively into a t quark and a Z boson, it is $Q\overline{Q} \to tZ\bar{t}Z \to bW^+Z\bar{b}W^-Z$. The search is performed in events in which one of the W bosons (originating either from the decay of the heavy quark, or from the subsequent decay of a top quark) decays leptonically, while the other bosons decay into quark-antiquark pairs.

Selected events are required to have exactly one charged lepton, an imbalance in transverse momentum $\not{p}_{\mathrm{T}}$, and at least four jets with high transverse momenta p_{T}, at least one of which is consistent with the decay of a bottom quark.

The dominant standard-model (SM) processes that result in the same signature include $\mathrm{t\bar{t}}$ production, as well as production of W bosons with associated jets. These background processes are characterized by smaller lepton and jet transverse momenta and lower jet multiplicities than those in heavy quark decays. The search for heavy quarks is performed by classifying events based on the number of final-state jets. For each jet multiplicity, the scalar sum (S_{T}) of the transverse momenta of the lepton, the jets, and $\not{p}_{\mathrm{T}}$ are used to test for the presence of a new physics signal in the data. Signatures with high jet multiplicity and large values of S_{T} are predicted in a variety of new physics scenarios [10], making the search presented in this Letter sensitive to a broad class of models of new physics.

2 The CMS detector and data samples

The data were recorded during 2011 by the Compact Muon Solenoid (CMS) experiment at the LHC, which delivered proton-proton collisions at $\sqrt{s} = 7\,\mathrm{TeV}$, and correspond to an integrated luminosity of $5.0\,\mathrm{fb}^{-1}$. The CMS detector uses a polar coordinate system with the z axis pointing along the counterclockwise circulating beam. The x axis points towards the center of the Large Hadron Collider (LHC) ring, and the y axis points up. Angular coordinates are specified by the pseudorapidity $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle measured with respect to the positive z axis, and by ϕ, the azimuthal angle about this axis.

A characteristic feature of the CMS detector is its superconducting solenoid, which is 6 m in diameter and 13 m in length, and provides an axial magnetic field of 3.8 T. Located inside the solenoid is a multilayer silicon-pixel and silicon-strip tracker, covering the pseudorapidity region $|\eta| < 2.5$, the electromagnetic calorimeter (ECAL), covering $|\eta| < 3.0$ made of lead-tungstate crystals, the preshower detector covering $1.65 < |\eta| < 2.6$, and the hadronic calorimeter (HCAL) made of brass and scintillators, covering $|\eta| < 3.0$. Muons are measured with gas-ionization detectors embedded in the return yoke of the solenoid, which cover $|\eta| < 2.4$, and complement the measurement in the inner tracking detector. The CMS detector is nearly hermetic, allowing for momentum balance measurements in the plane transverse to the beam direction. A two-tier trigger system selects the most interesting pp collision events for use in physics analysis. A detailed description of the CMS detector is given in ref. [11].

The e+jets events were collected with triggers requiring at least one electron candidate, with a p_{T} threshold ranging from 25 to 32 GeV. When the LHC instantaneous luminosity increased, at least three jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ were also required. The μ+jets events were collected with triggers that required at least one muon candidate with a p_{T} threshold ranging between 30 and 40 GeV. The presence of jets was not required in the triggers for the μ+jets events, and no conditions were placed on the $\not{p}_{\mathrm{T}}$ for either channel.

The background processes $\mathrm{t\bar{t}}$+jets, W+jets, and Z+jets, are simulated using the MadGraph 5.1.1 event generator [12] with CTEQ6L1 [13] parton distribution functions (PDF). The single top quark production via tW, s and t channels is simulated using the powheg 1.0 event generator [14–16] with CTEQ6M PDF [13]. The multijet and diboson processes

(WW, WZ, and ZZ) are generated using the PYTHIA 6.424 event generator [17] with CTEQ6M PDF. PYTHIA is also used to model the parton shower and hadronization for both MADGRAPH and the POWHEG Monte Carlo (MC) samples. The generated events are processed through a CMS detector simulation based on GEANT4 [18]. Additional minimum-bias events (pileup) are generated with PYTHIA and superimposed on the hard-scattering events to simulate multiple collisions within the same bunch crossing. All the MC simulated events are weighted to reproduce the distribution of the number of interaction vertices observed in data.

