Search for single production of a vector-like T quark decaying to a Z boson and a top quark in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

A search is presented for single production of a vector-like quark (T) decaying to a Z boson and a top quark, with the Z boson decaying leptonically and the top quark decaying hadronically. The search uses data collected by the CMS experiment in proton-proton collisions at a center-of-mass energy of 13 TeV in 2016, corresponding to an integrated luminosity of 35.9 fb$^{-1}$. The presence of forward jets is a particular characteristic of single production of vector-like quarks that is used in the analysis. Different T quark width hypotheses are studied, from negligibly small to 30% of the new particle mass. At the 95% confidence level, the product of cross section and branching fraction is excluded above values in the range 0.27–0.04 pb for T quark masses in the range 0.7–1.7 TeV, assuming a negligible width. A similar sensitivity is observed for widths of up to 30% of the T quark mass. The production of a heavy Z' boson decaying to Tt, with $T \rightarrow tZ$, is also searched for, and limits on the product of cross section and branching fractions for this process are set between 0.13 and 0.06 pb for Z' boson masses in the range from 1.5 to 2.5 TeV. These are the best limits to date on the single production of heavy vector-like T quarks, the first to set limits for a variety of resonance widths, and the best limits for the production of a Z' boson decaying to Tt.

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1 Introduction

A possible extension of the standard model (SM), able to address some of the problems related to the nature of electroweak symmetry breaking, involves heavy particles called vector-like quarks (VLQs) [1–5]. Unlike the chiral fermions of the SM, these new particles do not obtain mass through a Yukawa coupling but through a direct mass term. This means that they are not excluded by precision SM measurements as are fourth-generation chiral quarks [6].

Previous searches for VLQs have been performed by both the ATLAS [7–13] and CMS [14–21] Collaborations, as well as by the D0 [22, 23] and CDF [24–29] Collaborations.

We study the single production of vector-like T quarks with charge $+2/3$ that decay to a Z boson and a t quark. We search for a final state with a Z boson decaying to electrons or muons, and a t quark producing jets via the decay $t \rightarrow Wb \rightarrow q\bar{q}b$. An example of a leading-order (LO) Feynman diagram for the single production of a T quark in association with either a b quark, denoted $T(b)$, or a t quark, denoted $T(t)$, is shown in Fig. 1 (left). The three decay channels of the T quark into SM particles are $bW$, $tZ$, and $tH$. If the T is a singlet of the SM, the equivalence theorem [30] implies that the branching fractions for the three decay modes of the T quark are approximately 0.5, 0.25, and 0.25, respectively. If the T is a doublet of the SM, the decay modes are $tZ$ and $tH$, each with a branching fraction of 0.5.

The T quark could be singly produced in association with either a t or a b quark and an additional quark would be produced in the forward region of the detector. The coupling coefficients of the T quark to SM particles are denoted $C(bW)$ for the $T(b)$ process, and $C(tZ)$ for the $T(t)$ process. The production cross section of the T quark depends on its mass and width, as well as on these couplings. The T quark can have both left-handed (LH) and right-handed (RH) couplings to SM particles. In the case of a singlet T quark, the RH chirality is suppressed by a factor proportional to the SM quark mass divided by the T quark mass. In the case of a doublet T quark, it is the LH chirality that is suppressed [31].

The present search is also sensitive to the production of a T quark together with a t quark in the decay of a heavy neutral spin-1 $Z'$ boson [32–34]. A LO Feynman diagram for this production mode is shown in Fig. 1 (right). This channel was also considered in Refs. [17, 35].

In this analysis, the signal is searched for as an excess in the mass spectrum of reconstructed T quark candidates, $m_{TZ}$, which is used as the discriminating variable. The background is largely

![Figure 1: Leading-order Feynman diagrams for the production of a single vector-like T quark and its decay to a Z boson and a t quark, either in association with a b quark or a t quark (left), or in the decay of a $Z'$ boson to Tt (right).](image-url)
The CMS detector, data, and simulation

The CMS detector operates at one of the four interaction points of the LHC. Its central feature is a 3.8 T superconducting solenoid magnet with an inner diameter of 6 m. The following subdetectors are found within the magnet volume: a silicon tracker, a crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL). Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. In addition, the CMS detector has extensive forward calorimetry: two steel and quartz-fiber hadron forward calorimeters that extend the HCAL coverage to regions close to the beam pipe, and cover the pseudorapidity range $3.0 < |\eta| < 5.2$. A more detailed description of the CMS detector, together with a definition of the coordinate system and kinematic variables, can be found in Ref. [36].

This analysis is based on the data collected by the CMS experiment in proton-proton collisions at a center-of-mass energy of 13 TeV in 2016, corresponding to an integrated luminosity of 35.9 fb$^{-1}$. Events with a Z boson decaying to muons are selected online by requiring the presence of an isolated muon with transverse momentum $p_T > 24$ GeV. Events with the Z boson decaying to electrons are selected online if an electron is reconstructed with $p_T > 115$ GeV. It is possible to use this relatively high $p_T$ threshold without losing signal efficiency, since the electrons of interest arise from the decay of a heavy resonance.

Background events are generated using the next-to-LO (NLO) generator MadGraph5_aMC@NLO 2.2.2 [37] for $Z/\gamma^*+\text{jets}$, $t\bar{t}+V$, and $tZq$ processes, and the NLO generator Powheg 2.0 [38–41] for $t\bar{t}$ and single $t$ quark production. They are interfaced with Pythia 8.212 [42], with the tune CUETP8M2T4 [43] used for the description of parton hadronisation and fragmentation. Events for SM diboson production are generated at LO using MadGraph 5.2 or at NLO with Powheg 2.0.

Signal events for the single production of the T quark are generated at LO using MadGraph 5.2 interfaced to Pythia, for different T quark width hypotheses: negligibly small and larger widths (10, 20, and 30% of the T quark mass). Spin correlations are treated in the decay with Madspin [44].

