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## *Search for Pair Production of Vector-Like Quarks in the $bWb\#W$ channel from Proton-proton Collisions at $\sqrt{s} = 13$ TeV*

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# Search for pair production of vector-like quarks in the $bW\bar{b}W$ channel from proton–proton collisions at $\sqrt{s} = 13$ TeV

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## ABSTRACT

A search is presented for the production of vector-like quark pairs,  $T\bar{T}$  or  $Y\bar{Y}$ , with electric charge of  $2/3$  (T) or  $-4/3$  (Y), in proton–proton collisions at  $\sqrt{s} = 13$  TeV. The data were collected by the CMS experiment at the LHC in 2016 and correspond to an integrated luminosity of  $35.8 \text{ fb}^{-1}$ . The T and Y quarks are assumed to decay exclusively to a W boson and a b quark. The search is based on events with a single isolated electron or muon, large missing transverse momentum, and at least four jets with large transverse momenta. In the search, a kinematic reconstruction of the final state observables is performed, which would permit a signal to be detected as a narrow mass peak ( $\approx 7\%$  resolution). The observed number of events is consistent with the standard model prediction. Assuming strong pair production of the vector-like quarks and a 100% branching fraction to bW, a lower limit of 1295 GeV at 95% confidence level is set on the T and Y quark masses.

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## 1. Introduction

Vector-like quarks (VLQs) are hypothetical spin-1/2 fermions, whose left- and right-handed components transform in the same way under the standard model (SM) symmetries, and hence have vector couplings. Nonchiral VLQs appear in a number of beyond-the-SM scenarios, such as “Randall–Sundrum” and other extra-dimensional models [1,2]; the beautiful mirrors [3], little Higgs [4–8], and composite Higgs [9] models; grand unified theories [10]; and also other models that provide insights into the SM flavor structure [11]. These models provide possible solutions to a number of problems, such as electroweak symmetry breaking, a poor general fit to the precision electroweak data, the origin of flavor patterns, and the hierarchy problem. In particular, the hierarchy problem, namely the instability within the SM of the Higgs boson mass parameter to quantum corrections, can be solved through the introduction of VLQ contributions that cancel the contributions from the top quark.

In general, VLQs T, with charge  $+2/3$ , are expected to mix significantly only with the top quark, leading to the dominant T quark decay  $T \rightarrow bW$  [12]. We consider the case in which this decay has a branching fraction  $\mathcal{B}(T \rightarrow bW) = 100\%$ . Also in some models [13], a VLQ Y with an electric charge of  $-4/3$  is predicted, either with

or without the presence of a T VLQ. The Y quark is expected to decay with a 100% branching fraction via the same bW channel. Since jets originating from the hadronization of b quarks and  $\bar{b}$  antiquarks are not distinguished in this analysis, the results presented apply equally to the strong pair production of both T and Y VLQs. We consider the case where either only T quarks or only Y quarks are produced. This assumption produces a more conservative estimation of the lower mass limit on VLQs. Throughout the rest of this paper, we will use T to represent both the T and Y VLQs.

In this paper, results are presented of a search for the strong pair production of heavy VLQs and their subsequent decays through the signal channel

$$T\bar{T} \rightarrow bW\bar{b}W \rightarrow b\ell\nu\bar{b}q\bar{q}'$$

in proton–proton (pp) collisions at  $\sqrt{s} = 13$  TeV using the CMS detector at the CERN LHC, where  $\ell$  is an electron or muon from the leptonic decay of one of the W bosons, and q and  $\bar{q}'$  are the quark and antiquark from the hadronic decay of the other W boson. The analyzed data set corresponds to an integrated luminosity of  $35.8 \text{ fb}^{-1}$ . This analysis is an extension to higher mass values of an earlier CMS search for the T quark at  $\sqrt{s} = 8$  TeV. Both the previous analysis and the present one are based on a kinematic reconstruction with a constrained fit to the  $bW\bar{b}W$  final state in the signal decay channel shown above. Kinematic reconstruction

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enables detection of the signal as a narrow mass peak. The previous results were combined with other CMS T quark searches in Ref. [14]. The present observed lower mass limits for a T quark decaying 100% via the bW channel are 920 GeV for CMS [14] at  $\sqrt{s} = 8$  TeV, and 770 GeV at 8 TeV [15] and 1350 GeV at 13 TeV for ATLAS [16].

The search strategy requires that one of the W bosons decays leptonically, producing an electron or a muon accompanied by a neutrino, and the other decays hadronically to a quark–antiquark pair. We select events with a single isolated muon or electron, missing transverse momentum, and at least four jets with high transverse momenta, arising from the hadronization of the quarks in the final state. We classify such events as  $\mu$ +jets or e+jets.

We perform a constrained kinematic fit on each selected event for the signal decay process shown above. The full kinematic quantities of the final state are reconstructed, and the invariant mass of the T quark,  $m_{\text{reco}}$ , is obtained. We consider also cases when W bosons decaying hadronically at high Lorentz boosts are reconstructed as single jets. Such merged jets are then resolved into two subjets by employing jet substructure techniques based on the “soft drop” grooming algorithm [17]. These resolved subjets are counted individually when selecting four-jet final states and contribute separately in the kinematic fit (see Section 5). Events with leptonically decaying W bosons include those decaying into a  $\tau$  lepton (in the decay sequence  $W \rightarrow \tau + \nu$ ,  $\tau \rightarrow \ell + 2\nu$ ). They are treated in the same way as events with direct decays to muons or electrons.

## 2. The CMS detector

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 superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL) with preshower detector, and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity [18] coverage provided by the barrel and endcap detectors. The detector is nearly hermetic, allowing for momentum balance measurements in the plane transverse to the beam direction. 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. [18].

## 3. Event samples

The analysis is based on integrated luminosities of  $35.8 \text{ fb}^{-1}$  in the muon channel and  $35.6 \text{ fb}^{-1}$  in the electron channel. The trigger providing the muon data sample requires the presence of at least one muon with  $p_T > 50 \text{ GeV}$  and pseudorapidity  $|\eta| < 2.5$ . For the electron data sample, events are required to have a single isolated electron with  $p_T > 32 \text{ GeV}$  and  $|\eta| < 2.1$ .

Simulated event samples are used to estimate the signal efficiencies and background contributions. The following background production processes are modeled:  $t\bar{t}$ +jets; W+jets and Z+jets (single boson production); single top quark via the tW, s- and t-channel processes; WW, WZ, and ZZ (diboson production); and quantum chromodynamic (QCD) multijet production. The dominant background is from  $t\bar{t}$ +jets production. All other background processes are collectively referred to as non- $t\bar{t}$ . The non- $t\bar{t}$  background excluding multijets is called the electroweak background.