3 Event reconstruction

Events are reconstructed using the CMS particle-flow (PF) algorithm [19–21], which identifies all observable particles in an event by combining the information from charged particles in the silicon tracker, energy deposited in the ECAL and HCAL, and signals in the preshower detector and the muon systems. This procedure separates all particles into five categories: muons, electrons, photons, and charged and neutral hadrons. Energy calibration is performed separately for each particle type. The imbalance in transverse momentum $\not{p}_{\mathrm{T}}$ in an event is defined as the negative vector sum of the transverse momenta of all objects from the PF algorithm. Events must also have an acceptable primary vertex, and we select the vertex with the largest value for the scalar sum of the p_{T}^2 of the associated tracks.

Electron candidates are reconstructed from clusters of energy deposited in the ECAL. The clusters are first matched to track seeds in the pixel detector. The track trajectories of electron candidates are reconstructed using a dedicated modeling of the electron energy loss, and fitted with a Gaussian-sum filter [22].

Muon candidates are identified through different reconstruction algorithms using hits in the central silicon tracker and signals in the outer muon system [23]. A standalone muon algorithm uses only information from the muon chambers. The tracker muon algorithm begins with tracks found in the inner tracker, and associates these with matching segments in the muon chambers. In this analysis, all muons have to pass the global muon algorithm, which starts off with the standalone muons and then performs a global fit to the hits in the tracker and the muon system for each muon candidate.

Jets are reconstructed using the anti-k_{T} jet clustering algorithm [24] with a distance parameter $R = 0.5$, as implemented in FASTJET version 2.4 [25–28]. Jets are identified as originating from the decay of a bottom quark through the combined secondary vertex (CSV) algorithm at the medium operating point [29]. The CSV algorithm provides optimal b-tagging performance by combining information on the impact parameter significance, the properties of the secondary vertex, and the jet kinematics. The variables are combined using a likelihood-ratio technique to compute a b-tagging discriminant. The residual differences in the performance of the b-tagging algorithm between data and simulation are accounted for by p_{T}- and η-dependent data/simulation scale factors [29].

4 Event selection

Charged leptons from the decay of W bosons are typically well isolated from jets. The lepton isolation can be expressed in terms of the quantity I_r^ℓ, defined as the scalar sum of the p_{T}

of charged hadrons, neutral hadrons and photons in a cone of $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.3$ around the lepton momentum vector, divided by the lepton p_{T}. The isolation requirements are optimized to be $I_r^{\mathrm{e}} < 0.1$ for electrons, and $I_r^{\mu} < 0.125$ for muons. The electrons (muons) also must have $p_{\mathrm{T}}^{\mathrm{e}} > 35\,\mathrm{GeV}$ ($p_{\mathrm{T}}^{\mu} > 42\,\mathrm{GeV}$), and $|\eta^{\mathrm{e}}| < 2.5$ ($|\eta^{\mu}| < 2.1$). The lepton trajectories are required to have a magnitude of the transverse impact parameter less than 0.02 cm and a magnitude of the longitudinal impact parameter along the beam direction less than 1 cm relative to the primary vertex.

The final selection requires events to have exactly one isolated lepton and at least four jets with $|\eta| < 2.4$ and $p_{\mathrm{T}} > 100$, 60, 50, 35 GeV. Additional jets having $p_{\mathrm{T}} > 35\,\mathrm{GeV}$ are also counted. The minimum number of jets, and the jet p_{T} requirements are optimized to enhance the sensitivity to the $\mathrm{Q\overline{Q}}$ signal. The thresholds for lepton p_{T}^{l} and the third jet p_{T} are driven by trigger conditions. Jets that are within a cone of $\Delta R < 0.3$ of the lepton direction are ignored. At least one jet must be b-tagged by the CSV algorithm. The event is also required to have $\not{p}_{\mathrm{T}} > 20\,\mathrm{GeV}$.

Table 1 lists the number of events observed and the number expected for the background sources, following all selections. The cross section for $\mathrm{t\bar{t}}$ production is taken from ref. [30]. The single top quark cross sections are approximate NNLO calculations obtained from ref. [31–33]. The cross sections for W+jets and Z+jets are computed to NNLO using FEWZ [34]. The cross sections for the diboson processes WW, WZ, and ZZ are calculated to NLO using MCFM [35]. The expected number of SM background events is evaluated based on the cross sections given in table 1, the corresponding efficiencies and acceptances for each background, and integrated luminosity, with exception of the contributions from multijet processes, which are estimated from data. We perform a fit of SM contributions, normalized as described above, to the $\not{p}_{\mathrm{T}}$ distribution in data. In the fit, we constrain the $\mathrm{t\bar{t}}$+jets contribution within its measured uncertainty, while Z+jets, single top and diboson production processes are constrained within their theoretical uncertainties. The normalizations for the W+jets and multijet contributions are allowed to float freely. We obtain multijet scale factors as a function of the lepton η and use them to correct for the multijet normalization from simulation. For μ+jets, the multijet background using this technique is found to be negligible.