In the case the $T$ and $Z'$ particles are generated with narrow widths, i.e., negligibly small with respect to the experimental reconstructed mass resolution, T quark masses $m_T$ between 0.7 and 1.7 TeV in steps of 0.1 TeV, and $Z'$ masses $m_{Z'}$ of 1.5, 2.0, and 2.5 TeV are considered. The singlet $T(b)$ signal process with LH couplings to SM particles, and doublet $T(t)$ signal process with RH couplings, are generated. Theoretical cross sections for the narrow-width T quark assumption are listed in Table 1, calculated following the procedures described in Ref. [4], where a simplified approach is used to provide a model-independent interpretation of experimental results. The width of the VLQ is negligible compared to the experimental mass resolution for $C(bW)$.
Table 1: Theoretical cross sections at next-to-leading order for single production of a T quark in association with a b or t quark for the benchmark masses considered in the analysis, with the couplings set to 0.5 and using the narrow-width T quark assumption, calculated following the procedures described in Ref. [4]. The cross sections do not depend on the chirality of the T quark. The narrow-width assumption is valid for any value of the couplings less than or equal to 0.5.

| Mass [TeV] | $\sigma(pp \rightarrow Tbq)$ [pb] | $\sigma(pp \rightarrow Ttq)$ [pb] |
|------------|-------------------------------|-------------------------------|
| 0.7        | 1.455                         | 0.125                         |
| 0.8        | 0.965                         | 0.091                         |
| 0.9        | 0.680                         | 0.068                         |
| 1.0        | 0.488                         | 0.051                         |
| 1.1        | 0.338                         | 0.038                         |
| 1.2        | 0.246                         | 0.029                         |
| 1.3        | 0.179                         | 0.022                         |
| 1.4        | 0.135                         | 0.017                         |
| 1.5        | 0.102                         | 0.014                         |
| 1.6        | 0.076                         | 0.011                         |
| 1.7        | 0.058                         | 0.008                         |

and C(tZ) couplings ≤ 0.5.

Signals for T quarks with larger widths (10, 20, and 30% of the T quark mass) are generated in the same mass range but in steps of 0.2 TeV. The effect of the finite-width approximation is evaluated using a modified version of the model constructed by the authors of Refs. [5, 45, 46]. Modifications of the published versions were necessary to provide a simulation of the full $2 \rightarrow 4$ process, i.e., $pp \rightarrow Tbq/Ttq \rightarrow tZbq/tZtq$, in the finite-width hypothesis. It has been verified that the interference of the $2 \rightarrow 4$ process with the SM background processes is negligible.

In the general case, the total production cross section for a T quark with a finite width (FW) can be written as:

$$\sigma_{FW}(C_1, C_2, m_T, \Gamma(C_1, C_2, C_i, m_T, m_j)) = C_1^2 C_2^2 \tilde{\sigma}_{FW}(m_T, \Gamma(C_1, C_2, C_i, m_T, m_j)),$$

where $\Gamma(C_1, C_2, C_i, m_T, m_j)$ is the width of the T quark, $C_1$ and $C_2$ are its couplings to SM quarks and bosons in the specific single-production process under consideration, $C_i$ summarizes other possible couplings that allow the T to decay to other final states, and the quantities $m_j$ represent the masses of the decay products of the T quark. For the process $pp \rightarrow Ttq \rightarrow tZtq$ the couplings are $C_1 = C_2 = (g_w/2) C(tZ)$, while for $pp \rightarrow Tbq \rightarrow tZbq$ the couplings are $C_1 = (g_w/2) C(bW)$ and $C_2 = (g_w/2) C(tZ)$. The normalisation factor $g_w/2$ has been introduced to properly compare the couplings as defined in Ref. [4] and in Eq. [1]. In Table 2, the values for the reduced cross section $\tilde{\sigma}_{FW}$ are shown together with the cross sections for the singlet T(b) and doublet T(t) signals used to interpret the results. These cross sections are calculated by fixing the branching fractions of the T to the expected values in the narrow-width approximation, as described above and in Ref. [4].

The generated events are passed through a simulation of the CMS detector based on GEANT4 [47, 48]. The number of additional interactions in the same or adjacent bunch crossings (pileup) is included in simulation with a distribution of the number of additional interactions matching that observed in data. Samples are generated using the NNPDF 3.0 [49] parton distribution function (PDF) sets, matching the perturbative order used in simulation.
Table 2: Theoretical reduced cross sections $\tilde{\sigma}$ for single production of a T quark with a b or a t quark, where the T quark decays to $tZ$ and its width is 10, 20, and 30% of its mass, for the benchmark masses considered in the analysis. The corresponding leading order cross sections $\sigma$ are shown in parentheses.

| Mass [TeV] | $\tilde{\sigma}$ for $pp \to Tbq \to tZbq$ [pb] | $\tilde{\sigma}$ for $pp \to Ttq \to tZtq$ [pb] |
|------------|---------------------------------|---------------------------------|
| 0.8        | 226 (0.675)                     | 19 (0.144)                      |
| 1.0        | 183 (0.314)                     | 14 (0.075)                      |
| 1.2        | 145 (0.158)                     | 11 (0.024)                      |
| 1.4        | 112 (0.084)                     | 8.2 (0.014)                     |
| 1.6        | 85 (0.047)                      | 29 (0.041)                      |

3 Object reconstruction

Primary vertices are reconstructed using a deterministic annealing filter algorithm [50]. The reconstructed vertex with the largest value of summed physics-object $p_T^2$ is taken to be the primary pp interaction vertex. The physics objects are the objects returned by a jet finding algorithm [51, 52] applied to all charged tracks associated with the vertex, plus the corresponding associated missing transverse momentum. Selected events are required to have this primary vertex within 24 cm of the center of the detector along the $z$-direction, and within 2 cm in the $x$-$y$ plane.

A particle-flow (PF) algorithm [53] is used to identify and to reconstruct charged and neutral hadrons, photons, muons, and electrons, through an optimal combination of the information from the entire detector.

Electron candidates are reconstructed by combining the information from the ECAL and from the silicon tracker [54]. Electrons are then selected if they are isolated and if they have $p_T > 20$ GeV and pseudorapidity $|\eta| < 2.5$. Additional requirements are applied to the energy distribution in the ECAL, to the geometrical matching of the tracker information to the ECAL energy cluster, on the impact parameters of the charged tracks, and on the ratio of the energies measured in the HCAL and the ECAL in the region around the electron candidate. The leading electron is required to have $p_T > 120$ GeV, in order to be in the region where the trigger is close to 100% efficiency.

Muon candidates are reconstructed by combining in a global fit the information from the silicon tracker and the muon system [55]. Muons are then required to be isolated, to satisfy $p_T > 20$ GeV and $|\eta| < 2.4$, and to pass additional identification criteria based on the track impact parameter, the quality of the track reconstruction, and the number of hits recorded in the tracker and the muon systems. Like the leading electron, the leading muon is required to have $p_T > 120$ GeV.

For both muons and electrons, a lepton isolation variable is used to reduce background from events in which a jet is misidentified as a lepton. This variable is defined as the scalar sum of the $p_T$ of the charged and neutral hadrons and photons in a cone of size $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$ around the original lepton track, corrected for the effects of pileup [54, 55], and divided by the lepton $p_T$. The cone size is 0.4 for muons and 0.3 for electrons.

