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Search for a heavy resonance decaying into a top quark and a W boson in the lepton+jets final state at $\sqrt{s} = 13\,\text{TeV}$

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Abstract

A search for a heavy resonance decaying into a top quark and a W boson in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ is presented. The data analyzed were recorded with the CMS detector at the LHC and correspond to an integrated luminosity of $138\,\text{fb}^{-1}$. The top quark is reconstructed as a single jet and the W boson, from its decay into an electron or muon and the corresponding neutrino. A top quark tagging technique based on jet clustering with a variable distance parameter and simultaneous jet grooming is used to identify jets from the collimated top quark decay. The results are interpreted in the context of two benchmark models, where the heavy resonance is either an excited bottom quark b^* or a vector-like quark B. A statistical combination with an earlier search by the CMS Collaboration in the all-hadronic final state is performed to place upper cross section limits on these two models. The new analysis extends the lower range of resonance mass probed from 1.4 down to 0.7 TeV. For left-handed, right-handed, and vector-like couplings, b^* masses up to 3.0, 3.0, and 3.2 TeV are excluded at 95% confidence level, respectively. The observed upper limits represent the most stringent constraints on the b^* model to date.

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1 Introduction

The remarkable success of the standard model (SM) of particle physics is built upon extensive experimental tests and verifications. However, there are indications that extensions of the SM are needed to explain observed phenomena. Many possibilities for physics beyond the SM have been proposed, including a scenario of compositeness, where excited states of quarks are predicted to exist [1]. These states can have masses of the order of 1 TeV and can be probed in high-energy proton-proton (pp) collisions [2]. Evidence for such new physics could be signaled by the observation of a heavy resonance that decays into a top quark (t) and a W boson [3, 4]. In this paper, we present a search for such a resonance using pp collision data at $\sqrt{s} = 13\,\text{TeV}$ collected by the CMS experiment [5] at the CERN LHC, corresponding to an integrated luminosity of $138\,\text{fb}^{-1}$.

A model where a heavy resonance takes the form of an excited bottom quark (b^*) is used as a benchmark scenario. In pp collisions, a b^* would be singly produced via the strong interaction, described by the following effective Lagrangian

$$\mathcal{L}_1 = \frac{g_\mathrm{s}}{2\Lambda} G_{\mu\nu} \overline{\mathrm{b}} \sigma^{\mu\nu} \left(\kappa_\mathrm{L}^\mathrm{b} P_\mathrm{L} + \kappa_\mathrm{R}^\mathrm{b} P_\mathrm{R} \right) \mathrm{b}^* + \text{h.c.}, \tag{1}$$

where g_s is the strong coupling constant, $G_{\mu\nu}$ is the field strength tensor of the gluon, b is the bottom quark field, b^* is the excited b quark field, $\sigma^{\mu\nu}$ is the Pauli spin matrix, and Λ is the scale of compositeness, chosen to be the b^* mass [2]. The left- and right-handed chiral projection operators are P_L and P_R, with respective relative coupling strengths $\kappa_\mathrm{L}^\mathrm{b}$ and $\kappa_\mathrm{R}^\mathrm{b}$.

The possible b^* decay modes include bg, bZ, bH and tW. The decay to tW is predicted to be dominant for b^* masses $m_{\mathrm{b}^*} > 700\,\text{GeV}$, approaching a branching fraction of 40% [4]. This decay can be described by the following effective Lagrangian

$$\mathcal{L}_2 = \frac{g_2}{\sqrt{2}} \mathrm{W}_\mu^+ \bar{\mathrm{t}} \gamma^\mu \left(g_\mathrm{L} P_\mathrm{L} + g_\mathrm{R} P_\mathrm{R} \right) \mathrm{b}^* + \text{h.c.}, \tag{2}$$

where g_2 is the $SU(2)_L$ weak coupling constant, γ^μ are the gamma matrices, and g_L and g_R are the relative coupling strengths of the W boson field W_μ^+ to the left- and right-handed b^* chirality states, respectively. Three choices of coupling parameters are considered: purely left-handed (LH) ($g_\mathrm{L} = 1$, $\kappa_\mathrm{L}^\mathrm{b} = 1$, $g_\mathrm{R} = 0$, $\kappa_\mathrm{R}^\mathrm{b} = 0$), purely right-handed (RH) ($g_\mathrm{L} = 0$, $\kappa_\mathrm{L}^\mathrm{b} = 0$, $g_\mathrm{R} = 1$, $\kappa_\mathrm{R}^\mathrm{b} = 1$) and vector-like (VL) ($g_\mathrm{L} = 1$, $\kappa_\mathrm{L}^\mathrm{b} = 1$, $g_\mathrm{R} = 1$, $\kappa_\mathrm{R}^\mathrm{b} = 1$).

Searches for a b^* in the tW decay channel have been performed at $\sqrt{s} = 7$ and $8\,\text{TeV}$ by the ATLAS [6, 7] and CMS [8] Collaborations. In these analyses, the highest mass limits for LH, RH and VL couplings were obtained by the CMS Collaboration with values of 1.4, 1.4 and 1.5 TeV [8] at 95% confidence level (CL), respectively. A recent analysis [9] by the CMS Collaboration in the all-hadronic final state used the same pp collision data as the present paper. The analysis considered b^* masses above 1.4 TeV and improved the limits to 2.6, 2.8 and 3.1 TeV for LH, RH and VL couplings, respectively. Masses below 1.4 TeV were inaccessible to that analysis because of high trigger thresholds, where the presence of highly energetic jets was required to record events.