The  $t\bar{t}$  + jets events are generated using the POWHEG v2.0 [19–22] event generator. The diboson samples are produced us-

ing the PYTHIA 8.205 [23] generator. The W+jets, Z+jets, and QCD multijet simulated events are produced with the generator MADGRAPH5\_AMC@NLO v2.2.2 [24]. Single top quark events are generated with POWHEG and MADGRAPH5\_AMC@NLO.

The simulated  $T\bar{T}$  signal events are generated with MADGRAPH5\_AMC@NLO at leading order for T quark masses from 800 to 1600 GeV in 100 GeV steps. The total  $T\bar{T}$  inclusive cross section ( $gg \rightarrow T\bar{T} + X$ ) is computed for each T quark mass value at next-to-next-to-leading order, using a soft-gluon resummation with next-to-next-to-leading-logarithmic accuracy [25]. Signal samples are produced in the narrow-width approximation in which the width of the generated T quark mass distribution of 1 GeV is much less than the mass resolution of the detector.

The generated events are processed through the CMS detector simulation based on GEANT4 [26]. Additional minimum-bias events, generated with PYTHIA, are superimposed on the hard-scattering events to simulate multiple inelastic pp collisions in the same or nearby beam crossings (pileup). The simulated events are weighted to reproduce the distribution of the number of pileup interactions observed in data, with an average of 23 collisions per beam crossing. All samples have been generated with the NNPDF 3.0 set [27] of parton distribution functions (PDFs), using the tune CUETP8M1. PYTHIA is used to shower and hadronize all generated partons.

## 4. Event reconstruction

Events are reconstructed using a particle-flow (PF) algorithm [28] that combines information from all the subdetectors: tracks in the silicon tracker and energy deposits in the ECAL and HCAL, as well as signals in the preshower detector and the muon system. This procedure categorizes all particles into five types: muons, electrons, photons, and charged and neutral hadrons. An energy calibration is performed separately for each particle type.

Muon candidates are identified by multiple reconstruction algorithms based on hits in the silicon tracker and signals in the muon system. The standalone-muon algorithm uses only information from the muon chambers. The silicon tracker muon algorithm starts from tracks found in the silicon tracker and then associates them with matching signals in the muon detectors. In the global-muon algorithm, for each standalone-muon track a matching tracker muon is found by comparing parameters of the two tracks propagated onto a common surface. A global-muon track is fitted by combining hits from the silicon tracker muon and the standalone-muon track, using the Kalman-filter technique [29]. The PF algorithm uses global muons.

Electron candidates are reconstructed from clusters of energy deposited in the ECAL matched with tracks in the silicon tracker. Electron tracks are reconstructed using a dedicated modeling of the electron energy loss and are fitted with a Gaussian sum filter algorithm. Finally, electrons are further distinguished from charged hadrons using a multivariate approach [30].

Charged leptons, originating from decays of heavy VLQs, are expected to be isolated from nearby jets. Therefore, a relative isolation parameter ( $I_{\text{rel}}$ ) is used, which is defined as the sum of the  $p_T$  of charged hadrons, neutral hadrons, and photons in a cone with distance parameter  $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$  around the lepton direction, where  $\Delta\phi$  and  $\Delta\eta$  are the azimuthal and pseudorapidity differences, divided by the lepton  $p_T$ . The isolation cone radius is taken as  $\Delta R = 0.4$  for muons. Pileup corrections to  $I_{\text{rel}}$  are computed using tracks from reconstructed vertices [29]. For electrons,  $\Delta R = 0.3$  and pileup corrections are calculated using jet effective areas [31,32] separately for the barrel and endcap regions.

Particles found by the PF algorithm are clustered into jets using the PF jet identification procedure [28]. Using the charged-hadron subtraction (CHS) algorithm, charged hadrons associated

with pileup vertices are not considered, and particles that are identified as isolated leptons are removed from the jet clustering procedure. In the analysis, two types of jets are used: jets reconstructed using the anti- $k_T$  algorithm [33] with distance parameters of either  $R = 0.4$  (AK4) or  $0.8$  (AK8), as implemented in FASTJET v3.0.1 [34,35]. An event-by-event jet area-based correction [31,32,36,37] is applied to remove on a statistical basis pileup contributions that are not already removed by the CHS procedure.

Since most jet constituents are identified and reconstructed with close to a correct energy by the PF algorithm, only a small residual energy correction must be applied to each jet. These corrections were obtained as a function of jet  $p_T$  and  $\eta$  from a comparison of GEANT4-based CMS Monte Carlo (MC) simulation [38] and collision data. Jet energy corrections (JEC) are applied to each jet as a function of  $p_T$  and  $\eta$ .

For the identification of jets originating from the hadronization of a  $b$  quark ( $b$ -tagged jets) we use the combined secondary vertex (CSVv2) algorithm [39]. This provides  $b$  tagging identification by combining information about impact parameter significance, secondary vertex reconstruction, and jet kinematic distributions. We use two operating points: medium (CSVM), with a mistagging rate of 1%, and loose (CSVL), with a 10% mistagging rate, for which the efficiencies of correctly tagging jets coming from  $b$  quark hadronization are 66% and 82%, respectively [39]. The differences in the performance of the  $b$  tagging algorithm in data and MC simulation are accounted for by data/MC scale factors (SFs).

The missing transverse momentum in an event,  $p_T^{\text{miss}}$ , is defined as the magnitude of the missing transverse momentum vector, which is the projection on the plane perpendicular to the beams of the negative vector sum of the momenta of all reconstructed particles in the event. The vertex with the highest sum of squared  $p_T$  of all associated tracks is taken as the hard-scattering primary vertex.

## 5. Event selection and mass reconstruction

Selected events are required to contain exactly one charged lepton (muon or electron). Muon candidates are required to have  $p_T > 55$  GeV and  $|\eta| < 2.4$ . The relative muon isolation parameter must satisfy  $I_{\text{rel}} < 0.15$ . Selected electrons should have  $|\eta| < 2.1$ . To ensure that the  $e$ +jets channel covers a similar kinematic phase space to the  $\mu$ +jets channel, electron candidates must satisfy the same  $p_T > 55$  GeV requirement. Simulation shows that lowering the  $p_T$  threshold would not improve the signal significance. Events with a second more loosely identified electron or muon, with  $p_T > 20$  GeV and  $|\eta| < 2.5$  ( $2.4$ ) for electrons (muons), are vetoed.

