Search for flavor-changing neutral currents in top quark decays $t \to Hc$ and $t \to Hu$ in multilepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

M. Aaboud et al.*
(ATLAS Collaboration)

(Received 10 May 2018; published 6 August 2018)

Flavor-changing neutral currents are not present in the Standard Model at tree level and are suppressed in loop processes by the unitarity of the Cabibbo-Kobayashi-Maskawa matrix; the corresponding rates for top quark decay processes are experimentally unobservable. Extensions of the Standard Model can generate new flavor-changing neutral current processes, leading to signals which, if observed, would be unambiguous evidence of new interactions. A data set corresponding to an integrated luminosity of 36.1 fb$^{-1}$ of $pp$ collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV recorded with the ATLAS detector at the Large Hadron Collider is used to search for top quarks decaying to up or charm quarks with the emission of a Higgs boson, with subsequent Higgs boson decay to final states with at least one electron or muon. No signal is observed and limits on the branching fractions $B(t \to Hc) < 0.16\%$ and $B(t \to Hu) < 0.19\%$ at 95% confidence level are obtained (with expected limits of 0.15% in both cases).

DOI: 10.1103/PhysRevD.98.032002

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI. Funded by SCOAP³.

1. INTRODUCTION

In the Standard Model (SM), the mass eigenstates in the quark sector couple diagonally to the photon, Z boson, and Higgs boson, with the result that quark flavors can only change at tree level by emission of $W^\pm$ bosons (charged currents). Although processes that change quark flavors without external emission of $W^\pm$ bosons—i.e., flavor-changing neutral currents (FCNC)—occur via loops in the SM, they are suppressed by the Glashow-Iliopoulos-Maiani mechanism [1]. The decay of a top quark to a Higgs boson and a lighter up-type quark $q$ ($t \to Hq$) is estimated to have a branching fraction of about $3 \times 10^{-15}$ in the SM [2], which is unobservable with any current or foreseeable data set. An observation of this process with current sensitivity would be unambiguous evidence of physics beyond the Standard Model (BSM). Searches for $t \to Hq$ decays are part of a broader FCNC program that includes searches for $tqg$, $tZq$, and $tgq$ interactions [3–7].

Models of BSM physics can feature nontrivial flavor structures that produce tree-level or large effective loop-induced $tHq$ couplings. Tree-level couplings are generic in two-Higgs-doublet models unless discrete symmetries are introduced to forbid them [8], and can also be present in models with heavy vectorlike quarks [9]. The Cheng-Sher ansatz [10] of off-diagonal light Higgs boson interactions in models with multiple Higgs doublets gives couplings that scale as $\lambda_{tHq} \sim \sqrt{2m_H m_q}/v$, where $m_t$ is the top quark mass, $m_q$ is the light up-type quark mass, and $v$ is the SM Higgs field vacuum expectation value. This would lead to a branching fraction $B(t \to Hc) \approx 0.15\%$, close to current experimental bounds. Smaller loop-induced enhancements can be present in two-Higgs-doublet models even without off-diagonal tree-level couplings [11], the minimal supersymmetric Standard Model [12], R-parity-violating supersymmetry [13], models with warped extra dimensions [14], and composite Higgs boson models [15]. A summary of expectations for $t \to Hq$ branching fractions in various BSM models can be found in Ref. [16].

The ATLAS and CMS collaborations have carried out searches [17–21] for $tHq$ interactions with 7, 8, and 13 TeV $pp$ collision data from the Large Hadron Collider (LHC). These primarily searched for $t\bar{t}$ production where one top quark decays via $t \to Wb$ and the other decays via $t \to Hq$; the analyses are distinguished by the targeted Higgs boson decay. The results at 13 TeV benefit from the large integrated luminosity delivered by the LHC in 2015–2016 and from the $t\bar{t}$ cross section being larger at 13 than at 8 TeV. Using 13 TeV data, ATLAS obtained $B(t \to Hc) < 0.22\%$ with $H \to \gamma\gamma$ decays [20] and CMS obtained $B(t \to Hc) < 0.47\%$ with $H \to bb$ decays [21], in both cases at 95% confidence level (C.L.) and assuming $B(t \to Hu) = 0$. Similar limits apply for $B(t \to Hu)$ assuming $B(t \to Hc) = 0$.