The analysis presented here is performed in the ℓ+jets final state, where ℓ denotes an electron or a muon. The analysis targets the $\mathrm{W} \to \ell\nu$ and $\mathrm{t} \to \mathrm{Wb} \to \mathrm{q\overline{q}'b}$ decay, where the t quark decay is reconstructed using a single jet with adaptive angular size, obtained with the Heavy Object Tagger with Variable R (HOTVR) [10] algorithm. The probed final state consists of one lepton, missing transverse momentum (p_T^miss), and one jet with high transverse momentum

(p_T), identified by its substructure to originate from collimated t quark decay products [11, 12]. The presence of a lepton in the final state allows the use of lepton triggers with lower p_T thresholds than jet triggers, thus extending the range of the analysis down to b^* masses of 0.7 TeV. In order to achieve a stable selection efficiency over a large range of probed b^* masses, the HOTVR algorithm is employed for the identification of collimated t quark decays. The t jet, lepton and p_T^{miss} are used to reconstruct the invariant mass of the tW system, M_{tW}. The spectrum of M_{tW} is used to search for the heavy resonance, using a binned maximum likelihood fit to data in both a signal and a control region simultaneously with the distributions of the all-hadronic search, mentioned above.

Finally, the results are interpreted for evidence of the production of a vector-like quark, B [13, 14], decaying into tW, which has a similar signature to the b^* quark decay described above. The mixing parameter V_{tB}^{L} in the considered model, defined in Ref. [13], is set to unity, resulting in a resonance with a relative width of less than 5% in the probed B mass range and a branching fraction to tW of approximately 50%. In contrast to the b^* model, the vector-like B quark is produced via an electroweak interaction in association with either a t quark (B+t) or a b quark (B+b). Besides the third generation quarks produced together with the heavy resonance, the electroweak interaction results in an additional jet at leading order (LO), which is not present in the b^* model at this order. We consider both B production modes, but the search is not optimized for these more complex final states.

Tabulated results are provided in the HEPData record for this analysis [15].

2 Data and simulated samples

This analysis uses pp collision data at $\sqrt{s} = 13$ TeV recorded by the CMS detector in the years 2016, 2017 and 2018. The data were recorded with electron and muon triggers [16]. For the electron trigger, an isolated electron candidate with $p_T > 27$, 35 and 32 GeV was required in the years 2016, 2017 and 2018, respectively. To recover trigger inefficiencies at high electron p_T, events are accepted if recorded with a trigger requiring a photon candidate with an energy $E > 175$ GeV in the year 2016, and $E > 200$ GeV in the years 2017 and 2018. For the muon trigger [17], an isolated muon candidate with $p_T > 24$ (27) GeV was required in 2016 and 2018 (2017). Varying trigger thresholds reflect the changing experimental conditions between the years. The data set corresponds to an integrated luminosity of 138 fb^{-1}. Data and simulation are categorized by year, and dedicated corrections are applied before combining the distributions from all three years to derive the final result.

The SM production of top quark-antiquark pairs ($t\bar{t}$) in the ℓ+jets final state constitutes the main background for this search. It is simulated at next-to-leading order (NLO) with the POWHEG v2 [18–22] matrix element generator. Single t quark production in association with a W boson has the same signature as the signal, making it an irreducible background. Single top quark production in the s and t channels is considered as well, but its contribution is small. The tW and t-channel events are produced at NLO with POWHEG v2, while s-channel events are produced at LO with MADGRAPH5_aMC@NLO [23, 24] in version 2.2.2 for 2016 and version 2.4.2 for 2017 and 2018. The cross section for the $t\bar{t}$ background is adjusted to a prediction at next-to-next-to-leading order (NNLO) precision in perturbative quantum chromodynamics (QCD), including resummation of next-to-next-to-leading-logarithmic soft gluon terms, obtained with TOP++ 2.0 [25]. The cross section of single t quark production in association with a W is adjusted to NNLO approximate calculations taken from Refs. [26, 27]. The s- and t-channel cross sections are adjusted to predictions at NLO precision obtained with HATHOR v2.1 [28].

Because of a difference between data and simulation in the top quark p_T spectrum in $t\bar{t}$ production [29, 30], the top quark p_T in the $t\bar{t}$ simulation is corrected using the procedure described in Section 3 of Ref. [9]. A weight is assigned to each event, proportional to $\exp(-\beta p_T)$, which results in a softer simulated p_T spectrum than predicted by POWHEG. The free parameter β is initialized to $0.5\,\text{TeV}^{-1}$ and later determined in a fit to data, as described below in Sec. 7.

Simulated background events from the production of electroweak vector bosons in association with jets (W/Z + jets) and diboson production are used in the data-driven background estimation described in Section 5. The W/Z + jets samples are simulated with MADGRAPH5_aMC@NLO at NLO precision. Diboson events are produced at LO using the PYTHIA event generator [31] in version 8.212 for 2016 and version 8.230 for 2017 and 2018.

The simulations of b^* and vector-like B production and decay are performed at LO using the MADGRAPH5_aMC@NLO generator. The five-flavor scheme is used in the simulation of the initial state. Masses in the range of 0.7 to 4.0 TeV are used with LH and RH b^* couplings. The VL b^* samples are obtained as the sum of the respective LH and RH samples. The B signal samples are simulated using 2016 conditions and then scaled to the luminosity of the full data set. We estimate the selection efficiencies in the years 2017 and 2018 by calculating the differences in selection efficiencies between 2016 and 2017/2018 using the b^* simulations. Separate signal samples for the B+t and B+b production modes are simulated for B masses between 0.7 and 1.8 TeV.