Jet candidates are clustered from the PF candidates using the anti-$k_T$ clustering algorithm [51] with distance parameters of 0.4 ("AK4 jets") and 0.8 ("AK8 jets"). The jet energy scale (JES) is calibrated through correction factors dependent on the $p_T$, $\eta$, energy density, and area of the jet.
The jet energy resolution (JER) for the simulated jets is degraded to reproduce the resolution observed in data. The AK4 jet candidates are required to have \( p_T > 20 \text{ GeV}, |\eta| < 2.4 \) and to be separated by \( \Delta R > 0.4 \) from an identified lepton. The AK8 jet candidates are required to have \( p_T > 180 \text{ GeV}, |\eta| < 2.4 \) and to be separated by \( \Delta R > 0.8 \) from an identified lepton. The AK8 jets may be tagged as coming from a W boson decaying to q'q (denoted “W jets”) or from a t quark decaying fully hadronically (“t jets”). For the W jets, a pruning algorithm \([56]\) is applied. The mass of the jet, after the pruning is performed, is used as a discriminant to select W bosons and reject quark and gluon jets. The discrimination between W jets and jets from quarks and gluons is further improved by requiring the \( N\)-subjettiness ratio \( \tau_{21} \) to be less than 0.6, where \( \tau_{21} = \tau_2/\tau_1 \) \([57]\), and the mass of the pruned AK8 jet to be within the range 65–105 GeV. In a similar way, AK8 jets may be identified as arising from the all-jets final state of a t quark. These t jets are required to have \( p_T > 400 \text{ GeV}, \) mass of the jet reconstructed through the modified mass drop tagger algorithm \([58, 59]\) between 105 and 220 GeV, and \( \tau_{32} = \tau_3/\tau_2 \) less than 0.81. Finally, AK4 jets may be tagged as arising from a b quark (“b jets”) using the combined secondary vertex algorithm \([60, 61]\). A “medium” working point with an efficiency of 70% for genuine b jets and a rejection of 99% of light-flavour jets is used, together with a “loose” working point that has an 85% identification efficiency and rejects 90% of light-flavoured jets. The efficiency for identifying W, t, and b jets in simulation is corrected to match the results found in data.

An interesting feature of the direct production of a single vector-like T quark is the presence of an additional jet that is produced in the forward direction. Forward jets are reconstructed as AK4 jets using the same selections and corrections as defined above, but have \( 2.4 < |\eta| < 5.0 \) and \( p_T > 30 \text{ GeV} \).

## 4 Event selection

Events are required to have two oppositely charged leptons (either muons or electrons) forming a Z boson with an invariant mass between 70 and 110 GeV. A t quark from a T quark decay can be identified in three different ways: fully merged (a t jet is identified), partially merged (a W jet and a b jet are identified), or resolved (three AK4 jets are reconstructed). We therefore define ten event categories, depending on how the Z boson or the t quark candidates are reconstructed and on the number of forward jets present, as summarized in Table 3.

| Category | Z boson | t quark         | N(forward jets) |
|----------|---------|-----------------|-----------------|
| 1        | two muons | fully merged    | \( \geq 0 \)   |
| 2        | two electrons | fully merged   | \( \geq 0 \)   |
| 3        | two muons | partially merged | 0              |
| 4        | two muons | partially merged | \( \geq 1 \)   |
| 5        | two electrons | partially merged | 0              |
| 6        | two electrons | partially merged | \( \geq 1 \)   |
| 7        | two muons | resolved       | 0              |
| 8        | two muons | resolved       | \( \geq 1 \)   |
| 9        | two electrons | resolved   | 0              |
| 10       | two electrons | resolved   | \( \geq 1 \)   |

The hierarchy places the most sensitive categories first. If an event falls into two or more categories it is assigned only to the first. For categories 1 and 2, the t quark candidate is given by the t jet; for categories 3–6 it is reconstructed by summing the momentum vectors of the W jet.
and the b jet; while for categories 7–10 the momenta of the three jets are summed. If more than one t quark candidate is found, the one with the largest $p_T$ is selected for subsequent analysis.

In addition to requiring a Z boson and a t quark in the event, for each category at least one “medium” b jet has to be present, the two leptons from the Z boson decay have to be close to each other ($\Delta R < 0.6–1.4$, depending on the category), and the leading lepton (muon or electron) must have $p_T > 120$ GeV. Furthermore, in the resolved categories, the two jets with the lowest b tagging discriminant of the three jets forming the t quark candidate are required to have a dijet invariant mass $m_{j1,j2}$ below 200 GeV. All these requirements were optimized to increase the sensitivity of the analysis.

The T quark candidate mass $m_{tZ}$ is obtained by summing the momenta of the Z candidate, given by the two muons or the two electrons, and the t quark candidate, reconstructed for the three scenarios as described above.

5 Background estimate

To reduce the dependence on the simulation, a background estimate is used that is primarily obtained from a control region in data. The method consists of an extrapolation from a background-enriched control region into the signal region. This control region is defined by the event selection described in Section 4, except for the veto on the presence of any jets passing the “loose” working point of the b tagging algorithm.

The background yield in the signal region is evaluated through the formula:

$$N_{bkg}(m_{tZ}) = N_{CR}(m_{tZ}) \alpha(m_{tZ}),$$

where $N_{CR}(m_{tZ})$ is the number of events found in the data in the control region as a function of $m_{tZ}$, and $\alpha(m_{tZ})$ is the ratio obtained from simulation of the number of background events in the signal region to that in the control region, at each value of $m_{tZ}$. A closure test is performed to validate the method in an independent signal-free region, defined by considering the resolved categories and inverting the cut on $m_{j1,j2}$. Good agreement is found between the predicted background and the observed data.