*Full author list given at the end of the article.
In this paper, a search for production of $t\bar{t}$ pairs in which one top quark decays via $t \to Hq$ is reported, targeting multilepton final states with either three light leptons ($\ell = e$ or $\mu$) or two light leptons of the same electric charge. The multilepton final states can be produced via Higgs boson decays which involve light leptons in the final state through $H \to WW^* \to \ell \ell q\bar{q}$, or $H \to ZZ^* \to \ell\ell\ell\ell$. A $t\bar{t}$ pair with a $t \to Hq$ decay, followed by $H \to WW^*$, would feature the intermediate state $(Wb)(WW'g)$, which can yield the final states $\ell\ell b\ell q\ell_3q_3v$ or $\ell\ell b\ell q\ell_3\ell_2q_2v$ ($q$ representing any quark lighter than the $b$-quark). Events with hadronically decaying $t$-lepton candidates are vetoed to avoid overlap with dedicated searches for those Higgs boson decay modes.

The sought-after $t\bar{t}$, $t \to Hq$ signature with Higgs boson decays into final states with leptons is in many respects similar to the corresponding channel for $t\bar{t}H$ production, although $t \to Hq$ has one fewer $b$-jet and one fewer light-quark jet for the same lepton multiplicity in the absence of additional radiation. The sample of events and background simulations used for the 13 TeV ATLAS search for $t\bar{t}H$ production in the multilepton final state [22] is therefore leveraged in this search, similar to the strategy used in the 8 TeV multilepton $t \to Hq$ search [17]. Unlike the 8 TeV search, however, in this analysis multivariate discriminants (boosted decision trees, BDTs) are used, optimized to separate the FCNC signal from SM processes.

The analysis proceeds as follows. The same-charge dilepton and trilepton categories (with no hadronic $t$-lepton candidates) from the 13 TeV $t\bar{t}H$ search [22] are used. The same event preselection, calibration, and SM simulation samples are used as in the $t\bar{t}H$ search, but the $t\bar{t}H$ process is now treated as a background and fixed to the expected SM rate. The FCNC processes $t \to Hu$ and $t \to Hc$ are simulated and BDTs are trained to separate these from SM processes in the two categories. Care is taken to account for FCNC signal contamination in control regions which are used to constrain backgrounds arising from lepton production in hadron decays and photon conversions. The results are obtained by fitting the data distributions of the BDT discriminants.

II. ATLAS DETECTOR AND OBJECT RECONSTRUCTION

The ATLAS experiment [23] at the LHC is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and near $4\pi$ coverage in solid angle. It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. A new innermost silicon pixel layer was installed prior to data-taking at $\sqrt{s} = 13$ TeV [24]. Lead-liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity for $|\eta| < 3.2$. A hadron steel/scintillator-tile calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for both the EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large air-core toroidal superconducting magnets with eight coils each. The muon spectrometer includes a system of precision tracking chambers and fast detectors for triggering. A combined hardware and software trigger system is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information to reduce the accepted rate to a design maximum of 100 KHz. This is followed by a software-based trigger that further reduces the accepted event rate to a sustained rate of about 1 KHz.

This analysis uses an integrated luminosity of 36.1 fb$^{-1}$ of $pp$ collision data with $\sqrt{s} = 13$ TeV collected during 2015 and 2016, corresponding to approximately $30 \times 10^6$ $t\bar{t}$ pair production events [25]. The mean number of $pp$ interactions per bunch crossing in the data set is 24. A full description of the reconstruction and selection of physics objects can be found in Ref. [22], and only a brief description follows.