The parton shower and hadronization are simulated using PYTHIA 8.212 with the CUETP8M1 [32] underlying event tune for the 2016 simulation of samples other than $t\bar{t}$, while the CUETP8M2T4 [33] tune is used for the simulation of $t\bar{t}$. For the 2017 and 2018 simulations, PYTHIA 8.230 is used with the CP5 [34] tune. The NNPDF3.0 [35] parton distribution functions (PDFs) are used for 2016 simulation and the NNPDF3.1 [36] PDFs are used for 2017 and 2018 simulations. Additional inelastic pp collision events are simulated using PYTHIA and superimposed on simulated events to model the effect of additional pp collisions within the same or adjacent bunch crossings (pileup). We use a total inelastic cross section of 69.2 mb [37] to estimate the expected number of pp interactions per bunch crossing and correct the simulation to match the corresponding distribution to that observed in data. The CMS detector simulation is performed with GEANT4 [38].

3 The CMS detector and event reconstruction

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are silicon pixel and strip tracking detectors, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [5]. Between the 2016 and 2017 data taking runs, the CMS pixel detector was upgraded. Details about the changes can be found in Ref. [39].

Events of interest are selected using a two-tiered trigger system. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 μs [40]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [16].

A particle-flow (PF) algorithm [41] aims to reconstruct and identify each individual particle in an event, using an optimized combination of information from the various elements of the CMS detector. The energy of photons is obtained from the ECAL measurement. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracking detectors, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track [42]. The energy of muons is obtained from the curvature of the corresponding track [43]. The energy of charged hadrons is determined from a combination of their momentum measured in the tracking detectors and the matching ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies. The candidate vertex with the largest sum of the square of the transverse momenta p_{T}^2 of the physics objects is taken to be the primary pp interaction vertex. The physics objects are the jets, clustered using the jet finding algorithm [44, 45] with the tracks assigned to candidate vertices as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the p_{T} of those jets. More details are given in Section 9.4.1 of Ref. [46].

Electrons and muons are required to fulfill $|\eta| < 2.4$ and $p_{\mathrm{T}} > 30\,\mathrm{GeV}$. We require tight quality criteria with small misidentification probabilities of about 1% for electrons [42] and 0.1% for muons [43]. In addition, electrons and muons are required to be isolated, where the relative isolation is measured by the p_{T} sum of all PF particles in a cone around the lepton relative to the lepton p_{T} [43, 47]. The cone is defined by a distance in $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ of 0.3 for electrons and 0.4 for muons, where ϕ is the azimuthal angle. The isolation must be less than $0.0445 + 0.963\,\mathrm{GeV}/E_{\mathrm{T}}$ for electrons, with E_{T} the transverse energy of the electron, and less than 0.15 for muons. The lepton isolation is corrected for the contribution of neutral hadrons from pileup. The identification, isolation, and trigger efficiencies are measured in dedicated analyses and are adjusted in simulation to match those in data.

Jets are reconstructed from PF candidates, using the anti-k_{T} [44] or HOTVR [10] algorithm, as implemented in the FASTJET software package [45]. The anti-k_{T} jets are obtained using a distance parameter of $R = 0.4$, and referred to as "AK4 jets". For these jets, charged PF candidates are excluded from the clustering if their tracks are matched to pileup vertices. The HOTVR algorithm makes use of an effective distance parameter R_{eff}, scaling with ρ/p_{T} [48]. The parameter ρ controls the slope of R_{eff} and p_{T} denotes the jet p_{T}. The slope parameter is set to $\rho = 600\,\mathrm{GeV}$. The maximum of R_{eff} is set to 1.5, such that jets with $p_{\mathrm{T}} < 400\,\mathrm{GeV}$ do not have an active area [49] larger than Cambridge/Aachen [50, 51] jets with $R = 1.5$. Jet grooming is performed during the jet clustering, by suppressing the clustering of additional radiation into the jet using a veto based on the mass jump algorithm [52] in each iteration. This veto rejects light clusters if the product of the combined mass of two clusters and the mass jump parameter θ is smaller than the mass of the heavier cluster. In this step, subjets are also identified. The HOTVR parameters are set to the values described in Ref. [53]. The pileup per particle identification (PUPPI) algorithm [54, 55] is used to mitigate the effects of pileup, where HOTVR jets are clustered using PUPPI-corrected PF candidates. Jet energy corrections [56] are applied to AK4 jets and HOTVR subjets. We have verified that the corrections derived for AK4 jets clustered with PUPPI are suitable for correcting HOTVR subjets, using a sample enriched with events from $\mathrm{t\bar{t}}$ production. The corrected HOTVR jet four-momentum is obtained from the sum of corrected subjet four-momenta. The jet energy resolution in simulated events is smeared to match the resolution in data.

The presence of boosted t quarks from the b^* decay with Lorentz factors larger than approximately 1.5 allows one to reconstruct the full hadronic t decay in a single HOTVR jet. Information about the jet substructure enables discrimination of these t jets from jets originating from light quarks and gluons. A stable performance over a wide range of jet p_T is obtained by using HOTVR jets for t tagging, because of the adaptive jet size. The following selection criteria for HOTVR jets are used:

- the p_T fraction of the leading subjet s_1 with respect to the jet, $f_{p_T} = p_T^{s_1} / p_T^{jet} < 0.8$,
- the number of subjets $N_{sub} \geq 3$,
- the jet mass $140 < m_{jet} < 220\,\text{GeV}$, and
- the minimum mass of pairs of subjets $m_{min} = \min(\sqrt{(P_i + P_j)^2}) > 50\,\text{GeV}$.

Additionally, a requirement on the ratio of the N-subjettiness [57, 58] variables $\tau_3/\tau_2 < 0.56$ is imposed to further increase the discrimination power against the QCD background [53]. The resulting t tagging algorithm has an efficiency of 25% at $p_T = 200\,\text{GeV}$, increasing to 40% at $p_T = 2\,\text{TeV}$, with a constant misidentification rate for jets from QCD multijet scattering of about 1%. A comprehensive comparison of t tagging algorithms in CMS can be found in Ref. [53]. Covering a larger range in t quark p_T than comparable tagging algorithms, HOTVR offers a straightforward solution to extend the sensitivity of the analysis from the highly boosted regime to a kinematic regime where the t quark decay products can be resolved, in a single approach.