At the next step, we select a collection of jets that are used as input to the kinematic fit. The collection includes AK4 jets that have  $p_T > 30$  GeV and  $|\eta| < 2.4$ , and AK8 jets that satisfy  $p_T > 200$  GeV and  $|\eta| < 2.4$ . A selected event must have either at least four AK4 jets, or at least three AK4 jets and at least one AK8 jet for the case where the AK8 jet overlaps an AK4 jet (see explanations below). This is needed to satisfy the requirement to have at least four jets in the final jet collection used for the kinematic fit.

As the mass of a heavy VLQ increases, the reconstructed topology of its decay is modified by the overlapping and merging of jets owing to the high Lorentz boosts its decay products receive. The quark pair from the hadronically decaying  $W$  boson becomes increasingly collimated, producing overlapping hadronic showers that cannot be resolved as separate jets. This precludes performing constrained kinematic fits that use jets as proxies for the final-state quarks in the signal decay process.

The AK8 jets are used to identify the merged hadronic  $W$  boson decays by applying the “soft drop” (SD) grooming algorithm [17], with parameters  $z_{\text{cut}} = 0.1$  and  $\beta = 0$ . This procedure removes soft

and wide-angle radiation from jets and resolves the internal structure of the wide jet into two distinct subjets, associated with the underlying  $W$  boson decay. The JECs that are applied to the AK8 jets are propagated to the pair of subjets by scaling them so that the sum of their four-momenta is equal to the parent AK8 jet four-momentum. The groomed jet mass, called the soft drop mass,  $m_{\text{SD}}$ , is taken as the invariant mass of the constituents of the AK8 jet with the SD algorithm applied, and thus is equal to the invariant mass of the two subjets. It is required to be within the  $W$  boson mass window  $60 < m_{\text{SD}} < 100$  GeV, in which case the AK8 jet is labeled “ $W$ -tagged”.

For each  $W$ -tagged AK8 jet, representing an identified footprint of a highly boosted, hadronically decaying  $W$  boson, we search for the corresponding footprint of the same  $W$  boson decay in the AK4 jet collection. This is done by trying to match a  $W$ -tagged AK8 jet to an AK4 jet or to the vector sum of a pair of nearby AK4 jets for which  $\Delta R(\text{AK8}, \text{AK4}) < 0.8$ . Since the opening angle of AK8 subjets, resolved by the SD algorithm, can go down up to  $\Delta R = 0.15$ , the system of the two subjets represents a more accurate assignment of jet constituents to two separate subjets compared to the clustering into two AK4 jets, with their more coarse threshold of  $\Delta R = 0.4$ . A match requires  $\Delta R(\text{AK8}, \text{AK4}) = \Delta R_{\text{match}} < 0.05$ . Matching with a pair of AK4 jets is preferred to a matching with only one AK4 jet, when the  $\Delta R_{\text{match}}$  value for that pair is smaller than the values for any of the single jets in the pair. In this case matching with the pair (represented by the vector sum of the two AK4 momenta) provides the best association of AK4/AK8 jets.

A matched AK4 jet is replaced by the two subjets of the  $W$ -tagged AK8 jet, thus using the full kinematic information obtained by the  $W$  tagging and including that into a jet collection used for the kinematic fit. This procedure results in a hybrid jet collection, consisting of AK4 jets left unmatched and subjets of  $W$ -tagged AK8 jets, thus excluding the possibility of double counting the jets later used as input to the kinematic fit.

Only the jets in the hybrid collection are used in the rest of the analysis. A set of preselection requirements is now applied to the event:

- The missing transverse momentum in the event must satisfy  $p_T^{\text{miss}} > 30$  GeV. This requirement is designed to both select final states containing neutrino and suppress QCD multijet background contribution.
- Each of the jets must have  $p_T > 30$  GeV and  $|\eta| < 2.4$  (these requirements were not applied to the newly included  $W$ -tagged subjets).
- Jets too close to the lepton direction are discarded by requiring  $\Delta R(\text{jet}, \ell) > 0.4$ .
- There must be at least 4 remaining jets in the event after the previous criteria.
- The two highest- $p_T$  jets must satisfy  $p_T > 100$  and  $70$  GeV, respectively.

Events that pass all these requirements are used as input to the kinematic fit, which is performed using the HttFit package [40]. This fitting program was developed by the D0 experiment [41] for the measurement of the top quark mass in the lepton+jets channel. It contains a fitting engine, which minimizes a  $\chi^2$  quantity subject to a set of constraints, and an interface.

The input to the fitting engine comprises the two-dimensional vector  $\vec{p}_T^{\text{miss}}$  and the measured three-dimensional momenta of the charged lepton and four jets. The four quarks in the final state of the signal decay process manifest themselves as jets whose measured three-momenta are used as estimates of the quark momenta. The  $p_T^{\text{miss}}$  in the event is used as an estimate of the transverse momentum of the neutrino. The unmeasured longitudinal component

of the neutrino momentum is calculated from one of the kinematic constraints shown in Eqs. (1) and (3) below.

The fit is performed by minimizing a  $\chi^2$  computed from the differences between the measured momentum components and their fitted values, divided by the corresponding uncertainties, summed over all the reconstructed objects in the final state. The fit is subject to the following constraints:

$$m(\ell\nu) = m_W, \quad (1)$$

$$m(q\bar{q}') = m_W, \quad (2)$$

$$m(\ell\nu b) = m(q\bar{q}'b) = m_{\text{reco}}, \quad (3)$$

where  $m_W$  is the W boson mass [42],  $\ell$  stands for electron or muon, and  $\ell$ ,  $\nu$ ,  $b$  can denote either a particle or antiparticle. Equation (2) requires that the invariant mass of the quark–antiquark pair equals the W boson mass. Equation (3) demands that the reconstructed invariant masses  $m_{\text{reco}}$  of the two produced T quarks are equal. After one constraint is used for the calculation of the longitudinal neutrino momentum, two constraints are left. To check to what extent the assumed kinematic hypothesis is compatible with the fitted momenta, a so-called “goodness-of-fit” is calculated, given by the probability  $P(\chi^2 \geq \chi^2_{\text{min}})$  for the  $\chi^2_{\text{min}}$  value obtained after minimization.

For events with exactly 4 jets, all jet permutations in which jets are assigned specific quark roles in the final state of the signal process are prepared by the HttFit interface and entered in turn into the fitting engine. If there are more than four jets in an event passing the jet requirements, then the five jets with the highest  $p_T$  are considered and all permutations of four jets out of five are used as input to the fitter. The calculation of the longitudinal component of the neutrino momentum has a two-fold ambiguity from solving a quadratic equation. This doubles the number of fitted combinations, based on the jet permutations. At the end of the fitting process, HttFit delivers information about 24(120) fitted permutations for the case of 4(5) jets.