Events in this analysis are selected using triggers which require the presence of one or two light leptons [26]. The single-lepton triggers have transverse momentum ($p_T$) thresholds that vary from 20 to 26 GeV depending on lepton flavor and instantaneous luminosity. In the dilepton triggers the thresholds for the higher-$p_T$ lepton vary from 12 to 22 GeV depending on lepton flavor and instantaneous luminosity.

Muon candidates are formed using inner detector tracks and muon spectrometer tracks, track segments, or for $|\eta| < 0.1$, calorimeter signals consistent with the passage of a minimum-ionizing particle. They are required to satisfy $p_T > 10$ GeV and $|\eta| < 2.5$ and to pass loose identification requirements [27], as well as transverse and longitudinal track impact parameter requirements with respect to the primary vertex. The primary vertex in an event is defined as the reconstructed $pp$ collision vertex with the highest $\sum p_T^2$ of associated tracks with $p_T > 400$ MeV.

Electron candidates are formed from energy clusters in the electromagnetic calorimeter associated with inner detector tracks. They are required to satisfy $p_T > 10$ GeV and the pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln (\tan(\theta/2))$. Angular distance is measured in units of $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$.\footnote{ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe. The x axis points from the IP to the center of the LHC ring, and the y axis points upwards. Cylindrical coordinates ($r, \phi$) are used in the transverse plane, $\phi$ being the azimuthal angle around the z axis. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln (\tan(\theta/2))$.
\[ |\eta_{\text{cluster}}| < 2.47, \text{ excluding the transition region } 1.37 < |\eta_{\text{cluster}}| < 1.52 \text{ between the barrel and endcap electromagnetic calorimeters. A likelihood discriminant is used to separate isolated prompt electrons from hadronic jets, photon conversions, and nonisolated electrons from hadron decays; two working points of the discriminant (loose and tight [28]) are used in this analysis. Electron candidates must also pass transverse and longitudinal track impact parameter requirements.}

Jets are reconstructed using clusters built from energy deposits in the calorimeters [29–31] using the anti-\( k_t \) algorithm [32,33] with radius parameter \( R = 0.4 \). Considered jets are required to satisfy \( p_T > 25 \) \( \text{GeV} \) and \( |\eta| < 2.5 \). Jets with \( p_T < 60 \) \( \text{GeV} \) and \( |\eta| < 2.4 \) are required to be matched to the primary vertex using their associated inner detector tracks [34]. Jets containing \( b \)-hadrons (\( b \)-jets) are tagged using a multivariate discriminant combining information about secondary vertices, reconstructed decay chains, and impact parameters of tracks associated with the jet [35,36]. The working point for \( b \)-jet identification used in this analysis corresponds to an average efficiency of 70% for jets containing \( b \)-hadrons with \( p_T > 20 \) \( \text{GeV} \) and \( |\eta| < 2.5 \) in simulated \( t\bar{t} \) events. Jets which contain \( c \)-hadrons but not \( b \)-hadrons have approximately a one in twelve probability of being misidentified as \( b \)-jets; the same probability for light-quark or gluon jets is one in 380, leading to different responses for the \( t \to H u \) and \( t \to H c \) processes. 

Hadronically decaying \( \tau \)-lepton (\( \tau_{\text{had}} \)) candidates are reconstructed from hadronic jets associated with either one or three inner detector tracks with a total charge of ±1 [37,38]. A BDT discriminant is used to distinguish \( \tau_{\text{had}} \) candidates from quark- or gluon-initiated jets. A working point with 55% (40%) efficiency for one-prong (three-prong) \( \tau_{\text{had}} \) decays is used for the veto. Candidates with \( p_T > 25 \) \( \text{GeV} \) and \( |\eta| < 2.5 \) are considered.

The missing transverse momentum, with magnitude \( E_T^{\text{miss}} \), is defined as the negative vector sum of the transverse momenta of all calibrated and identified leptons and jets and the remaining unclustered energy of the event, which is estimated from low-\( p_T \) tracks associated with the primary vertex but not with any considered lepton or jet [39].