Table 2 presents the $\mathrm{Q\overline{Q}}$ production cross sections that are computed at approximate NNLO using HATHOR [36], along with the expected number of events for the e+jets and μ+jets channels.

5 Likelihood fit and systematic uncertainties

The search for a $\mathrm{Q\overline{Q}}$ signal is performed by fitting the data to the distribution of S_{T} as a function of jet multiplicity (N_J). The fit is performed for the combination of e+jets and μ+jets channels and for $N_J = 4$, 5, 6, and ≥ 7 jets. The bins are chosen so that the MC statistical uncertainty in each bin is less than 17%.

The dominant SM background is from $\mathrm{t\bar{t}}$ production. Because the jet multiplicity for the $\mathrm{t\bar{t}}$+jets events is not well modeled, the $\mathrm{t\bar{t}}$ contributions for $N_J = 4$, 5, 6, and ≥ 7 are allowed to vary independently in the fit. A log-normal constraint is imposed on the expected

Background process	Cross section	e+jets events	μ+jets events
$\mathrm{t\bar{t}}$+jets	154 ± 19 pb	7521 ± 38	7190 ± 37
Single top	84.9 ± 2.5 pb	399 ± 4	391 ± 4
W+jets	31 ± 2 nb	798 ± 16	790 ± 16
Z+jets	3.1 ± 0.3 nb	104 ± 3	63 ± 2
Diboson (WW, WZ, ZZ)	67 ± 2 pb	17 ± 1	15 ± 1
Multijet	from data	334 ± 8	—
Total background		9173 ± 42	8449 ± 41
Data		9109	8211

Table 1. Background cross sections, expected number of background events and observed number of events in 5.0 fb^{-1} data, for the e+jets and μ+jets samples prior to the likelihood fit. The uncertainties on the expected number of events reflect only the statistics of the simulation. The quoted uncertainties on the cross sections are theoretical or measured in the case of $\mathrm{t\bar{t}}$+jets.

M_{Q} (GeV)	σ (pb)	$\mathrm{Q} \to \mathrm{tW}$ e+jets	$\mathrm{Q} \to \mathrm{tW}$ μ+jets	$\mathrm{Q} \to \mathrm{tZ}$ e+jets	$\mathrm{Q} \to \mathrm{tZ}$ μ+jets
500	0.33	136.9 ± 1.4	137.0 ± 1.4	91.2 ± 1.2	85.9 ± 1.1
550	0.17	74.6 ± 0.8	74.9 ± 0.8	49.1 ± 0.6	46.7 ± 0.6
600	0.092	41.2 ± 0.4	41.7 ± 0.4	27.1 ± 0.3	26.1 ± 0.3
650	0.051	22.9 ± 0.2	23.4 ± 0.2	15.9 ± 0.3	15.1 ± 0.3

Table 2. Signal cross sections [36] and expected number of $\mathrm{Q\bar{Q}}$ signal events in the e and μ channels for four quark masses. The uncertainties reflect the statistics of the MC simulations.

yield of $\mathrm{t\bar{t}}$ events for each jet multiplicity sub-sample. The normalization uncertainty for each sub-sample is determined from the difference that results from changing the renormalization and factorization scales by a factor of two relative to the nominal value equal to $Q = \sqrt{m_{\mathrm{t}}^2 + \sum p_{\mathrm{T,jet}}^2}$, where the sum is taken over jets produced in association with the $\mathrm{t\bar{t}}$ pair. The inclusive top quark pair production cross section $\sigma_{\mathrm{t\bar{t}}}$ and its uncertainty are taken from the recent CMS measurement [30]. The uncertainty on $\sigma_{\mathrm{t\bar{t}}}$ is used in the fit as a log-normal constraint correlated between different jet multiplicities.

Other SM contributions include electroweak processes: W+jets, Z+jets, single top quark, and diboson production, as well as multijet events. They are combined into a single background template. The sum of these backgrounds is allowed to vary independently across each jet multiplicity sub-sample, with an uncertainty of 50% assigned to the normalization of each sub-sample.