After the event fitting is done, we have to decide which fitted combination must be chosen to represent the final state of the signal process. To reduce the number of accidental combinatoric assignments, we use information on b tagging and W tagging. Pairs of W-tagged subjects (if available) are assigned to the hadronic W boson decay. To identify the most likely lepton+4 jets combination arising from the decay chain of the signal process, we inspect each fitted combination in turn, proceeding as follows:

- In each fit combination, two jets are taken to be the b jets from the T and  $\bar{T}$  decays. We call  $b_l$  the b jet accompanying the leptonic W boson decay, and  $b_h$  the b jet accompanying the hadronic W boson decay. Combinations in which neither of these jets is b-tagged or only one has a CSVL tag are rejected.
- The four jets in the fitted combination, designated in the order:  $b_h$  jet,  $b_l$  jet, highest- $p_T$  jet in the hadronic W boson decay, second-highest- $p_T$  jet in the hadronic W boson decay, must satisfy the requirements  $p_T > 200, 100, 100$ , and 30 GeV, respectively.
- For each fitted jet combination a variable  $S_T$  is calculated, defined as the scalar sum of  $p_T^{\text{miss}}$  and the transverse momenta of the lepton and the four jets in that combination:  $S_T = p_T^{\text{miss}} + p_L^\ell + p_L^{J_1} + p_L^{J_2} + p_L^{J_3} + p_L^{J_4}$ , where  $J_i$  (with  $i = 1$  to 4) refers to the four jets and  $S_T$  is evaluated using the measured momenta. To select hard-scattering processes resulting in the production of heavy objects, we require  $S_T > 1000$  GeV.
- $S_L^{\text{fit}}/S_T^{\text{fit}} < 1.5$ , where  $S_L^{\text{fit}} = p_L^\nu + p_L^\ell + p_L^{J_1} + p_L^{J_2} + p_L^{J_3} + p_L^{J_4}$ , and  $p_L$  is the longitudinal momentum of each of the corresponding objects. Both  $S_L^{\text{fit}}$  and  $S_T^{\text{fit}}$  are calculated using the

**Table 1**

The numbers of expected background events for each process in the  $\mu$ +jets and e+jets channels, normalized to the integrated luminosity of the data, the number of observed events, and the ratio of the observed to predicted events. The uncertainties in the predicted numbers of background events are statistical only.

|                       | $\mu$ + jets    | e + jets        |
|-----------------------|-----------------|-----------------|
| Background process    |                 |                 |
| $t\bar{t}$ +jets      | 533 $\pm$ 6     | 470 $\pm$ 5     |
| Single top            | 115 $\pm$ 5     | 100 $\pm$ 4     |
| W+jets                | 94 $\pm$ 2      | 73 $\pm$ 2      |
| Z+jets                | 10.7 $\pm$ 0.3  | 9.4 $\pm$ 0.3   |
| QCD multijet          | 8.8 $\pm$ 4.4   | 15 $\pm$ 8      |
| Diboson               | 4.4 $\pm$ 4.4   | 1.8 $\pm$ 1.8   |
| $t\bar{t}$ V          | 10.9 $\pm$ 0.9  | 8.0 $\pm$ 0.8   |
| Total background (MC) | 777 $\pm$ 10    | 678 $\pm$ 11    |
| Total observed (Data) | 768             | 684             |
| Data/MC               | 0.99 $\pm$ 0.04 | 1.01 $\pm$ 0.04 |

**Table 2**

Selection efficiencies from MC simulation for the  $T\bar{T}$  signal as a function of the T quark mass assuming  $\mathcal{B}(T \rightarrow bW) = 100\%$ , and the numbers of expected signal events after the final selection for the integrated luminosity of the data. The uncertainties are statistical only.

| Mass [GeV] | $\mu$ + jets    |                 | e + jets        |                 |
|------------|-----------------|-----------------|-----------------|-----------------|
|            | Efficiency (%)  | Events          | Efficiency (%)  | Events          |
| 800        | 2.37 $\pm$ 0.05 | 166.1 $\pm$ 3.7 | 2.20 $\pm$ 0.05 | 153.5 $\pm$ 3.5 |
| 900        | 2.71 $\pm$ 0.06 | 87.8 $\pm$ 1.9  | 2.36 $\pm$ 0.05 | 75.8 $\pm$ 1.8  |
| 1000       | 2.97 $\pm$ 0.06 | 46.7 $\pm$ 0.9  | 2.69 $\pm$ 0.06 | 42.2 $\pm$ 0.9  |
| 1100       | 3.08 $\pm$ 0.06 | 24.7 $\pm$ 0.5  | 2.77 $\pm$ 0.06 | 22.1 $\pm$ 0.4  |
| 1200       | 3.14 $\pm$ 0.06 | 13.3 $\pm$ 0.3  | 2.80 $\pm$ 0.06 | 11.8 $\pm$ 0.2  |
| 1300       | 3.10 $\pm$ 0.07 | 7.09 $\pm$ 0.15 | 2.79 $\pm$ 0.06 | 6.34 $\pm$ 0.14 |
| 1400       | 3.14 $\pm$ 0.06 | 3.98 $\pm$ 0.08 | 2.77 $\pm$ 0.06 | 3.50 $\pm$ 0.07 |
| 1500       | 3.21 $\pm$ 0.06 | 2.30 $\pm$ 0.04 | 2.76 $\pm$ 0.06 | 1.96 $\pm$ 0.04 |
| 1600       | 3.01 $\pm$ 0.06 | 1.24 $\pm$ 0.02 | 2.84 $\pm$ 0.06 | 1.16 $\pm$ 0.02 |

fitted momenta. This requirement relies on the fact that the final-state objects from the signal process typically have both high- $p_T$  and moderate- $p_z$  values.

- The invariant mass of the two jets attributed to the W boson hadronic decay must be in the range 60–100 GeV.
- $P(\chi^2) > 0.1\%$  (corresponding to 3 standard deviations for a one-sided Gaussian distribution).