Comparisons between the background estimates and the observations in data in the $m_{tZ}$ distribution are shown in Figs. 2, 3, and 4. The number of predicted background events and the number of observed events are reported in Tables 4, 5, and 6 together with the number of expected signal events for two example masses. The numbers of observed events are consistent with SM background predictions.
Figure 2: Comparison between the data, the background estimate, and the expected signal for the 2 categories where the T quark is reconstructed in the fully merged topology, for events with the Z boson decaying into muons (left) and electrons (right). The background composition is taken from simulation. The uncertainties in the background estimate include both statistical and systematic components. The lower panel in each plot shows the ratio of the data and the background estimation, with the shaded band representing the uncertainties in the background estimate. The vertical bars for the data points show the Poisson errors associated with each bin, while the horizontal bars indicate the bin width.
Figure 3: Comparison between the data, the background estimate, and the expected signal for the 4 categories where the T quark is reconstructed in the partially merged topology, for events with the Z boson decaying into muons (left) and electrons (right), and zero (at least one) forward jets in the upper (lower) row. The background composition is taken from simulation. The uncertainties in the background estimate include both statistical and systematic components. The lower panel in each plot shows the ratio of the data and the background estimation, with the shaded band representing the uncertainties in the background estimate. The vertical bars for the data points show the Poisson errors associated with each bin, while the horizontal bars indicate the bin width.
Figure 4: Comparison between the data, the background estimate, and the expected signal for the 4 categories where the T quark is reconstructed in the resolved topology, for events with the Z boson decaying into muons (left) and electrons (right), and zero (at least one) forward jets in the upper (lower) row. The background composition is taken from simulation. The uncertainties in the background estimate include both statistical and systematic components. The lower panel in each plot shows the ratio of the data and the background estimation, with the shaded band representing the uncertainties in the background estimate. The vertical bars for the data points show the Poisson errors associated with each bin, while the horizontal bars indicate the bin width.
Table 4: The number of estimated background events compared to the observed number of events for the two fully merged categories. The quoted uncertainties in the background estimates include both statistical and systematic components, as described in Section 6. Expected signal yields, and their respective efficiencies with parentheses, for events with the Z boson decaying to electrons or muons, are given for two benchmark masses and two values of the width “w”, for a T quark produced in association with a b, T(b), and a T quark produced in association with a t, T(t).

| Channel | 2µ+1t-jet | 2e+1t-jet |
|---------|-----------|-----------|
| Estimated background | 37.3 ± 4.6 | 25.8 ± 4.1 |
| Data events | 33 | 31 |
| T(b), \(m_T = 0.8 \) TeV, \(w \simeq 0\) | 1.2 (0.2%) | 0.9 (0.1%) |
| T(b), \(m_T = 0.8 \) TeV, \(w = 0.3m_T\) | 22.9 (1%) | 17.1 (1%) |
| T(t), \(m_T = 0.8 \) TeV, \(w \simeq 0\) | 1.3 (1%) | 1.0 (1%) |
| T(t), \(m_T = 0.8 \) TeV, \(w = 0.3m_T\) | 6.3 (2%) | 5.4 (2%) |
| T(b), \(m_T = 1.6 \) TeV, \(w \simeq 0\) | 2.9 (6%) | 2.6 (6%) |
| T(b), \(m_T = 1.6 \) TeV, \(w = 0.3m_T\) | 5.3 (5%) | 4.8 (5%) |
| T(t), \(m_T = 1.6 \) TeV, \(w \simeq 0\) | 0.8 (6%) | 0.7 (6%) |
| T(t), \(m_T = 1.6 \) TeV, \(w = 0.3m_T\) | 1.5 (5%) | 1.4 (5%) |

Table 5: The number of estimated background events compared to the observed number of events for the four partially merged categories. The quoted uncertainties in the background estimates include both statistical and systematic components, as described in Section 6. Expected signal yields, and their respective efficiencies with parentheses, for events with the Z boson decaying to electrons or muons, are given for two benchmark masses and two values of the width “w”, for a T quark produced in association with a b, T(b), and a T quark produced in association with a t, T(t).

| Channel | 2\(\mu+1\)W-jet+1b-jet \(N(\text{forward jets}) = 0\) | 2\(e+1\)W-jet+1b-jet \(N(\text{forward jets}) = 0\) | 2\(\mu+1\)W-jet+1b-jet \(N(\text{forward jets}) > 0\) | 2\(e+1\)W-jet+1b-jet \(N(\text{forward jets}) > 0\) |
|---------|-----------------|-----------------|-----------------|-----------------|
| Estimated background | 17.2 ± 1.9 | 14.5 ± 1.9 | 8.5 ± 1.8 | 5.7 ± 1.6 |
| Data events | 21 | 16 | 3 | 7 |
| T(b), \(m_T = 0.8 \) TeV, \(w \simeq 0\) | 2.7 (0.5%) | 1.7 (0.3%) | 5.4 (0.9%) | 4.3 (0.7%) |
| T(b), \(m_T = 0.8 \) TeV, \(w = 0.3m_T\) | 8.2 (0.5%) | 5.0 (0.3%) | 12.2 (0.8%) | 9.5 (0.6%) |
| T(t), \(m_T = 0.8 \) TeV, \(w \simeq 0\) | 0.9 (0.8%) | 0.8 (0.7%) | 2.0 (2%) | 1.5 (1%) |
| T(t), \(m_T = 0.8 \) TeV, \(w = 0.3m_T\) | 2.8 (0.9%) | 2.1 (0.6%) | 4.7 (1%) | 3.9 (1%) |
| T(b), \(m_T = 1.6 \) TeV, \(w \simeq 0\) | 0.2 (0.3%) | 0.2 (0.3%) | 0.4 (0.9%) | 0.3 (0.6%) |
| T(b), \(m_T = 1.6 \) TeV, \(w = 0.3m_T\) | 0.4 (0.4%) | 0.3 (0.3%) | 0.7 (0.7%) | 0.6 (0.6%) |
| T(t), \(m_T = 1.6 \) TeV, \(w \simeq 0\) | 0.1 (0.7%) | 0.1 (0.5%) | 0.2 (1%) | 0.2 (1%) |
| T(t), \(m_T = 1.6 \) TeV, \(w = 0.3m_T\) | 0.2 (0.7%) | 0.2 (0.6%) | 0.4 (1%) | 0.4 (1%) |
Table 6: The number of estimated background events compared to the observed number of events for the four resolved categories. The quoted uncertainties in the background estimates include both statistical and systematic components, as described in Section 6. Expected signal yields, and their respective efficiencies with parentheses, for events with the Z boson decaying to electrons or muons, are given for two benchmark masses and two values of the width “w”, for a T quark produced in association with a b, T(b), and a T quark produced in association with a t, T(t).