The relatively long lifetime of bottom hadrons can result in a secondary vertex in events with b quarks. These secondary vertices can be reconstructed with information from the tracking detectors in CMS and used to distinguish b jets from light-quark and gluon jets (referred to in what follows as “light jets”). The DEEPJET b tagging algorithm [59] with the medium working point is used to identify AK4 b jets arising from the t quark decay, with a selection efficiency of 80–85% and a misidentification rate for light jets of 1%.

The missing transverse momentum vector $\vec{p}_T^{miss}$ is computed as the negative vector sum of the transverse momenta of all the PF candidates in an event, and its magnitude is denoted as p_T^{miss} [60]. The $\vec{p}_T^{miss}$ is modified to account for corrections to the energy scale of the reconstructed AK4 jets in the event.

4 Event selection

In the offline analysis, we select events with exactly one isolated lepton with $p_T > 50\,\text{GeV}$ and $|\eta| < 2.4$. Events with an additional lepton with $p_T > 30\,\text{GeV}$ and $|\eta| < 2.4$ are discarded. The selected lepton does not overlap with any AK4 jet because of the requirement $\Delta R(\ell, \text{jet}) > 0.4$. To account for the presence of a neutrino from the leptonic W decay in the final state, $p_T^{miss} > 50\,\text{GeV}$ is required and $\vec{p}_T^{miss}$ must point in roughly the same azimuthal direction (to within $\Delta\phi(\ell, \vec{p}_T^{miss}) < \pi/2$) as the momentum of the isolated lepton. The SM backgrounds are suppressed by requiring $H_T > 200\,\text{GeV}$, where H_T is the p_T-sum of all AK4 jets, as well as $S_T > 400\,\text{GeV}$, where S_T is the sum of H_T, lepton p_T, and p_T^{miss}. Finally, exactly one HOTVR jet with $p_T > 200\,\text{GeV}$ and $|\eta| < 2.5$ is required, fulfilling the HOTVR t tagging criteria.

The b^* mass is reconstructed from the mass of the tW system, M_{tW}. The tW system is reconstructed from the t-tagged HOTVR jet and the estimated W boson four-momentum, which is obtained from the four-momentum of the charged lepton and $\vec{p}_T^{miss}$. Assuming that the W boson from the b^* decay is on its mass shell, the neutrino is reconstructed using the W boson mass as a constraint. In cases where two solutions are found, the solution is selected that has the smaller value of $|p_{z,\nu} - p_{z,\ell}|$, where $p_{z,\nu}$ and $p_{z,\ell}$ denote the components of the neutrino and charged lepton four-momenta, respectively, along the beam direction. The large boost of the W boson ensures that this solution gives an accurate reconstruction of the neutrino four-momentum.

A χ^2-like estimator X^2 is calculated for the reconstructed tW system, indicating how signal-like the event is, under the assumption that the heavy resonance is produced at rest,

$$X^2 = \left(\frac{\Delta\phi_{\mathrm{t,W}} - \pi}{\sigma_{\Delta\phi_{\mathrm{t,W}}}} \right)^2 + \left(\frac{A_{p_\mathrm{T}}}{\sigma_{A_{p_\mathrm{T}}}} \right)^2 . \qquad (3)$$

The first term exploits the back-to-back signature of the signal. It becomes small if the azimuthal angular distance between the t quark and the W boson candidates $\Delta\phi_{\mathrm{t,W}}$ is close to π. The second term utilizes momentum conservation. Since the t quark and W boson originate from the decay of a heavy resonance in signal events, their transverse momenta should be of similar size. Hence, the second term becomes small if the p_T asymmetry $A_{p_\mathrm{T}} = (p_\mathrm{T}^\mathrm{t} - p_\mathrm{T}^\mathrm{W})/(p_\mathrm{T}^\mathrm{t} + p_\mathrm{T}^\mathrm{W})$ is close to zero. The width parameters $\sigma_{\Delta\phi_{\mathrm{t,W}}}$ and $\sigma_{A_{p_\mathrm{T}}}$ are determined from simulation.

Events passing the selection are categorized according to the number of b-tagged AK4 jets. Three categories are defined by having either zero ("0b"), one ("1b"), or more than one ("2b") b-tagged jets. The 0b category is used to estimate the SM background containing no top quarks (non-top background) from data, as described in Section 5. The 2b category is dominated by SM $\mathrm{t\bar{t}}$ production and is used as a control region to constrain systematic uncertainties associated with the modeling of this background. Two additional selection criteria are imposed in the 1b category, to increase the signal sensitivity. We require the b-tagged jet to be at a large angular distance from the isolated lepton, $\Delta R(\ell, \mathrm{b}) > 2.0$, and the X^2 value must be smaller than 20. Both requirements help to suppress the contribution from $\mathrm{t\bar{t}}$ production. The 1b category with these two additional requirements is the signal region of this search. The signal efficiency for b^* quarks decaying in the ℓ+jets final state is between 4 and 9% for the LH model, and 4 to 10% for the RH model. The efficiency for the RH model is slightly higher, because of the harder jet p_T spectra.

5 Background estimation

The dominant background in the selected phase space of the signal region originates from SM production of top quarks, $\mathrm{t\bar{t}}$ and single t, and is constrained using the 2b control region. Top tagging scale factors [53] are applied to the simulated samples, in order to correct for differences in t tagging efficiencies. The scale factors are found to be consistent with unity.