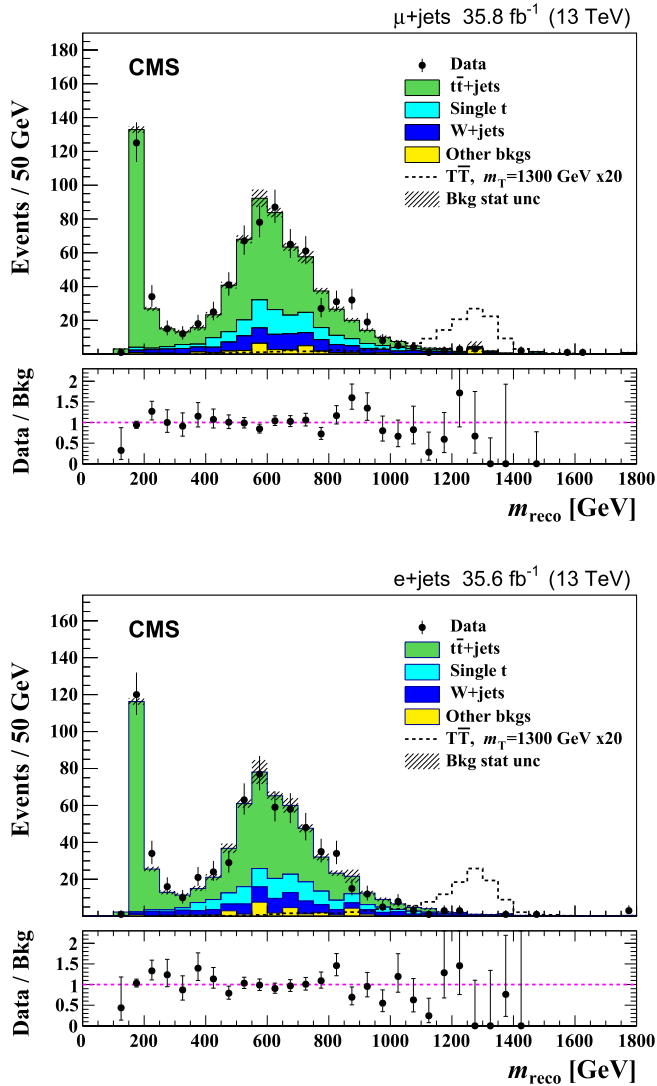
The signal decay process contains two b quarks, which manifest themselves as b-tagged jets. The fit combinations passing the above selection are sorted into four groups according to the b tagging categories of the  $\{b_l, b_h\}$  jet pair: two CSVM b tags; one CSVM and one CSVL b tag; only one CSVM b tag; and two CSVL b tags. The combination with the largest  $P(\chi^2)$  value from the group with the tightest b tagging is selected for the signal sample.

Combinations containing W-tagged subjects are considered first, if such exist in the event. If no combination with W-tagged subjects passes the selection criteria, then the other combinations are considered.

### 5.1. Results of the event selection

Table 1 presents the numbers of observed and predicted background events, normalized to the integrated luminosity. Selection efficiencies for the  $T\bar{T}$  signal, including acceptance and branching fractions of decays, and the number of expected signal events are given in Table 2 as a function of the T quark mass.

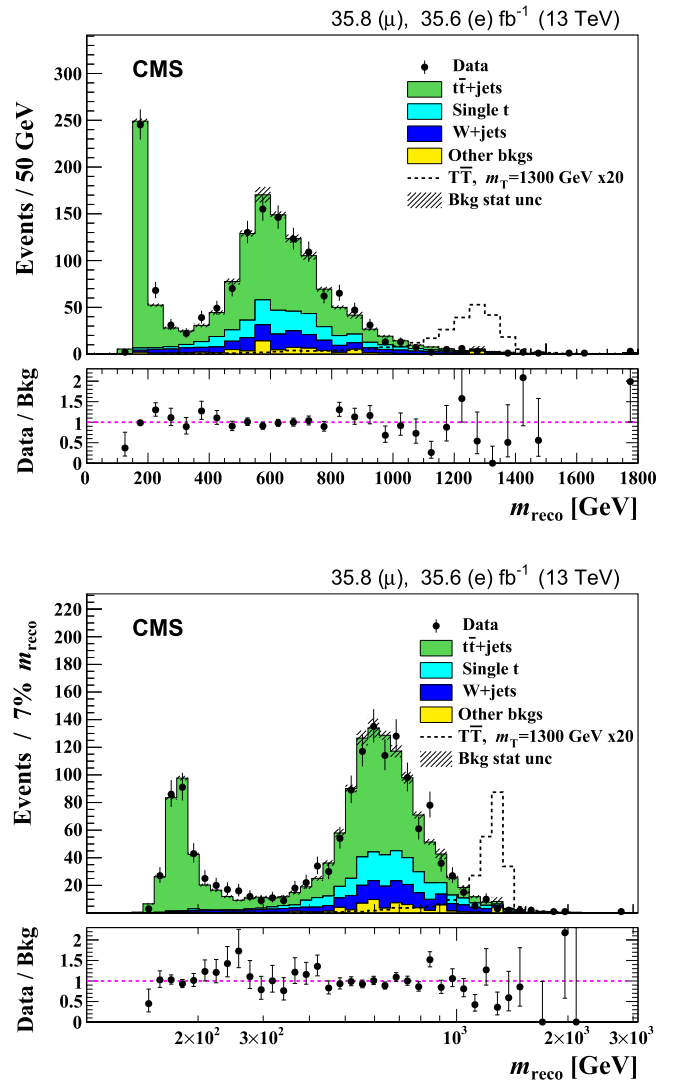
Fig. 1 shows the distributions of the T quark reconstructed mass,  $m_{\text{reco}}$ , obtained from the selected  $\mu$ +jets and e+jets events, and Fig. 2 shows their sum. The integrated luminosity and cross



**Fig. 1.** The T quark reconstructed mass spectra for the  $\mu$ +jets (upper plot) and e+jets (lower plot) channels from data and from MC simulations of signal and background processes. The MC prediction for pair production of a T quark with a mass of 1300 GeV is shown by a dashed line, enhanced by a factor of 20. The lower panels show the ratio of the data to the background prediction. The uncertainties represented by the vertical bars on the points are statistical only. The shaded regions show the total statistical uncertainties in the background.

sections of the background processes are used for normalization of the background contributions. Only the statistical uncertainties are shown for the estimated background, since the systematic uncertainties enter the workflow later and are not available at this point of the analysis. Nevertheless, it is evident that the data distributions are well described by the predicted backgrounds alone.