| Channel | 2µ+1 b-jet+2 jets | 2e+1 b-jet+2 jets | 2µ+1 b-jet+2 jets | 2e+1 b-jet+2 jets |
|---------|------------------|------------------|------------------|------------------|
|         | N(forward jets) = 0 | N(forward jets) > 0 | N(forward jets) = 0 | N(forward jets) > 0 |
| Estimated background | 315 ± 15 | 228 ± 12 | 108.3 ± 7.3 | 66.2 ± 5.6 |
| Data events | 339 | 239 | 115 | 88 |
| T(b), m_T = 0.8 TeV, w ≃ 0 | 13.7 (2%) | 10.0 (2%) | 25.7 (4%) | 18.5 (3%) |
| T(b), m_T = 0.8 TeV, w = 0.3m_T | 35.9 (2%) | 29.7 (2%) | 66.5 (4%) | 52.7 (3%) |
| T(t), m_T = 0.8 TeV, w ≃ 0 | 2.5 (2%) | 2.0 (2%) | 5.0 (5%) | 4.0 (4%) |
| T(t), m_T = 0.8 TeV, w = 0.3m_T | 8.9 (3%) | 6.7 (2%) | 15.8 (5%) | 12.0 (4%) |
| T(b), m_T = 1.6 TeV, w ≃ 0 | 1.0 (2%) | 0.9 (2%) | 2.5 (5%) | 2.0 (4%) |
| T(b), m_T = 1.6 TeV, w = 0.3m_T | 2.2 (2%) | 1.9 (2%) | 4.7 (5%) | 3.9 (4%) |
| T(t), m_T = 1.6 TeV, w ≃ 0 | 0.3 (3%) | 0.3 (2%) | 0.8 (6%) | 0.7 (5%) |
| T(t), m_T = 1.6 TeV, w = 0.3m_T | 0.8 (3%) | 0.7 (2%) | 1.7 (6%) | 1.5 (5%) |
6 Systematic uncertainties

Systematic effects have been evaluated by propagating the uncertainties in the input quantities. Unless explicitly stated, the impact of these uncertainties are evaluated both in the normalization and in the shape of the distribution of $m_{tZ}$.

Five main sources of uncertainty contribute to the estimated background. The dominant ones are the statistical uncertainties in the control regions used to estimate the background, both in data, giving an uncertainty of 10–46% depending on the category, and in the simulation, with an uncertainty of 3–34%. The small differences between the observation and the prediction for the closure test described previously are taken as systematic uncertainties (6%). An uncertainty due to possible mismodelling of the Z+light quark and Z+b quark fractions in the simulation is evaluated. This systematic uncertainty is evaluated by observing the effect of changing the $Z+b$ fraction by 10% [62], yielding a contribution to the uncertainty in the background estimation of between 0.1 and 0.8%. Finally, the uncertainty from the b tagging efficiency for the b, c, and light-flavour jets is evaluated by changing the b tagging corrections by their uncertainties [60, 61], yielding a change in the normalization of between 0.1% and 0.5%, depending on the category.

The systematic uncertainty in the signal is estimated from the corrections applied to the simulation to match distributions in data. The corrections for lepton identification and lepton trigger efficiency are obtained from dedicated analyses, using the “tag-and-probe” method [54, 55]. Changing these corrections by their uncertainties provides an estimate of the uncertainties in the signal yield of 3% for muons and electrons for a mass hypothesis of 1.0 TeV, and 1% for the trigger. The jet four-momenta are varied by the JES and JER uncertainties, which provide respective changes in the signal yield of 1% (JES) and 0.5% (JER), while for forward jets a change of 8% is observed. For W and t jet tagging, the same procedure of varying the corrections is applied, yielding an uncertainty of 4 and 8%, respectively. The uncertainty in the b tagging efficiency is evaluated, as for the background, by scaling up and down the b tagging corrections by their uncertainties [60, 61]; the change in yield of the signal is found to be 2.5%. The uncertainties from the choice of PDF are evaluated using the NNPDF 3.0 PDF eigenvectors [63], considering only at the change in the shape of the $m_{tZ}$ distribution. The uncertainty in the simulation of pileup is obtained by changing the inelastic cross section, which controls the average pileup multiplicity, by 5% [64], resulting in a signal yield uncertainty of 1%. Additional sources of systematic uncertainty are the integrated luminosity (2.5%, normalization only) [65] and the factorization and renormalization scales used in simulation (shape only).

7 Results

No significant deviations from the expected background are observed in any of the search channels. We set upper limits on the product of the cross section and branching fraction of a T quark decaying to $tZ$. The exclusion limits at a confidence level (CL) of 95% are obtained using the asymptotic CLs criterion [66–69], with templates for background and signal given by the binned distributions in Figs. 2, 3, and 4. Systematic uncertainties are treated as nuisance parameters, assuming a log-normal distribution for normalization parameters and a Gaussian distribution for systematic uncertainties that affect the $m_{tZ}$ shape.

In Fig. 5, the observed and expected limits from the ten categories of the T quark search are shown combined together, for the singlet LH T(b) (left) and doublet RH T(t) (right) production modes. Limits on $\sigma(pp \rightarrow T_{bq} \rightarrow tZ_{bq})$ for the singlet LH T(b) exclude values greater than 0.27–0.04 pb at 95% CL, for masses in the range 0.7–1.7 TeV. For an RH T(t) signal, the region
above 0.15–0.04 pb is excluded for the same mass range. Upper limits are compared with theoretical cross sections calculated at NLO in Ref. [4]. For this model, a singlet LH T quark with C(bW) = 0.5 is excluded at 95% CL for masses below 1.2 TeV.

Figure 5: Observed and expected limits at 95% CL on the product of the single production cross section and branching fraction for the singlet LH T quark produced in association with a b quark (left) and for the doublet RH T quark produced in association with a t quark (right), where the T quark has a narrow width and decays to tZ. The inner green and outer yellow bands represent the 1 and 2 standard deviation uncertainties in the expected limit. The red lines indicate theoretical cross sections, as calculated at next-to-leading order in Ref. [4]. The branching fraction \( B(T \rightarrow tZ) \) is 0.25 (0.5) for the left (right) plot.

In Fig. 6, the observed and expected upper limits at 95% CL are shown as a function of the T quark width and T quark mass in the ranges from 10 to 30% and 0.8 to 1.6 TeV, respectively. A sensitivity similar to that obtained assuming a narrow-width T quark is observed. In this case the experimental results are compared with the theoretical cross sections calculated at LO using a modified version of the model constructed by the authors of [5, 45, 46] and reported in Table 2. For this model, the data exclude a singlet LH T quark produced in association with a b quark, for masses below values in the range 1.34 and 1.42 TeV depending on the width. A doublet RH T quark produced in association with a t quark is excluded for masses below values in the range 0.82 and 0.94 TeV.

In addition to being singly produced directly, as diagrammed in Fig. 1 (left), the T quark may also appear singly in events where a single Z’ is produced that decays Z’ \( \rightarrow Tt \), as illustrated in Fig. 1 (right). Observed and expected limits for the production of a T quark via the decay of a Z’ boson, Z’ \( \rightarrow Tt \) and T \( \rightarrow tZ \), are shown in Table 7. We assume negligible widths for both the Z’ boson and the T quark. The product of cross section and branching fractions is excluded above 0.13–0.06 pb, for a Z’ boson mass in the range from 1.5 to 2.5 TeV and for a T quark mass from 0.7 to 1.5 TeV.
Figure 6: Observed (upper) and expected (lower) limits at 95% CL on the product of the single production cross section and branching fraction for the singlet LH T quark produced in association with a b quark (left) and for the doublet RH T quark produced in association with a t quark (right), where the T quark has a width from 10% to 30% of its mass and decays to tZ. The solid black lines indicate theoretical cross sections, as calculated at leading order using a modified version of the model constructed by the authors of Refs. [5, 45, 46] and reported in Table 2. In each plot, the excluded region lies to the left of the line, except in the lower-left plot where the entire region shown is excluded.