To eliminate ambiguity between reconstructed objects and reduce the fraction of leptons arising from hadron decay, the following additional requirements are imposed: if two electrons are separated by \( \Delta R < 0.1 \), only the higher-\( p_T \) electron is considered; any electron within \( \Delta R = 0.1 \) of a selected muon is rejected; jets within \( \Delta R = 0.3 \) of a selected electron are removed; any \( \tau_{\text{had}} \) candidate within \( \Delta R = 0.2 \) of a selected electron or muon is ignored; and muons must be separated by \( \Delta R > \min(0.4, 0.04 + (10 \text{ GeV})/p_T, 1) \) from a jet surviving the above selection.

To further reject backgrounds, BDTs are trained to discriminate against electrons arising from asymmetric trident processes \( e^\pm \to e^\pm e^\mp e^- \) in detector material which may induce an apparent change of the electron charge, and against leptons which arise from decays of \( b \)-hadrons [22]. The former discriminant (“charge misassignment BDT”) uses track and calorimeter cluster information; the latter (“nonprompt lepton BDT”) uses information about additional particle activity and properties of low-\( p_T \) jets formed from tracks near the lepton, including the output of \( b \)-tagging algorithms run on those jets. Working points with efficiencies of 95% (60%–98%) are defined for the charge misassignment (nonprompt lepton) discriminants.

During the initial loose (L) selection of leptons, no isolation, charge misassignment discriminant, or nonprompt lepton discriminant requirements are imposed. Electrons are required to pass the loose electron identification discriminant selection. Two other lepton selections are used in the analysis:

(i) Modified loose (L*), in which the lepton must pass calorimeter- and track-based isolation criteria and the nonprompt lepton discriminant selection.

(ii) Tight (T), in which electrons must pass the tight electron identification discriminant selection and the charge misassignment discriminant selection. For muons the T and L* selections are identical; this corresponds to the T* selection of Ref. [22].

III. SIMULATION, EVENT SELECTION, AND ANALYSIS

The simulated \( pp \to \tau \bar{\tau}, t \to H q \) signals were generated with next-to-leading-order (NLO) QCD matrix elements computed by MadGraph5_AMC@NLO [40], with top quark decays performed by MadSpin [41]; Pythia8 [42] was used for Higgs boson decay, parton showering, hadronization, and underlying-event generation. Either the top quark or anti-quark may undergo the FCNC decay in this sample. The total top quark pair production cross section used to normalize the FCNC signal was set to \( 832^{+40}_{-40} \) \( \text{pb} \), as calculated with the Top++2.0 program at next-to-next-to-leading order in perturbative QCD, including soft-gluon resummation to next-to-next-to-leading-log order [25]. The systematic uncertainties include variation of factorization and renormalization scales as well as uncertainties in parton distribution functions (PDFs) and the QCD coupling \( \alpha_s \) [43–46].

The simulations of SM background processes are the same as those used in Ref. [22]. In particular, the major processes \( t\bar{t}Z, t\bar{t}W, \) and \( t\bar{t}H \) were generated at NLO in QCD with MadGraph5_AMC@NLO interfaced to Pythia8 for parton showering, hadronization, particle decay, and underlying-event generation. The top quark and Higgs boson masses were set to 172.5 and 125.0 \text{GeV} , respectively. Higgs boson decay branching fractions were taken from Ref. [47]. In all the preceding samples, the matrix element calculations used the NNPDF 3.0 NLO PDF set [48], while the parton shower calculations used the A14 tune of Pythia8 parameters [49] and the NNPDF 2.3 LO PDF set [46]. Diboson production was generated at NLO in
QCD with Sherpa [50,51] using the CT10 PDF set [52]. The response of the ATLAS detector to generated events was simulated with a Geant4-based detector model [53,54] with parametrization of the calorimeter response for some minor backgrounds [55].

The two categories of events used in this analysis, same-charge dilepton (2ℓSS) and trilepton (3ℓ) candidates, are selected by the same requirements as in Ref. [22]. In both cases the leptons identified by the trigger must correspond to leptons selected for this analysis, with sufficiently high \( p_T \) for the trigger to be fully efficient.