The resolution of the reconstructed mass was found to be proportional to the value of the mass, with the Gaussian core of the  $m_{\text{reco}}$  resolution curves having a width-to-mass ratio of  $\approx 7\%$ . We make use of this feature by employing variable bin widths equal to 7% of the bin-center values when plotting  $m_{\text{reco}}$  and using a logarithmic scale for the horizontal axis. In this way, the bin widths appear to be of the same size, equal to the local mass resolution. This helps smooth statistical fluctuations causing peaks that are narrower than the local mass resolution, and avoid wrong interpretations when searching for narrow structures in the observed mass distribution. Fig. 2 (lower plot) shows the resulting  $m_{\text{reco}}$  spectrum plotted this way for the sum of the  $\mu$ +jets and e+jets channels. The



**Fig. 2.** The T quark reconstructed mass spectra for the sum of  $\mu$ +jets and e+jets channels from data and from MC simulations of signal and background processes. The lower plot has a logarithmic x-axis scale and the bin size corresponds to 7% of the mass value in the middle of the bin. The MC prediction for the pair production of a T quark with a mass of 1300 GeV is shown by a dashed line, enhanced by a factor of 20. The lower panels show the ratio of the data to the background prediction. The uncertainties represented by the vertical bars on the points are statistical only. The shaded regions show the total statistical uncertainties in the background.

reconstructed top quark peak from the  $t\bar{t}$ +jets background process and the predicted signal for a T quark with a mass of 1300 GeV, enhanced by a factor of 20 for better visibility, appear in the figure as narrow peaks with similar widths.

The analysis selection has been optimized to obtain the best signal significance at high masses, and the mass reconstruction in the region of the top quark has not received special attention. As a result, the bin width used in Fig. 1 and the upper part of Fig. 2 is too coarse to reveal details of the mass reconstruction in this region. Nonetheless, the top quark peak provides a useful benchmark for checking the reconstructed mass scale and resolution in data and Monte Carlo.

## 6. Systematic uncertainties

In this section, we describe the systematic uncertainties in the calculation of the signal cross section. The uncertainties can be

divided into two categories: those that only impact the normalizations of the distributions, and those that also affect the shapes of the distributions. Each systematic uncertainty is included as a nuisance parameter in the likelihood fit described in Section 7.

The uncertainties in the  $t\bar{t}$ +jets, electroweak, and QCD multijet cross sections, the total integrated luminosity, and the lepton efficiencies affect only the normalization.

The uncertainty in the cross section for  $t\bar{t}$ +jets production of 5.3% is taken from a previous CMS measurement [43]. The integrated luminosity is known to a precision of 2.5% [44]. A 10% uncertainty is assigned to the sum of the non- $t\bar{t}$  backgrounds, which is dominated by the uncertainty in the W+jets and single top quark backgrounds. This uncertainty is obtained from earlier CMS measurements on single top quark production [45] and from a preliminary CMS measurement on inclusive W production.

Trigger and lepton identification efficiencies and data/MC SFs are obtained from data using decays of Z bosons to dileptons. The systematic uncertainty in the lepton identification and trigger efficiencies is 2.5%.

Uncertainties that affect the shapes of the  $m_{\text{reco}}$  distributions include those in the jet energy scales (JES), jet energy resolution (JER), b tagging efficiency, pileup, renormalization/factorization scale, and PDFs. To model these uncertainties, we produce additional distributions, called templates, by varying the nuisance parameter that characterizes each systematic effect by one standard deviation up and down. To determine the signal and background templates for any value of the nuisance parameter, we interpolate the content of each bin between the varied and nominal templates. This procedure is often referred to as vertical morphing [46].

The JES uncertainty affects the normalization and the shape of the  $m_{\text{reco}}$  distribution. This is taken into account by generating  $m_{\text{reco}}$  distributions for values of the jet energy scaled by one standard deviation of the  $\eta$ - and  $p_T$ -dependent uncertainties.

The MC was found to underestimate the JER observed in the data, and as a result the MC simulated jets are smeared to describe the data. To this end, the difference between the reconstructed jet  $p_T$  and the generated jet  $p_T$  is scaled by  $\eta$ -dependent SFs (the so-called “nominal” variation). To estimate the uncertainty in this rescaling, the analysis is repeated twice, each time applying additional sets of SFs that correspond to varying the nominal ones up and down by one standard deviation. Both AK4 and AK8 jets are subject to JER systematic variations. The JES and JER systematic variations are applied before the AK8 jet splitting. Systematic variations of each subjet are done with the same relative variation as the entire AK8 jet, so that their sum is equal to the modified AK8 four-momentum. The resulting jet momentum changes in the AK4 jet collection are propagated to  $p_T^{\text{miss}}$ .

The systematic uncertainty related to the b tagging efficiency is estimated by varying the b tagging SFs for both the medium and loose operating points by one standard deviation separately for heavy-flavor and light-flavor jets.

The pileup uncertainty is evaluated by varying the minimum-bias cross section used to calculate the pileup distribution in data by  $\pm 4.6\%$ , and adjusting the number of pileup interactions in the simulation to these distributions. This variation is taken from the uncertainty in a preliminary CMS measurement of the minimum-bias cross section.

The uncertainties due to variations in the renormalization and factorization scales are evaluated using per-event weights, corresponding to renormalization/factorization scale variations by a factor of two up and down. The combinations of scales corresponding to unphysical anti-correlated variations are not considered. The envelope of the observed variations in the  $m_{\text{reco}}$  spectrum is taken as an estimate of the uncertainty.

**Table 3**

Variations in percent on the yield of the selected MC events due to shape systematic uncertainties for a signal with a T quark mass of 1200 GeV and background.

|                             | Signal (%)  | Background (%) |
|-----------------------------|-------------|----------------|
| JES                         | +0.2, -2.5  | 17             |
| JER                         | +0.02, -0.3 | 0.03           |
| b tag heavy flavor          | 2.5         | +2.8, -1.4     |
| b tag light flavor          | 0.2         | 0.8            |
| Renorm./fact. scales        | 1.1         | +18, -14       |
| Pileup                      | 0.05        | 0.2            |
| PDF                         | 0.3         | 2.0            |
| Top quark $p_T$ reweighting | -           | 11             |
| W+jets reweighting          | -           | +4.9, -3.3     |
| $\Delta R_{\text{match}}$   | +0, -0.8    | +0, -1.9       |

For evaluating the uncertainty related to the PDFs, we use 100 MC replicas, generated with the NNPDF3.0 PDF set and their corresponding weights, to sample the  $m_{\text{reco}}$  distribution. The per-bin RMS in the  $m_{\text{reco}}$  distribution is taken as a measure of the PDF uncertainty in the corresponding templates. The PDF uncertainty is applied both to the background and the signal MC replicas. In the case of the signal, the uncertainty affects both the shape and yield, though the latter is only due to the signal acceptance, not to the signal cross section.