Table 7: Observed and expected 95% CL upper limit on $\sigma(pp\rightarrow Z')\, B(Z'\rightarrow Tt)\, B(T\rightarrow tZ)$. The ±1 and ±2 standard deviation (s.d.) expected limits are also given. The limits are given in pb.

| $m_{Z'}$ [TeV] | $m_T$ [TeV] | Observed | Expected | Expected $-1(2)$ s.d. | Expected $+1(2)$ s.d. |
|----------------|-------------|----------|----------|------------------------|------------------------|
| 1.5            | 0.7         | 0.13     | 0.10     | 0.07 (0.05)            | 0.14 (0.19)            |
| 1.5            | 0.9         | 0.11     | 0.08     | 0.06 (0.04)            | 0.12 (0.16)            |
| 1.5            | 1.2         | 0.09     | 0.05     | 0.04 (0.03)            | 0.07 (0.10)            |
| 2.0            | 0.9         | 0.09     | 0.06     | 0.04 (0.03)            | 0.08 (0.11)            |
| 2.0            | 1.2         | 0.08     | 0.05     | 0.03 (0.03)            | 0.07 (0.09)            |
| 2.0            | 1.5         | 0.06     | 0.03     | 0.03 (0.02)            | 0.05 (0.07)            |
| 2.5            | 1.2         | 0.07     | 0.05     | 0.03 (0.02)            | 0.06 (0.09)            |
| 2.5            | 1.5         | 0.06     | 0.04     | 0.03 (0.02)            | 0.05 (0.07)            |
8 Summary

Results were presented of a search for the single production of a T quark with a charge of $+2/3$, decaying to a Z boson and a t quark. No deviations were observed relative to the expected standard model background. Upper limits on the product of the cross section and branching fraction range between 0.27 and 0.04 pb at 95% confidence level for a left-handed T quark produced in association with a b quark, $T(b)$, and between 0.15 and 0.04 pb for a right-handed T quark produced in association with a t quark, $T(t)$, for the range of masses between 0.7 and 1.7 TeV. This result was obtained under the hypothesis of a narrow-width T quark, providing an interpretation of results through the simplified approach of Ref. [4]. In this case, left-handed T quarks produced in association with a b quark and with a coupling $C(bW)$ of 0.5 were excluded below the mass of 1.2 TeV. A large gain in the search sensitivity was found relative to previous results [17] because of improvements introduced in the analysis as well as the increase in the integrated luminosity. The effect of a nonnegligible width was also studied; values of the width between 10 and 30% of the T quark mass were considered, and similar sensitivities were observed. The results were interpreted using a modified version of the model constructed by the authors of Refs. [5, 45, 46], and a left-handed $T(b)$ signal was excluded for masses below values in the range 1.34–1.42 TeV, depending on the width, while a right-handed $T(t)$ signal was excluded for masses below values in the range 0.82–0.94 TeV. Finally, the production of a $Z'$ boson that decays to $Tt$ was excluded for values of the product of cross section and branching fractions below the range of 0.13–0.06 pb, for $Z'$ boson and T quark masses in the respective ranges of 1.5 to 2.5 TeV and 0.7 to 1.5 TeV. The results presented in this paper are the best limits to date on the single production of heavy vector-like T quarks, the first to set limits for a variety of resonance widths, and the best limits for the production of a $Z'$ boson decaying to $Tt$.

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References

[1] J. A. Aguilar-Saavedra, R. Benbrik, S. Heinemeyer, and M. Perez-Victoria, “Handbook of vectorlike quarks: Mixing and single production”, Phys. Rev. D 88 (2013) 094010, doi:10.1103/PhysRevD.88.094010, arXiv:1306.0572.

[2] J. A. Aguilar-Saavedra, “Identifying top partners at LHC”, JHEP 11 (2009) 030, doi:10.1088/1126-6708/2009/11/030, arXiv:0907.3155.

[3] A. De Simone, O. Matsedonskyi, R. Rattazzi, and A. Wulzer, “A first top partner hunter’s guide”, JHEP 04 (2013) 004, doi:10.1007/JHEP04(2013)004, arXiv:1211.5663.

[4] O. Matsedonskyi, G. Panico, and A. Wulzer, “On the interpretation of top partners searches”, JHEP 12 (2014) 097, doi:10.1007/JHEP12(2014)097, arXiv:1409.0100.

[5] M. Buchkremer, G. Cacciapaglia, A. Deandrea, and L. Panizzi, “Model independent framework for searches of top partners”, Nucl. Phys. B 876 (2013) 376, doi:10.1016/j.nuclphysb.2013.08.010, arXiv:1305.4172.

[6] O. Eberhardt et al., “Joint analysis of Higgs decays and electroweak precision observables in the standard model with a sequential fourth generation”, Phys. Rev. D 86 (2012) 013011, doi:10.1103/PhysRevD.86.013011, arXiv:1204.3872.

[7] ATLAS Collaboration, “Search for production of vector-like quark pairs and of four top quarks in the lepton-plus-jets final state in pp collisions at √s = 8 TeV with the ATLAS detector”, JHEP 08 (2015) 105, doi:10.1007/JHEP08(2015)105, arXiv:1505.04306.

[8] ATLAS Collaboration, “Search for vector-like B quarks in events with one isolated lepton, missing transverse momentum and jets at √s = 8 TeV with the ATLAS detector”, Phys. Rev. D 91 (2015) 112011, doi:10.1103/PhysRevD.91.112011, arXiv:1503.05425.

[9] ATLAS Collaboration, “Search for pair and single production of new heavy quarks that decay to a Z boson and a third-generation quark in pp collisions at √s = 8 TeV with the ATLAS detector”, JHEP 11 (2014) 104, doi:10.1007/JHEP11(2014)104, arXiv:1409.5500.
[10] ATLAS Collaboration, “Search for single production of a vector-like quark via a heavy
gluon in the 4b final state with the ATLAS detector in pp collisions at √s = 8 TeV”, Phys.
Lett. B 758 (2016) doi:10.1016/j.physletb.2016.04.061, arXiv:1602.06034.