Contributions from events with a misidentified t jet are estimated from data in the 0b category. By requiring a t-tagged HOTVR jet, but vetoing b-tagged AK4 jets, this category consists dominantly of events from W/Z + jets and diboson production with misidentified t jets. The α-ratio method [61] is used to extrapolate the normalization and shape in M_{tW} of these backgrounds into the 1b signal and 2b control regions. The ratio α is defined as the number of events in the 1b or 2b category to the number of events in the 0b category for a given bin in M_{tW}. It is calculated from simulated W/Z + jets and diboson samples. By multiplying the observed number of events in data in the 0b category with the ratio α, the background prediction for the 1b and 2b categories is obtained. A fit to the distributions of α is performed to obtain a smooth

Table 1: Summary of all considered sources of systematic uncertainties affecting the M_{tW} distributions in the 1b and 2b categories of the ℓ+jets channel. The source of the uncertainty is given in the first column. The second column indicates if the uncertainty results in a change of normalization or shape of the M_{tW} distribution. The samples affected by a given uncertainty source are shown in the third column. The fourth column shows the impact of these uncertainties, estimated for an LH b^* signal with a mass of 2.4 TeV. These are quantified by calculating the change in the fitted signal strength when a given parameter is displaced by ± 1 standard deviation from its post-fit value, divided by the total uncertainty in the fitted signal. Uncertainties taken to be fully correlated across the three years are given in the upper part of the table. Uncertainties affecting both the ℓ+jets and all-hadronic channels are marked by an asterisk.

Source	Uncertainty	Samples	Impact (up/down)
$t\bar{t}$ cross section*	± 20%	$t\bar{t}$	+5.1 / −5.0%
Single t cross section*	± 30%	single t	−4.2 / +4.8%
Luminosity*	± 1.6%	$t\bar{t}$, single t, signal	−1.4 / +1.5%
Top quark p_T reweighting*	Shape	$t\bar{t}$	−5.0 / +5.1%
PDF*	Shape	$t\bar{t}$, single t, signal	−4.1 / +4.6%
Background estimation (1b)	Shape	non-top (from data)	−5.3 / +6.9%
Background estimation (2b)	Shape	non-top (from data)	−0.3 / −0.4%
Pileup*	Shape	$t\bar{t}$, single t, signal	−0.4 / +0.5%
JES*	Shape	$t\bar{t}$, single t, signal	−1.3 / +2.3%
JER*	Shape	$t\bar{t}$, single t, signal	+0.0 / +0.4%
ECAL trigger timing*	Shape	$t\bar{t}$, single t, signal	+0.1 / −0.0%
Electron identification	Shape	$t\bar{t}$, single t, signal	+0.4 / −0.4%
Electron reconstruction	Shape	$t\bar{t}$, single t, signal	+0.2 / −0.0%
Electron trigger	Shape	$t\bar{t}$, single t, signal	+0.3 / −0.0%
Muon identification	Shape	$t\bar{t}$, single t, signal	+0.4 / −0.1%
Muon isolation	Shape	$t\bar{t}$, single t, signal	+0.3 / −0.1%
Muon trigger	Shape	$t\bar{t}$, single t, signal	−0.1 / +0.4%
t tagging (fully merged)	Shape	$t\bar{t}$, single t, signal	−1.2 / +1.5%
t tagging (partially merged)	Shape	$t\bar{t}$, single t, signal	−0.7 / +0.8%
t tagging (nonmerged)	Shape	$t\bar{t}$, single t, signal	−0.0 / +0.2%
b tagging (b, c)	Shape	$t\bar{t}$, single t, signal	−3.6 / +4.0%
b tagging (u, d, s, g)	Shape	$t\bar{t}$, single t, signal	+0.7 / −0.6%

background prediction with reduced sensitivity to bin-by-bin statistical fluctuations in the simulated samples. The systematic uncertainty arising from the choice of fit function is estimated using different fit parameterizations and is added in quadrature to the statistical uncertainty.

The resulting functions $\alpha(M_{tW})$ are used to estimate the non-top backgrounds in the 1b and 2b categories. In order to keep the background estimation in the 1b and 2b categories statistically independent, we split the data in the 0b category randomly into two subsets, thus two thirds of the data are used to estimate the non-top background in the 1b category and one third of the data are used in the 2b category. The statistical uncertainty from the non-top background obtained from data in the 0b category is negligible compared to other uncertainties, such that the exact proportions of the subsets are not important.

6 Systematic uncertainties

Several systematic uncertainties are taken into account in the analysis, affecting the normalization and shape of the final M_{tW} distributions in the 1b and 2b categories. A summary of all considered sources is given in Table 1. Some of these uncertainties are assumed to be fully correlated throughout all three years; these uncertainties are given in the upper part of the table. The contributions of uncertainties without year-to-year correlations are calculated for each year independently.

In the following, a detailed description of the considered sources of systematic uncertainties is given.