(i) Events in the 2ℓSS category must have at least four reconstructed jets, of which one or two must be b-tagged jets. Exactly two light-lepton candidates meeting L criteria (as described in Sec. II) must be found, along with no \( r_{\text{had}} \) candidates. The total charge of the leptons must be \( \pm 1 \). Of the three leptons, one (designated \( \ell_0 \)) is of opposite charge to the other two, and the other two leptons are designated \( \ell_1 \) and \( \ell_2 \) in order of increasing angular separation \( \Delta R \) from \( \ell_0 \). The two leptons \( \ell_1 \) and \( \ell_2 \) are required to meet the T criteria and have \( p_T > 15 \text{ GeV} \). The remaining lepton, \( \ell_0 \), is less likely to be nonprompt than either of the same-charge leptons \( \ell_1 \) or \( \ell_2 \). It is correspondingly only required to meet the L* criteria and to have \( p_T > 10 \text{ GeV} \).

(ii) Events in the 3ℓ category must have at least two reconstructed jets, of which at least one must be a b-tagged jet. Exactly three light-lepton candidates meeting L criteria must be found, along with no \( r_{\text{had}} \) candidates. The total charge of the leptons must be \( \pm 1 \). Of the three leptons, one (designated \( \ell_0 \)) is of opposite charge to the other two, and the other two leptons are designated \( \ell_1 \) and \( \ell_2 \) in order of increasing angular separation \( \Delta R \) from \( \ell_0 \). The two leptons \( \ell_1 \) and \( \ell_2 \) are required to meet the T criteria and have \( p_T > 15 \text{ GeV} \). The remaining lepton, \( \ell_0 \), is less likely to be nonprompt than either of the same-charge leptons \( \ell_1 \) or \( \ell_2 \). It is correspondingly only required to meet the L* criteria and to have \( p_T > 10 \text{ GeV} \).

After these selections, the \( t\to Hq \) signal is dominated by \( H\to WW^* \) (85% of the 2ℓSS and 71% of the 3ℓ category) with subleading contributions from \( H\to\tau\tau \) (12% and 16% respectively) and \( H\to ZZ^* \) (2% and 9% respectively). The fraction of \( \ell\ell \) events with a consequent \( t\to Hq \) decay which are expected to be reconstructed and selected is \( 5.1\times10^{-4} \) (2.6 \( \times \) 10\(^{-4} \)) for the 2ℓSS (3ℓ) category.

Following the initial selections, the largest sources of background are those arising from nonprompt leptons (from hadron decays, photon conversions, and charge misassignment), mainly from \( t\bar{t} \) decays, and prompt lepton backgrounds from \( t\bar{t}V \) production \((V=W\text{ or } Z)\) with leptonic decays of the vector boson. Further BDT discriminants are trained to separate the FCNC signal from these two background sources.

Inputs to the BDTs include lepton flavor and kinematic observables, jet properties including whether they are b-tagged, angular separations between objects, the \( E_T^{\text{miss}} \), and the quantity \( m_{\text{eff}}=E_T^{\text{miss}}+H_T \), where \( H_T \) is the scalar sum of the \( p_T \) of leptons and jets in the event. Signal events can be distinguished from \( t\bar{t}V \) and nonprompt lepton background by having only one true \( b \)-jet and being relatively soft events with low \( m_{\text{eff}} \) and \( H_T \). The spin correlation in the dominant \( H\to WW^* \) decay, and the presence of an off-mass-shell \( W^* \) boson, also yields a distinct signature where, in both categories, one lepton often has low \( p_T \), and in the 3ℓ category, both \( m(\ell_0\ell_1) \) and \( \Delta R(\ell_0,\ell_1) \) are small.