[11] ATLAS Collaboration, “Search for single production of vector-like quarks decaying into
Wb in pp collisions at √s = 8 TeV with the ATLAS detector”, Eur. Phys. J. C 76 (2016)
442, doi:10.1140/epjc/s10052-016-4281-8, arXiv:1602.05606.

[12] ATLAS Collaboration, “Search for the production of single vector-like and excited quarks
in the Wt final state in pp collisions at √s = 8 TeV with the ATLAS detector”, JHEP 02
(2016) 110, doi:10.1007/JHEP02(2016)110, arXiv:1510.02664.

[13] ATLAS Collaboration, “Search for pair production of vector-like top quarks in events
with one lepton, jets, and missing transverse momentum in √s = 13 TeV pp collisions
with the ATLAS detector”, (2017). arXiv:1705.10751 Submitted to JHEP.

[14] CMS Collaboration, “Search for vector-like charge 2/3 T quarks in proton-proton
collisions at √s = 8 TeV”, Phys. Rev. D 93 (2016) 012003,
doi:10.1103/PhysRevD.93.012003, arXiv:1509.04177

[15] CMS Collaboration, “Search for pair-produced vector-like B quarks in proton-proton
collisions at √s = 8 TeV”, Phys. Rev. D 93 (2016) 112009,
doi:10.1103/PhysRevD.93.112009, arXiv:1507.07129

[16] CMS Collaboration, “Search for top-quark partners with charge 5/3 in the same-sign
dilepton final state”, Phys. Rev. Lett. 112 (2014) 171801,
doi:10.1103/PhysRevLett.112.171801, arXiv:1312.2391

[17] CMS Collaboration, “Search for single production of vector-like quarks decaying to a Z
boson and a top or a bottom quark in proton-proton collisions at √s = 13 TeV”, JHEP 05
(2017) 029, doi:10.1007/JHEP05(2017)029, arXiv:1701.07409.

[18] CMS Collaboration, “Search for single production of a heavy vector-like T quark
decaying to a Higgs boson and a top quark with a lepton and jets in the final state”, Phys.
Lett. B 771 (2017) 80, doi:10.1016/j.physletb.2017.05.019, arXiv:1612.00999.

[19] CMS Collaboration, “Search for electroweak production of a vector-like quark decaying
to a top quark and a Higgs boson using boosted topologies in fully hadronic final states”,
JHEP 04 (2017) 136, doi:10.1007/JHEP04(2017)136, arXiv:1612.05336

[20] CMS Collaboration, “Search for single production of vector-like quarks decaying into a b
quark and a W boson in proton-proton collisions at √s = 13 TeV”, Phys. Lett. B 772
(2017) 634, doi:10.1016/j.physletb.2017.07.022, arXiv:1701.08328

[21] CMS Collaboration, “Search for pair production of vector-like T and B quarks in
single-lepton final states using boosted jet substructure techniques at √s = 13 TeV”,
(2017), arXiv:1706.03408 Submitted to JHEP.

[22] D0 Collaboration, “Search for single vector-like quarks in pp collisions at √s = 1.96 TeV”,
Phys. Rev. Lett. 106 (2011) 081801, doi:10.1103/PhysRevLett.106.081801, arXiv:1010.1466
[23] D0 Collaboration, “Search for a fourth generation $t'$ quark in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV”, *Phys. Rev. Lett.* **107** (2011) 082001, doi:10.1103/PhysRevLett.107.082001, arXiv:1104.4522

[24] CDF Collaboration, “Search for new particles leading to $Z$+jets final states in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV”, *Phys. Rev. D* **76** (2007) 072006, doi:10.1103/PhysRevD.76.072006, arXiv:0706.3264

[25] CDF Collaboration, “Search for new bottomlike quark pair decays $q\bar{q} \rightarrow (tW^{\pm})(t\bar{W}^{\pm})$ in same-charge dilepton events”, *Phys. Rev. Lett.* **104** (2010) 091801, doi:10.1103/PhysRevLett.104.091801, arXiv:0912.1057

[26] CDF Collaboration, “Search for New $T'$ Particles in Final States with Large Jet Multiplicities and Missing Transverse Energy in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV”, *Phys. Rev. Lett.* **107** (2011) 191803, doi:10.1103/PhysRevLett.107.191803, arXiv:1107.3574

[27] CDF Collaboration, “Search for Production of Heavy Particles Decaying to Top Quarks and Invisible Particles in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV”, *Phys. Rev. Lett.* **106** (2011) 191801, doi:10.1103/PhysRevLett.106.191801, arXiv:1103.2482

[28] CDF Collaboration, “Search for Heavy Bottomlike Quarks Decaying to an Electron or Muon and Jets in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV”, *Phys. Rev. Lett.* **106** (2011) 141803, doi:10.1103/PhysRevLett.106.141803, arXiv:1101.5728

[29] CDF Collaboration, “Search for a Heavy Top-Like Quark in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV”, *Phys. Rev. Lett.* **107** (2011) 261801, doi:10.1103/PhysRevLett.107.261801, arXiv:1107.3875

[30] B. W. Lee, C. Quigg, and H. B. Thacker, “Weak interactions at very high-energies: The role of the Higgs boson mass”, *Phys. Rev. D* **16** (1977) 1519, doi:10.1103/PhysRevD.16.1519

[31] G. Cacciapaglia et al., “Heavy vector-like top partners at the LHC and flavour constraints”, *JHEP* **03** (2012) 070, doi:10.1007/JHEP03(2012)070, arXiv:1108.6329

[32] C. Bini, R. Contino, and N. Vignaroli, “Heavy-light decay topologies as a new strategy to discover a heavy gluon”, *JHEP* **01** (2012) 157, doi:10.1007/JHEP01(2012)157, arXiv:1110.6058

[33] E. Accomando et al., “$Z'$ physics with early LHC data”, *Phys. Rev. D* **83** (2011) 075012, doi:10.1103/PhysRevD.83.075012, arXiv:1010.6058

[34] D. Greco and D. Liu, “Hunting composite vector resonances at the LHC: naturalness facing data”, *JHEP* **12** (2014) 126, doi:10.1007/JHEP12(2014)126, arXiv:1410.2883

[35] CMS Collaboration, “Search for a heavy resonance decaying to a top quark and a vector-like top quark at $\sqrt{s} = 13$ TeV”, (2017), arXiv:1703.06352, Submitted to JHEP.

[36] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004
[37] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* 07 (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.

[38] P. Nason, “A new method for combining NLO QCD with shower Monte Carlo algorithms”, *JHEP* 11 (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.

[39] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with Parton Shower simulations: the POWHEG method”, *JHEP* 11 (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.

[40] S. Alioli, P. Nason, C. Oleari, and E. Re, “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX”, *JHEP* 06 (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.