- The total integrated luminosity of the data set is assigned an uncertainty of 1.6% [62–64].
- We assign uncertainties of 20 and 30% to the $\mathrm{t\bar{t}}$ and single top quark production cross sections, respectively. These account for uncertainties due to missing higher orders, estimated by halving and doubling the renormalization and factorization scales in the corresponding simulations, and for the uncertainties from the normalization to the NNLO and NLO predictions.
- The uncertainty from the choice of PDFs is estimated by calculating the signal and background predictions in each bin of the M_{tW} distribution using 100 replicas of the NNPDF sets [65]. The standard deviation of these predictions is used to construct shape variations. In the case of the signal samples, the distributions are normalized to the respective cross sections, such that only the acceptance effects are considered.
- The uncertainty in the pileup distribution is estimated by varying the total inelastic cross section of 69.2 mb within the assigned uncertainty of $\pm 5\%$ [37], and propagating the changes to the event yields in the simulation.
- The jet energy scale (JES) and jet energy resolution (JER) corrections are varied within their uncertainties to derive their effect on the shapes of the M_{tW} distributions.
- A timing shift of the signals in ECAL cells with respect to the L1 trigger clock led to a trigger inefficiency in the years 2016 and 2017 for events with significant amount of energy in the ECAL in the region $2.0 < \eta < 3.0$. The simulations were corrected for this effect. The associated systematic uncertainties are estimated by varying the corrections within their uncertainties.
- Uncertainties from the electron and muon identification and reconstruction are estimated by varying the corresponding efficiency corrections within their uncertainties.
- Trigger efficiency corrections are also varied within their uncertainties.
- The transfer functions α used for the background estimations of the non-top backgrounds in the 1b and 2b categories are varied within their uncertainties, as discussed above.
- Differences in the t and b tagging efficiencies between data and simulation are accounted for by data-to-simulation scale factors. These scale factors are varied within their uncertainties. The HOTVR t tagging scale factors are split into fully merged, partially merged, and nonmerged cases, depending on how many partons from the t decay can be matched to the HOTVR jet [53]. These scale factors are varied independently to obtain the effect on the M_{tW} distributions. The b tagging scale factors are split into efficiencies for b, c, and light jets [66]. The uncertainties for b and c jets are taken to be correlated and varied simultaneously, while the uncertainties for

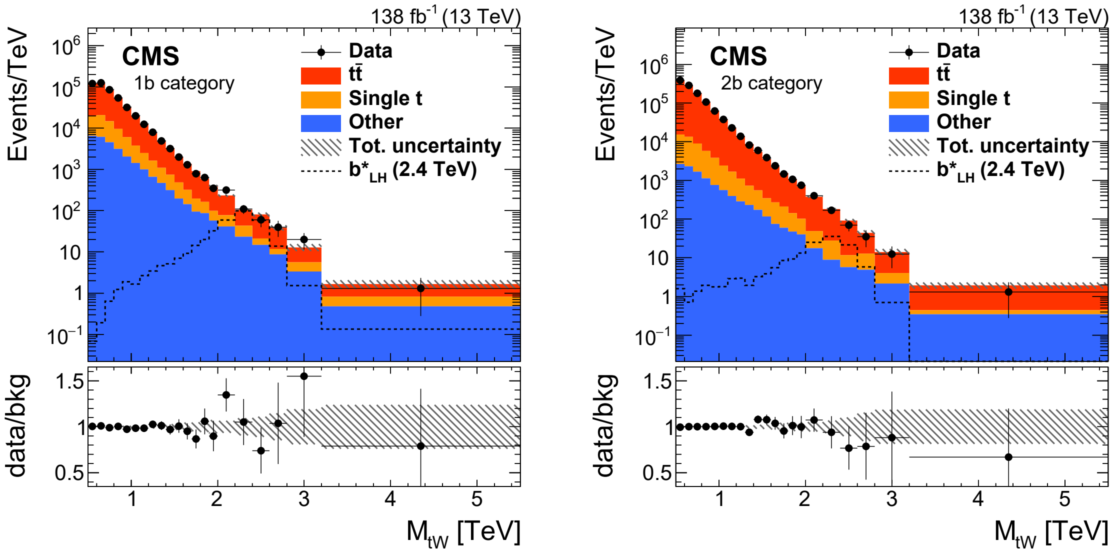

Figure 1: Distributions of M_{tW} in the 1b (left) and 2b (right) categories. The data are shown by filled markers, where the horizontal bars indicate the bin widths. The individual background contributions are given by filled histograms. The expected signal for an LH b^* with a mass of $m_{\mathrm{b}^*} = 2.4\,\mathrm{TeV}$ is shown by a dashed line. The shaded region is the uncertainty in the total background estimate. The lower panels of each figure show the ratio of data to the background estimate, with the total uncertainty in the predicted background displayed as shaded band.

light jets are taken to be uncorrelated and varied independently.

- The uncertainty arising from the modeling of the top quark p_{T} spectrum is estimated by varying the parameter β, affecting the shape of the p_{T} distribution, by $\pm 50\%$. This allows the fit to determine the correct shape of the $\mathrm{t\bar{t}}$ background and constrain the associated uncertainty from the 2b control region.

The results of this analysis are combined with a previously published analysis in the all-hadronic final state [9]. Systematic uncertainties affecting both final states are taken to be fully correlated between the two analyses, and are indicated in Table 1 by an asterisk. Systematic uncertainties affecting only the all-hadronic channel are not shown, but are described in detail in Ref. [9].

7 Results

For the statistical interpretation of the results, a combination with the analysis in the all-hadronic final state [9] is performed. That analysis considers events with a dijet topology, with two highly energetic jets with a large azimuthal separation. One jet is required to be t tagged, the other one is W tagged. The dominant background from multijet production with two misidentified jets is obtained from a control region with inverted t tagging requirements. The expected multijet background is extrapolated to the signal region with the help of a two-dimensional pass-fail-ratio in the jet mass of the top-tagged jet and M_{tW}. An additional control region enriched by events from $\mathrm{t\bar{t}}$ production is considered in order to constrain this background. Events containing isolated leptons with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ are rejected in the selection of the all-hadronic regions, to avoid double counting events that also appear in the ℓ+jets regions.