The luminosity is constrained to a log-normal distribution with an uncertainty of 2.2% [37]. The electron and muon trigger and identification efficiencies are obtained from data using dilepton decays of Z bosons. A conservative systematic uncertainty of 3.5% is attributed to account for pileup and lepton η dependence. These efficiencies together with their uncertainties are treated as normalization constraints, and applied to the electron and muon events respectively.

In addition to constraints on normalization, there are other parameters that affect both the normalization and the shape of S_{T} and the jet multiplicity spectra. These include the jet energy scale, the b-tagging efficiency, the matching between matrix element partons and parton showers and the renormalization and factorization scales. We incorporate these uncertainties in the fit by generating additional templates corresponding to shifts by ± 1 standard deviation on the parameter in question. The energies of the jets are corrected using the calibration constants determined in ref. [38] as a function of p_{T} and η. The uncertainties on b-tagging efficiencies are estimated by changing the b-tagging efficiency by ±1 of its standard deviation [29]. The uncertainty due to the choice of factorization and renormalization scales is estimated by simulating two sets of $\mathrm{t\bar{t}}$ samples in which both scales are increased or decreased by a factor of two relative to their nominal value. The uncertainty arising from matching matrix element partons with parton showers is estimated using two $\mathrm{t\bar{t}}$ simulated samples, with matching threshold shifted up or down by a factor of two relative to its default value (40 GeV). Other sources of systematic uncertainties, such as jet energy resolution, $\not{p}_{\mathrm{T}}$ resolution and pileup interactions have negligible impact on the limit for a $\mathrm{Q\overline{Q}}$ signal.

Systematic uncertainties enter the likelihood through "nuisance" parameters [39], that reflect the presence of imprecisely determined quantities that affect the S_{T} and jet multiplicity distributions. These are represented by resolution functions contained within the likelihood function, and are integrated over in the process of minimization, resulting in a reduction in the final systematic uncertainty.

Table 3 summarizes the systematic uncertainties included in the fit to S_{T} and N_J. Parameters labeled "Distribution" affect both shape and normalization of the S_{T} and N_J distributions, where only their effect on background normalization is quoted. Parameters labeled "Normalization" affect only the normalization of SM backgrounds and/or new physics signal.

The S_{T} distributions for different jet multiplicities are combined, and shown in figure 1, after the maximum-likelihood fit to data. No excess over the predicted SM background is observed, and we proceed to set an upper limit on the $\mathrm{Q\overline{Q}}$ cross section. The upper limit is extracted using a frequentist $\mathrm{CL_s}$ technique [40, 41] with an asymptotic approximation. The following likelihood ratio is used as a test statistic:

$$t(x|\sigma) = \begin{cases} L(x|\sigma, \hat{\nu}_\sigma)/L(x|\hat{\sigma}, \hat{\nu}) & \text{if } \sigma > \hat{\sigma} \\ 1 & \text{if } \sigma \leq \hat{\sigma}, \end{cases} \tag{5.1}$$

where $L(x|\sigma, \nu)$ is the likelihood that x is observed in data, given a hypothesized value of the $\mathrm{Q\overline{Q}}$ cross section and "nuisance" parameters ν. The values of σ and ν for which the likelihood reaches its maximum value are denoted $\hat{\sigma}$ and $\hat{\nu}$, respectively. The symbol $\hat{\nu}_\sigma$ refers to the values of the parameters ν that maximize the conditional likelihood for any given value of σ.

The probability to observe a value of t for the likelihood ratio that is larger than the observed value t_{obs} is determined using pseudo-experiments in which the expected

Parameter type	Source	Uncertainty (%)
Distribution	Q^2 scales for $t\bar{t}$+jet	8.7
	Matching partons	5.8
	Jet energy scale	5.4
	b-tagging efficiency	5.1
Normalization	Lepton ID/reco/trigger	3.5
	Luminosity	2.2
	$t\bar{t}$ cross section	12
	$N_{\text{jets}} = 4$	3.5
	$N_{\text{jets}} = 5$	16
	$N_{\text{jets}} = 6$	23
	$N_{\text{jets}} \geq 7$	22
	Other backgrounds	50

Table 3. List of systematic uncertainties included in the likelihood fit. Parameters labeled "Distribution" affect both shape and normalization of the S_{T} and N_J distributions. The quoted uncertainties correspond to their effect on normalization only.

numbers of signal and background events are allowed to vary according to their statistical and systematic uncertainties. For pseudo-experiments generated assuming a background-only hypothesis, the probability is denoted by CL_{b}. For pseudo-experiments assuming background plus signal with a cross section σ, the probability is denoted by $\mathrm{CL}_{\mathrm{s+b}}(\sigma)$. The 95% confidence level (CL) upper limit for the $\mathrm{Q\overline{Q}}$ cross section is the value of σ for which the ratio of $\mathrm{CL}_{\mathrm{s+b}}(\sigma)$ and CL_{b}, denoted as CL_{s}, is 0.05.