The variables used in the training of the BDTs in the two categories are shown in Table I, and example distributions are shown in Fig. 1. Good agreement is observed between the data and expected background distributions in each variable. In the 2ℓSS category, the variables that most

---

**Table I.** Variables used to construct the BDT discriminants for the 2ℓSS and 3ℓ categories. The symbol “×” indicates that this variable is used in the respective BDT. The “best Z candidate” is the opposite-charge lepton pair with same flavor with invariant mass closest to 91.2 GeV; if no such pair exists, zero is assigned for the invariant mass.

<table>
<thead>
<tr>
<th>Variable</th>
<th>2ℓSS</th>
<th>3ℓ</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_T ) of higher-( p_T ) lepton</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>( p_T ) of lower-( p_T ) lepton</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>( p_T ) of lepton ( \ell_0 )</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>( p_T ) of lepton ( \ell_1 )</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>( p_T ) of lepton ( \ell_2 )</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Dilepton invariant masses (all combinations)</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Trilepton invariant mass</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Best Z candidate invariant mass</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Maximum lepton (</td>
<td>\eta</td>
<td>)</td>
</tr>
<tr>
<td>Lepton flavor</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Number of jets</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Number of ( b )-tagged jets</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>( p_T ) of highest-( p_T ) jet</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>( p_T ) of second highest-( p_T ) jet</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>( p_T ) of highest-( p_T ) b-tagged jet</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>( \Delta R(\ell_0,\ell_1) )</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>( \Delta R(\ell_0,\ell_2) )</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>( \Delta R(\text{higher-}\ p_T \text{ lepton, closest jet}) )</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>( \Delta R(\text{lower-}\ p_T \text{ lepton, closest jet}) )</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>( \Delta R(\ell_0, \ell_1, \text{closest jet}) )</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Smallest ( \Delta R(\ell_0, \text{b-tagged jet}) )</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>( E_T^{\text{miss}} )</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>( m_{\text{eff}} )</td>
<td>×</td>
<td>×</td>
</tr>
</tbody>
</table>

---

\(^{2}\)These values include the effects of selection acceptance, detector efficiency, and decay branching fractions.
strongly separate $t \to Hq$ from the nonprompt lepton background are the number of $b$-jets, the $p_T$ of the lower-$p_T$ lepton, and the angular separation $\Delta R$ of the lower-$p_T$ lepton from the closest jet. The separation from $t\bar{t}V$ processes comes mainly from the number of $b$-jets, $m_{\text{eff}}$, $E_T^{\text{miss}}$, and the $p_T$ of the higher-$p_T$ lepton. In the $3\ell$ category the strongest separation from nonprompt lepton backgrounds comes from $\Delta R(\ell_0, \ell_1)$, the invariant masses $m(\ell_0, \ell_1)$ and $m(\ell_0, \ell_2)$, the $p_T$ of the highest-$p_T$ lepton, and the invariant mass of the opposite-charge, same-flavor lepton pair with mass closest to that of the $Z$ boson. The strongest separation from $t\bar{t}V$ comes from the invariant masses $m(\ell_0, \ell_1)$ and $m(\ell_0, \ell_2)$, $m_{\text{eff}}$, the number of $b$-jets, and the invariant mass of the three leptons. In both the $2\ell$SS and $3\ell$ categories and against both backgrounds, better separation is achieved for $t \to Hu$ than $t \to Hc$ signals, as the latter is more likely to have a second $b$-tagged jet arising from the hadronization products of the charm quark. In the $2\ell$SS category, $t \to Hu$ and $t \to Hc$ are sufficiently similar that only one discriminant is trained for the two decay modes. In the $3\ell$ category the two signals are treated separately.

In each case, two separate discriminants are trained: one to separate $t \to Hq$ from nonprompt leptons and one to separate $t \to Hq$ from $t\bar{t}V$ processes. The former is designated BDT($t\bar{t}, X$) and the latter BDT($t\bar{t}V, X$) for a given category/signal choice $X$ (i.e., $2\ell$SS, $3\ell t \to Hu$, or $3\ell t \to Hc$). The expected distributions for backgrounds with nonprompt leptons are obtained using the procedures described in Sec. IV. The two discriminants are combined into a single discriminant, designated BDT$(X)$, via a linear combination that yields the best expected limit on the FCNC branching fraction.