A fit is performed simultaneously to the M_{tW} distributions, not only in the 1b and 2b categories of this analysis, but also to the signal and multijet control regions in the earlier all-hadronic analysis. The $\mathrm{t\bar{t}}$ control region of the all-hadronic analysis is not considered, because of the

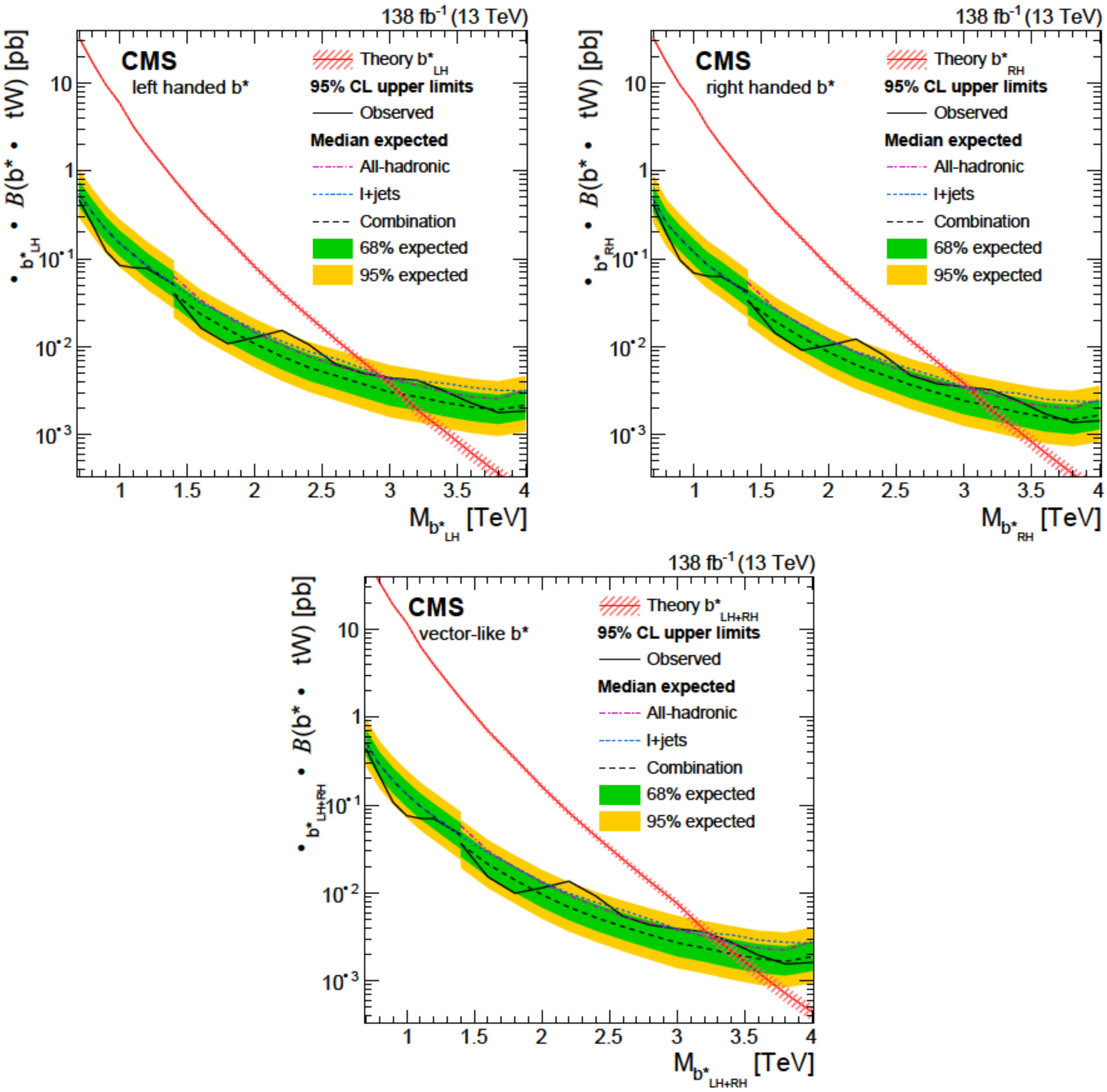

Figure 2: Upper limits on the product of production cross section and branching fraction of the left-handed (upper left), right-handed (upper right) and vector-like (lower) b^* hypotheses at 95% CL. Colored lines show the expected limits from the ℓ+jets (dotted) and all-hadronic (dash-dotted) channels, where the latter start at b^* masses of 1.4 TeV. The observed and expected limits from the combination are shown as solid and dashed black lines, respectively. The green and yellow bands show the 68 and 95% confidence intervals on the combined expected limits. The theoretical cross sections are shown as the red lines, where the uncertainties due to missing higher orders are depicted by shaded areas.