We also verify that the negative log likelihood is minimized at the value corresponding to the global minimum. We evaluate the likelihood as a function of the ν parameters and check for secondary minima. No such minima are observed, and the data constrain the nuisance parameters well within their a priori assumptions. Following the maximization of the likelihood, the dominant uncertainty is from the matching between matrix element partons and parton showers. To quantify this effect, the likelihood minimization is performed excluding the parton matching systematic uncertainty. This results in reduction of the upper limit on the signal cross section for $M_{\mathrm{Q}} = 600\,\mathrm{GeV}$ by 5%, and an increase in the exclusion limit by 15 GeV. This procedure provides an estimate of the impact of this uncertainty.

6 Results

Figure 2 shows the observed and expected 95% CL upper limit on the $\mathrm{Q\overline{Q}}$ production cross section, $\sigma_{\mathrm{Q\overline{Q}}}$, for a down-type heavy quark decaying exclusively to tW. The lower mass limit is determined by the value at which the observed upper limit curve for $\sigma_{\mathrm{Q\overline{Q}}}$ crosses the theoretical expectation. The observed (expected) limit corresponds to 675 (625) GeV.

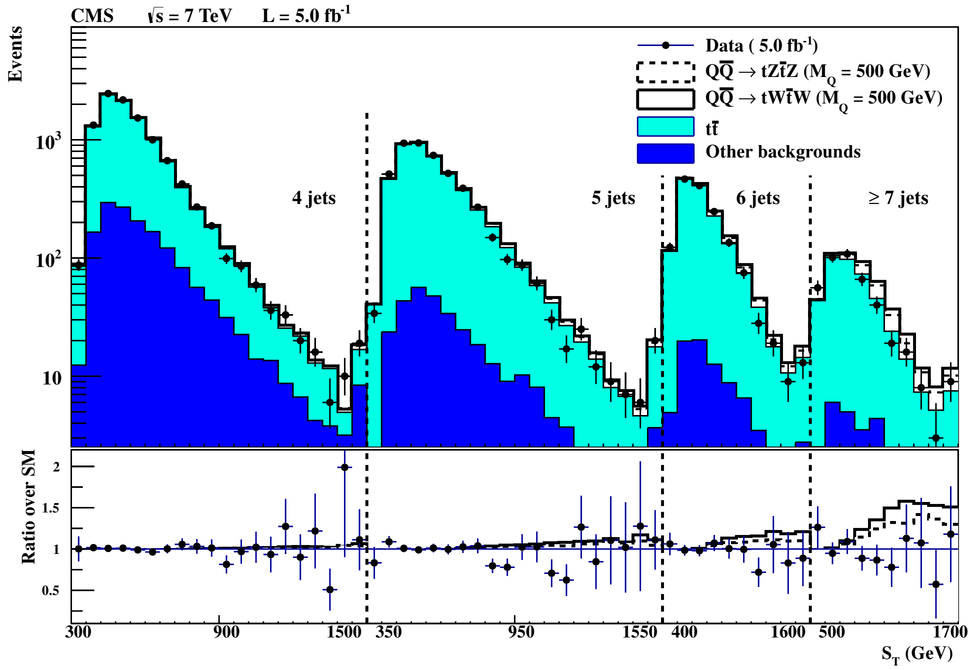

Figure 1. Distribution in S_{T} for different jet multiplicities after the maximum-likelihood fit to data. The last bin in each subfigure is the overflow bin.The bottom plot shows the ratios of data and SM plus signal over SM. Q → tW and Q → tZ distributions are shown for illustrative purposes for $M_{\mathrm{Q}} = 500\,\mathrm{GeV}$.

Figure 3 shows the observed and expected 95% CL upper limit on the $\sigma_{\mathrm{Q\overline{Q}}}$ as a function of quark mass (Q) for an up-type heavy quark decaying exclusively to tZ. The observed (expected) limit corresponds to 625 (550) GeV.