It is known that the top quark  $p_T$  distribution in the  $t\bar{t}$ +jets background process is not well modeled by the MC simulation [47]. Therefore, a reweighting of the top quark MC  $p_T$  distribution is applied. An event weight is calculated, based on the generator-level top quark  $p_T$ . The systematic uncertainty related to the top quark  $p_T$  distribution reweighting is determined from the difference between applying and not applying the reweighting, and by applying the reweighting twice.

For the W+jets background modeling, we use  $H_T$ -binned MC samples, for which the generator-level  $H_T$  distribution was found to deviate from the same distribution in the inclusive W+jets simulation. The variable  $H_T$  is defined as the scalar sum of the transverse momenta of all partons in a simulated event that originate from the hard-scattering process. In each  $H_T$ -binned sample, events are simulated in a certain range of  $H_T$  (200 to 400 GeV, 400 to 600 GeV, etc.). To improve the modeling, we implement an event-weighting technique in which each simulated W+jets event is weighted depending on its  $H_T$  value. The weight is based on a parametrization obtained from a fit to the ratio of the generator-level  $H_T$  distributions of inclusive and  $H_T$ -binned samples. The systematic uncertainty related to the event weighting is estimated from the difference between applying and not applying the weighting, and by applying the weighting twice.

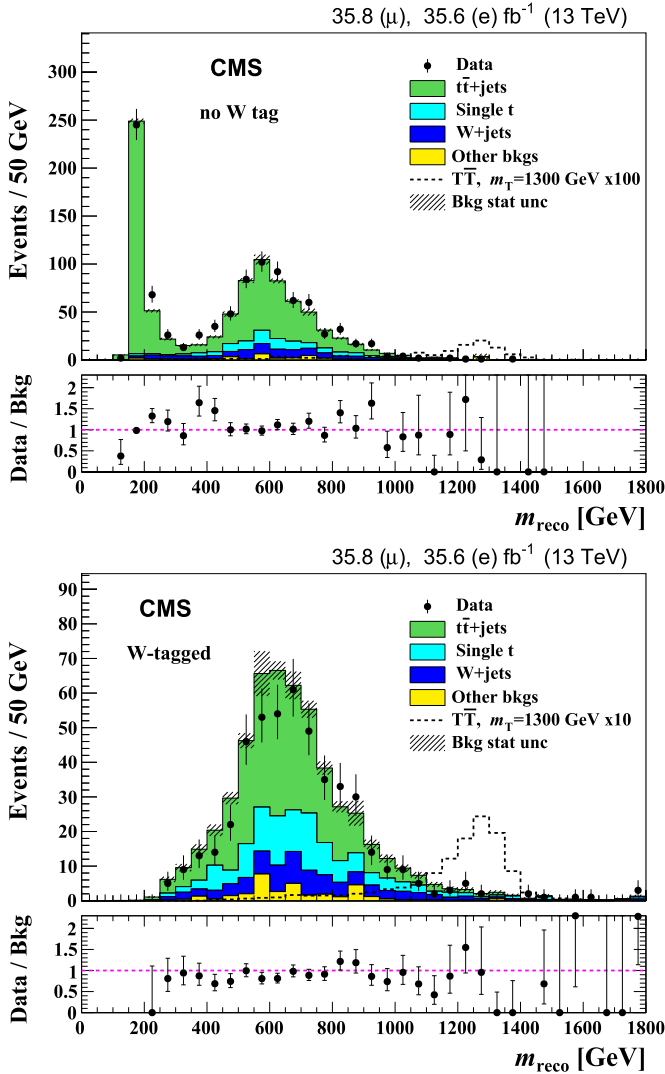
To estimate the systematic uncertainties related to the  $\Delta R_{\text{match}}$  requirement used to associate W-tagged AK8 jets with AK4 jets in the jet-splitting procedure, two templates with  $\pm 20\%$  variation in the maximum allowed  $\Delta R_{\text{match}}$  value were prepared.

Table 3 shows the influence of the shape systematic uncertainties on the signal, for a T mass of 1200 GeV, and background yields. Other sources of systematic uncertainties have a negligible impact on the analysis.

## 7. Cross section and mass limits

Since the observed distributions are consistent with the expected background, we use the results to set limits on the  $T\bar{T}$  production cross section and on the T quark mass.

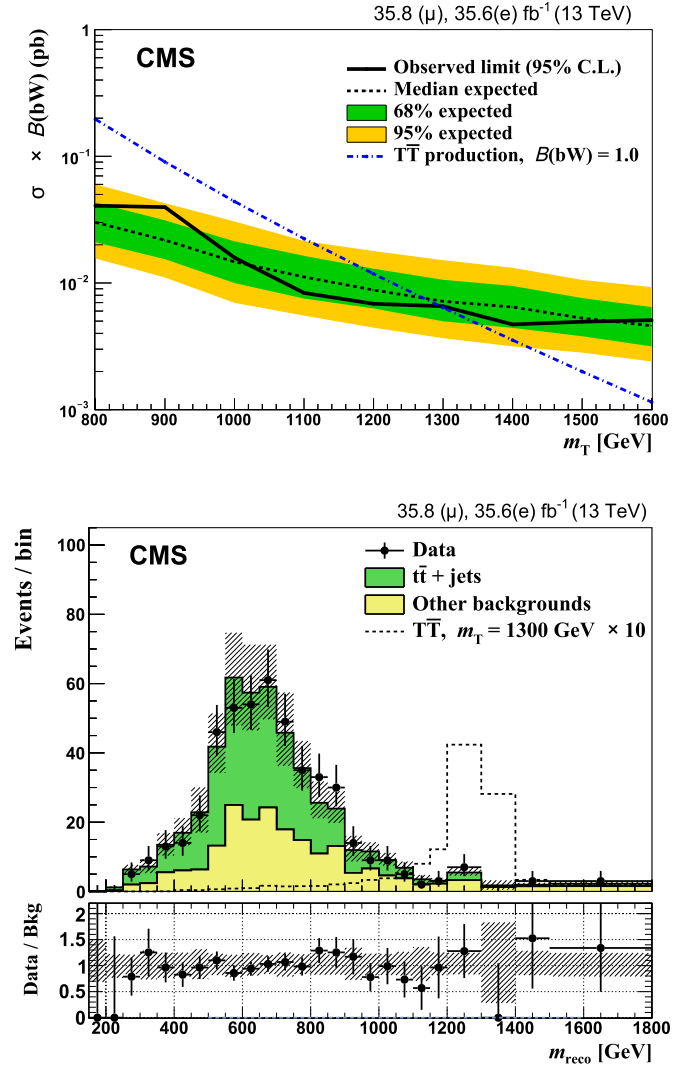
As discussed in Section 5, there are two types of selected events: those with W-tagged jets (labeled as “W-tagged”), and those without (labeled as “no W tag”). The  $m_{\text{reco}}$  invariant mass distributions for these two categories of events are shown sepa-