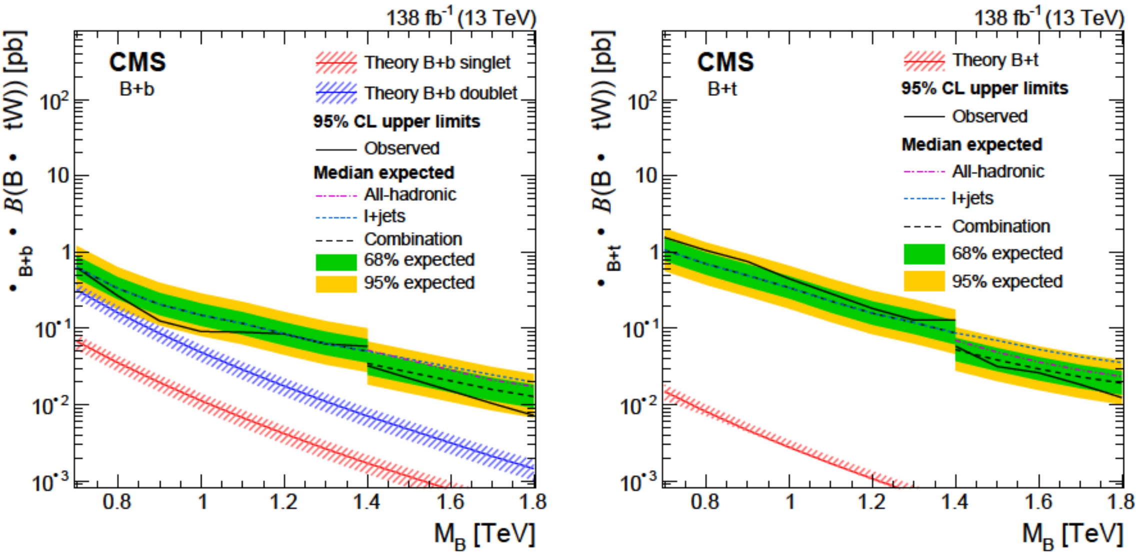

Figure 3: Upper limits on the product of production cross section and branching fraction of the B+b (left) and B+t (right) production modes at 95% CL. Colored lines show the expected limits from the ℓ+jets (dotted) and all-hadronic (dash-dotted) channels, where the latter start at B masses of 1.4 TeV. The observed and expected limits from the combination are shown as solid and dashed black lines, respectively. The green and yellow bands show the 68 and 95% confidence intervals on the combined expected limits. The theoretical cross sections are shown as the red and blue lines, where the uncertainties due to missing higher orders are depicted by shaded areas.

higher precision of the 2b category. The contributions from all background and signal processes are fitted simultaneously to data in a binned maximum likelihood fit. The signal strength is a free parameter in the model and systematic uncertainties are accounted for by nuisance parameters assigned to the sources of systematic uncertainties described in Section 6. These are profiled in the fit. Normalization uncertainties are modeled with log-normal priors, and uncertainties affecting shapes are modeled using a template morphing approach with Gaussian priors [67]. Statistical uncertainties are treated in a bin-by-bin approach using a simplified version of the Barlow–Beeston method [68]. The post-fit distributions of M_{tW} in the 1b and 2b categories are shown in Fig. 1. Data and background predictions are found to be statistically in agreement over the full spectrum of M_{tW}.

No significant excess of data over the expected SM background is observed. Upper limits on the product of production cross section and branching fraction into tW of the three coupling scenarios in the b* benchmark model at 95% CL are set using the CL_s method [69, 70] with an asymptotic approximation to the profile likelihood test statistic [71]. Figure 2 shows the expected and observed limits of the combination, as well as the expected limits of the two separate analyses in the all-hadronic and ℓ+jets final states. The step at $M_{tW} = 1.4$ TeV in the combined limits arises from the extended reach of the ℓ+jets channel towards lower masses, where it places unique constraints in the range 0.7–1.4 TeV. The sensitivity for masses above 1.4 TeV is comparable between the all-hadronic and ℓ+jets channels, resulting in stricter limits compared to the separate analyses. We derive b* mass exclusion limits by comparing the upper cross section limits with theoretical cross sections of b* production, calculated with MADGRAPH5_aMC@NLO. The observed (expected) mass limits are 3.0, 3.0, and 3.2 TeV (3.1, 3.2, and 3.4 TeV) for the LH, RH, and VL hypotheses, respectively. These are the most stringent constraints on this model to date.

The results can also be interpreted in the context of a singly produced vector-like B quark decaying into tW. The production modes B+t and B+b are tested separately and the upper limits on the product of production cross sections and branching fraction at 95% CL are shown in Fig. 3. Over a B mass range from 0.7 to 1.8 TeV, the observed upper limits range from 0.63 to 0.007 pb for the B+b production mode, and from 1.6 to 0.01 pb for B+t production. The upper cross section limits are compared to the theory predictions from Ref. [72]. Models with a VLQ singlet or VLQ doublet are considered in case of B+b production. For B+t production, both models result in the same production cross section. Because of the small theoretical cross sections for these processes, no mass limits are set.

The upper cross section limits can be compared to a previous search for singly produced vector-like B quarks at $\sqrt{s} = 13$ TeV using a data set corresponding to 35.9 fb^{-1} by the CMS collaboration [73]. For the B+b production mode, the expected limits are 8–29% better at low B masses, where the ℓ+jets channel alone sets limits, and 75% better at the highest considered B mass. For the B+t production mode, the ℓ+jets channel is less sensitive, because of the additional b jet from the decay of the associated t quark, leading to weaker limits at low B masses compared to the previous search. At high B masses, this search improves the upper limits by up to 50%.

8 Summary

A search for a heavy resonance decaying to tW in the final state with a lepton and a t-tagged jet has been presented. The data analyzed correspond to an integrated luminosity of 138 fb^{-1} of proton-proton collisions collected at a center-of-mass energy of 13 TeV. Final states where the W boson decays leptonically and the top quark decay results in a single jet are probed. Compared to an earlier analysis of the all-hadronic final state, the lower reach of the analysis is extended from 1.4 down to 0.7 TeV, because of lower lepton trigger thresholds and the extended range in t quark transverse momentum provided by the Heavy Object Tagger with Variable R. Above 1.4 TeV a combination with the search in the all-hadronic final state has been performed. The dominant $t\bar{t}$ background is constrained using a dedicated control region and the background from misidentified t jets is estimated from data. No significant excess of data over the background prediction is observed. Upper limits on the single production of a vector-like quark decaying to tW have been derived in the mass range of 0.7 to 1.8 TeV. The excited bottom quark b^* hypotheses with left-handed, right-handed, and vector-like chiralities are excluded at 95% confidence level up to masses of 3.0, 3.0, and 3.2 TeV, respectively. The upper limits on the product of cross section and branching fraction represent the most stringent constraints on the b^* model to date.

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