[41] S. Alioli, S.-O. Moch, and P. Uwer, “Hadronic top-quark pair-production with one jet and parton showering”, *JHEP* 01 (2012) 137, doi:10.1007/JHEP01(2012)137, arXiv:1110.5251.

[42] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* 191 (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[43] CMS Collaboration, “Investigations of the impact of the parton shower tuning in Pythia 8 in the modelling of $t\bar{t}$ at $\sqrt{s} = 8$ and 13 TeV”, CMS Physics Analysis Summary CMS-PAS-TOP-16-021, 2016.

[44] B. Fuks and H.-S. Shao, “QCD next-to-leading-order predictions matched to parton showers for vector-like quark models”, *Eur. Phys. J. C* 77 (2017) 135, doi:10.1140/epjc/s10052-017-4686-z, arXiv:1610.04622.

[45] A. Oliveira, “Gravity particles from warped extra dimensions, predictions for LHC”, (2014), arXiv:1404.0102.

[46] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* 506 (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

[47] J. Allison et al., “GEANT4 developments and applications”, *IEEE Trans. Nucl. Sci.* 53 (2006) 270, doi:10.1109/TNS.2006.869826.

[48] NNPDF Collaboration, “Parton distributions for the LHC Run II”, *JHEP* 04 (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.

[49] CMS Collaboration, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, *JINST* 9 (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.

[50] M. Cacciari, G. P. Salam, and G. Soyez, “The anti-$k_t$ jet clustering algorithm”, *JHEP* 04 (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
[52] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, *Eur. Phys. J. C* 72 (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.

[53] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, (2017). arXiv:1706.04969 Submitted to JINST.

[54] CMS Collaboration, “Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *JINST* 10 (2015) P06005, doi:10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.

[55] CMS Collaboration, “Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV”, *JINST* 7 (2012) P10002, doi:10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.

[56] CMS Collaboration, “Identification techniques for highly boosted W bosons that decay into hadrons”, *JHEP* 12 (2014) 017, doi:10.1007/JHEP12(2014)017, arXiv:1410.4227.

[57] CMS Collaboration, “Identification techniques for highly boosted W bosons that decay into hadrons”, *JHEP* 12 (2014) 017, doi:10.1007/JHEP12(2014)017, arXiv:1410.4227.

[58] M. Dasgupta, A. Fregoso, S. Marzani, and G. P. Salam, “Towards an understanding of jet substructure”, *JHEP* 09 (2013) 029, doi:10.1007/JHEP09(2013)029, arXiv:1307.0007.

[59] A. J. Larkoski, S. Marzani, G. Soyez, and J. Thaler, “Soft Drop”, *JHEP* 05 (2014) 146, doi:10.1007/JHEP05(2014)146, arXiv:1402.2657.

[60] CMS Collaboration, “Identification of b-quark jets with the CMS experiment”, *JINST* 8 (2013) P04013, doi:10.1088/1748-0221/8/04/P04013, arXiv:1211.4462.

[61] CMS Collaboration, “Identification of b quark jets at the CMS experiment in the LHC Run 2”, CMS Physics Analysis Summary CMS-PAS-BTV-15-001, 2016.

[62] CMS Collaboration, “Measurement of the production cross sections for a Z boson and one or more b jets in pp collisions at $\sqrt{s} = 7$ TeV”, *JHEP* 06 (2014) 120, doi:10.1007/JHEP06(2014)120, arXiv:1402.1521.

[63] J. Butterworth et al., “PDF4LHC recommendations for LHC Run II”, *J. Phys. G* 43 (2016) 023001, doi:10.1088/0954-3899/43/2/023001, arXiv:1510.03865.

[64] ATLAS Collaboration, “Measurement of the Inelastic Proton-Proton Cross Section at $\sqrt{s} = 13$ TeV with the ATLAS Detector at the LHC”, *Phys. Rev. Lett.* 117 (2016) 182002, doi:10.1103/PhysRevLett.117.182002, arXiv:1606.02625.

[65] CMS Collaboration, “CMS luminosity measurements for the 2016 data taking period”, CMS Physics Analysis Summary CMS-PAS-LUM-17-001, 2017.

[66] A. L. Read, “Presentation of search results: the $CL_s$ technique”, *J. Phys. G* 28 (2002) 2693, doi:10.1088/0954-3899/28/10/313.

[67] T. Junk, “Confidence level computation for combining searches with small statistics”, *Nucl. Instrum. Meth. A* 434 (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.
[68] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *Eur. Phys. J. C* 71 (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0 [arXiv:1007.1727] [Erratum: doi:10.1140/epjc/s10052-013-2501-z].

[69] ATLAS and CMS Collaborations, “Procedure for the LHC Higgs boson search combination in summer 2011”, Technical Report CMS-NOTE-2011/005, ATL-PHYS-PUB-2011-011, CERN, 2011.
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29: Also at Purdue University, West Lafayette, USA
30: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
31: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
32: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
33: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
34: Also at Czech Technical University, Praha, Czech Republic
35: Also at Institute for Nuclear Research, Moscow, Russia
36: Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
37: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
38: Also at University of Florida, Gainesville, USA
39: Also at P.N. Lebedev Physical Institute, Moscow, Russia
40: Also at California Institute of Technology, Pasadena, USA
41: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
42: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
43: Also at INFN Sezione di Roma; Sapienza Università di Roma, Rome, Italy
44: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
45: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
46: Also at National and Kapodistrian University of Athens, Athens, Greece
47: Also at Riga Technical University, Riga, Latvia
48: Also at Universitàt Zürich, Zurich, Switzerland
49: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
50: Also at Istanbul University, Faculty of Science, Istanbul, Turkey
51: Also at Adiyaman University, Adiyaman, Turkey
52: Also at Istanbul Aydin University, Istanbul, Turkey
53: Also at Mersin University, Mersin, Turkey
54: Also at Cag University, Mersin, Turkey
55: Also at Piri Reis University, Istanbul, Turkey
56: Also at Izmir Institute of Technology, Izmir, Turkey
57: Also at Necmettin Erbakan University, Konya, Turkey
58: Also at Marmara University, Istanbul, Turkey
59: Also at Kafkas University, Kars, Turkey
60: Also at Istanbul Bilgi University, Istanbul, Turkey
61: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
62: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
63: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
64: Also at Utah Valley University, Orem, USA
65: Also at Beykent University, Istanbul, Turkey
66: Also at Bingol University, Bingol, Turkey
67: Also at Erzincan University, Erzincan, Turkey
68: Also at Sinop University, Sinop, Turkey
69: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
70: Also at Texas A&M University at Qatar, Doha, Qatar
71: Also at Kyungpook National University, Daegu, Korea