**Fig. 3.** The T quark reconstructed mass spectra for the sum of the  $\mu$ +jets and  $e$ +jets channels for the “no W tag” category of events (upper plot), and for the “W-tagged” category (lower plot) from data and from MC simulations of the background processes. The MC prediction for  $T\bar{T}$  production of a T quark with a mass of 1300 GeV is shown by a dashed line, enhanced by a factor of 100 (upper) and 10 (lower). The lower panels show the ratio of the data to the background prediction. The uncertainties represented by the vertical bars on the data points are statistical only.

rately in Fig. 3 for data and simulated background, combining the  $\mu$ +jets and  $e$ +jets contributions. The no W tag category is more sensitive to lower-mass  $T\bar{T}$  signal events, as shown in the upper plot of Fig. 3 by the clear top quark mass peak. At high masses this category of events gives a very small contribution to the signal. Conversely, the W-tagged category is more sensitive to high-mass signal events, as can be seen in Fig. 3 from the predicted distributions for a  $T\bar{T}$  signal with a T mass of 1300 GeV for the two categories. We therefore use the data  $m_{\text{reco}}$  distribution from the W-tagged events in setting a lower limit on the T quark mass. We checked that using the no W tag category together with the W-tagged category did not improve the sensitivity at high masses.

The distribution shown in Fig. 3 (lower plot) is used for the limit calculations. For the MC background distribution we require that the relative statistical uncertainty in each bin is not worse than 20%. For masses above 1200 GeV the bins are merged to meet this requirement. The final binning can be seen on the post-fit distribution shown in Fig. 4 (lower plot).



**Fig. 4.** Upper plot: Observed and expected Bayesian upper limits at 95% CL on the product of the  $T\bar{T}$  or  $Y\bar{Y}$  production cross section and the branching fraction to  $bW$  using only the W-tagged events. The inner and outer bands show the 1 and 2 standard deviation uncertainty ranges in the expected limits, respectively. The dashed-dotted line shows the prediction of the theory. Lower plot: The post-fit distribution of the reconstructed T quark mass,  $m_{\text{reco}}$ . Horizontal bars on the data points show bin size. The shaded band on the histogram and on the ratio plot shows the quadrature sum of the statistical and systematic uncertainties. The MC prediction for heavy quark production with a mass of 1300 GeV is shown by a dashed line, enhanced by a factor of 10.

The 95% confidence level (CL) upper limits on the production cross section of  $T\bar{T}$  are computed within the THETA framework [48] using a Bayesian interpretation [49], in which the systematic uncertainties are taken into account as nuisance parameters. The binned maximum-likelihood fit to the data distribution is performed with a combination of the background contributions plus a signal. The main backgrounds are  $t\bar{t}$ +jets, single top quark, and W+jets production. Other smaller backgrounds, including electroweak and QCD multijet processes, are summed up with the single top quark and W+jets contributions and are called non- $t\bar{t}$  background (see Table 1). Distributions of possible  $T\bar{T}$  signals are considered for T masses from 800 to 1600 GeV (Table 2).

The likelihood function is marginalized with respect to the nuisance parameters representing the systematic uncertainties in the shape and normalization. Thirteen nuisance parameters are employed in the likelihood fit:  $t\bar{t}$ +jets cross section uncertainty of

5.3%, normalization of the non- $t\bar{t}$  contribution of 10%, the integrated luminosity uncertainty of 2.5%, lepton identification and trigger uncertainty of 2.5%; other uncertainties are the shape uncertainties that include the JES, JER, the  $b$  tag SFs for light- and heavy-flavor jets, the renormalization and factorization scales, pileup, PDFs, top quark  $p_T$  reweighting, and  $W$ +jets background reweighting. Shapes of the SM background and signal templates are changed (“morphed”) in the limit-setting procedure according to the varying values of the shape nuisance parameters. Contributions from the SM processes are allowed to vary independently within their systematic uncertainties, using log-normal priors [50, 51]. The nuisance parameters describing the shape uncertainties are constrained using Gaussian priors. A flat prior probability density function on the total signal yield is assumed. The MC statistical uncertainties in the simulated samples are also included in this calculation.

Fig. 4 (upper plot) shows the observed and expected 95% CL upper limits on the  $T\bar{T}$  cross section as a function of the  $T$  quark mass. Fig. 4 (lower plot) shows the post-fit distribution of the reconstructed mass. From the upper cross section limits we set lower limits on the  $T$  quark mass. The 95% CL lower limit on the  $T$  mass is given by the value at which the 95% CL upper limit curve for the  $T\bar{T}$  cross section intersects the theory curve, as shown in Fig. 4. In the  $bW\bar{b}W$  channel with an assumed branching fraction  $\mathcal{B}(T \rightarrow bW) = 100\%$ , the observed (expected) lower limit on the  $T$  quark mass is 1295 (1275) GeV.

## 8. Summary

The results of a search for vector-like quarks, either  $T$  or  $Y$ , with electric charge of  $2/3$  and  $-4/3$ , respectively, that are pair produced in  $pp$  interactions at  $\sqrt{s} = 13$  TeV and decay exclusively via the  $bW$  channel have been presented. Events are selected requiring that one  $W$  boson decays to a lepton and neutrino, and the other to a quark–antiquark pair. The selection requires a muon or electron, significant missing transverse momentum, and at least four jets. A kinematic fit assuming  $T\bar{T}$  or  $Y\bar{Y}$  production is performed and for every event a candidate  $T/Y$  quark mass  $m_{\text{reco}}$  is reconstructed. The analysis provides a high-resolution (7%) mass scan of the  $bW$  spectrum in the range from the top quark mass up to  $\approx 2$  TeV, in which the signal from pair production of equal mass objects decaying to  $bW$  would show up in a model-independent way as a narrow peak. A binned maximum-likelihood fit to the  $m_{\text{reco}}$  distribution is made and no significant deviations from the standard model expectations are found. Upper limits are set on the  $T\bar{T}$  and  $Y\bar{Y}$  pair production cross sections as a function of their mass. By comparing these limits with the predicted theoretical cross section of the pair production, the production of  $T$  and  $Y$  quarks is excluded at 95% confidence level for masses below 1295 GeV (1275 GeV expected). More generally, the results set upper limits on the product of the production cross section and branching fraction to  $bW$  for any new heavy quark decaying to this channel.

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