Several cross checks have been performed to investigate the difference between the observed and expected limits. We studied several models of the $\mathrm{t\bar{t}}$ S_{T} spectrum by using different generators, such as PYTHIA and POWHEG. All of the generators provide results similar to MadGraph within their systematic uncertainties. We also studied different models of the $\mathrm{t\bar{t}}$ S_{T} spectrum by changing internal parameters in MadGraph, such as the renormalization and factorization scales and the parameters responsible for matching jets originating from matrix element partons to their showers. We determine that a change of the matching parameters by one standard deviation from their nominal values provides good agreement between the simulated and observed spectrum of the S_{T} distribution, which can be accommodated in the fit because of the relatively weak dependence of the minimum on this parameter. The dependence of the S_{T} distribution for $\mathrm{t\bar{t}}$ background is covered by the systematic uncertainties included in the fit of the model to data.

7 Summary

A search for pair-produced new heavy quarks $\mathrm{Q\overline{Q}}$ decaying exclusively to $\mathrm{tW\bar{t}W}$ or to $\mathrm{tZ\bar{t}Z}$ is performed in lepton + jets events. The analysis is based on a data sample of proton-

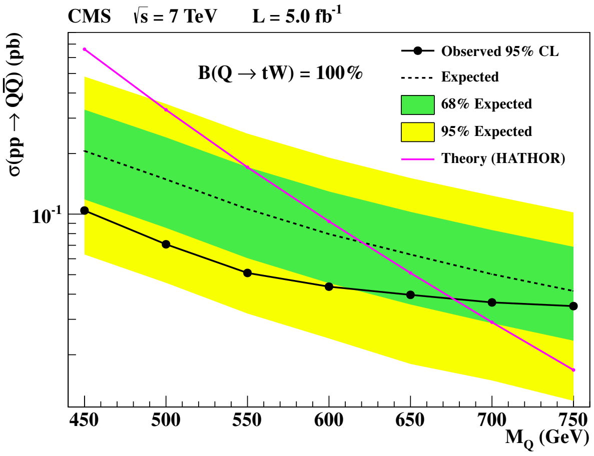

Figure 2. The observed (solid line with points) and the expected (dashed line) 95% CL upper limits on the $\mathrm{Q\overline{Q}}$ production cross section as a function of the heavy quark mass, M_Q, compared to the theoretical $\mathrm{Q\overline{Q}}$ cross section for the case of a down-type heavy quark decaying exclusively to tW.

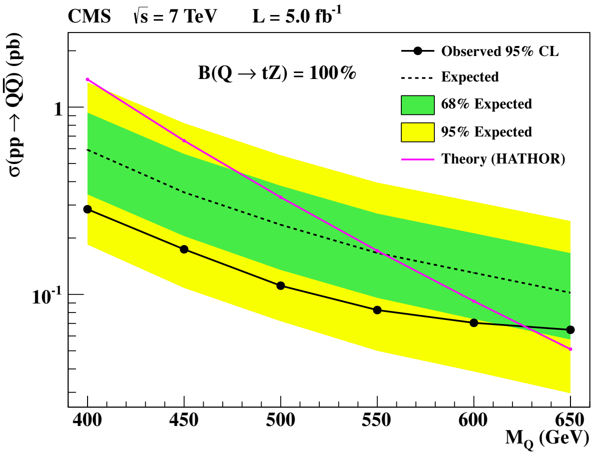

Figure 3. The observed (solid line with points) and the expected (dashed line) 95% CL upper limits on the $\mathrm{Q\overline{Q}}$ production cross section as a function of the heavy quark mass, M_Q, compared to the theoretical $\mathrm{Q\overline{Q}}$ cross section for the case of an up-type heavy quark decaying exclusively to tZ.

proton collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ corresponding to an integrated luminosity of $5.0\,\mathrm{fb}^{-1}$. Events are selected requiring an electron or a muon, missing transverse momentum, and at least four jets, one of which is identified as a bottom jet. A combined fit is performed to the scalar sum of the transverse momenta of all final reconstructed objects as a function of jet multiplicity. No significant deviations from SM expectations are found, and upper limits on the production cross section of $\mathrm{Q\overline{Q}}$ as a function of a heavy quark mass are computed. Assuming a strong production mechanism for both signal models, down-type quarks decaying exclusively to tW with masses below 675 GeV and up-type quarks decaying exclusively to tZ with masses below 625 GeV are excluded at 95% CL. These are the most stringent limits to date.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from: FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MSI (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MON, RosAtom, RAS and RFBR (Russia); MSTD (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA).

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