The BDT discriminant outputs in the $2\ell$SS and $3\ell$ categories are binned into six or four bins, respectively, with bin widths optimized to provide the best expected limits. Every bin contains a roughly equal number of signal events. The bin boundaries used for the fits to $t \to Hu$ and $t \to Hc$ signals in the $2\ell$SS category are optimized separately, although the discriminant used is the same for the two decays.

IV. BACKGROUND ESTIMATION

The estimation of rates and kinematic distributions of SM processes that form backgrounds with prompt leptons in the signal categories is performed using simulation. The processes considered include the following:

(i) $t\bar{t}W$, $t\bar{t}(Z/\gamma^* \to \ell\ell)$, $t\bar{t}H$, and $t\bar{t}WW$;
(ii) $t\bar{t}t$ and $t\bar{t}t\bar{t}$;
(iii) single top quark production in the $s$- and $t$-channels, $tW$, $tZ$, $tWZ$, $tHb$, and $tHW$;
(iv) production of two or three $W$ or $Z/\gamma^*$ bosons.

Details of the simulations used are given in Ref. [22]. The estimation of the nonprompt lepton background, including the contribution from charge-misassigned electrons, uses data-driven methods following Ref. [22]. One major modification to the treatment of leptons from hadron decays and conversions is made, arising from the lower expected jet multiplicity in $t \to Hq$ events compared to $t\bar{t}H$ production. A summary of the procedure is given below. The self-consistency of the methods is checked by
predicting the nonprompt lepton yields in simulated SM \( \bar{t}t \) and \( t\bar{t}\gamma \) events; good agreement is observed.

Rates for electron charge misassignment as functions of electron \( p_T \) and \( |\eta| \) are determined from a sample of \( Z \rightarrow ee \) events where both electrons are reconstructed with the same charge. The contribution of these events to the 2\( e \)SS signal region is determined by applying these misassignment rates to events selected with the 2\( e \)SS selection criteria except requiring opposite-charge leptons instead of same-charge leptons.

The estimation of nonprompt lepton background contributions other than electron charge misassignment is performed using the so-called matrix method [56,57]. This technique uses control regions with the same kinematic properties as the signal region, but with changed lepton identification criteria that enhance the nonprompt lepton contribution, to statistically estimate the fraction of signal region events that involve nonprompt leptons. Lepton candidates that meet \( L \), but not \( T \), identification criteria (\( \tilde{T} \)) are much more likely to be of nonprompt origin than those that meet \( T \) criteria; if the probabilities ("efficiencies") of prompt and nonprompt leptons to be identified as \( \tilde{T} \) or \( T \) are known, the fraction of tight-lepton events of nonprompt origin can be determined by solving a system of equations. The matrix method can be applied to estimate contributions arising from multiple nonprompt leptons in the same event. In this analysis, the two leptons in the 2\( e \)SS category events, and the two same-charge leptons in the 3\( e \) category events, are analyzed for a nonprompt contribution. The opposite-sign lepton \( \ell_0 \) in 3\( \ell \) events is found in simulation to be prompt 97% of the time, so the matrix method is not applied to that lepton.

The nonprompt efficiencies are measured in control regions with the same selection criteria as the 2\( e \)SS signal category except that the number of jets must be two or three, one lepton need only satisfy \( L \) criteria, and the lower-\( p_T \) lepton is only required to have \( p_T > 15 \) GeV. These are then separated into \( TT \) or \( \bar{T}T \) events. The expected number of events from SM processes with only prompt leptons in these regions is determined from simulation and subtracted from the observed number of events, giving a yield of nonprompt lepton events which is then used to determine the nonprompt efficiencies. In the case of a nonzero \( t \rightarrow Hq \) branching fraction, a significant fraction of the signal will be reconstructed in these control regions. This will act as an additional source of prompt leptons which is not accounted for in the SM prediction and will bias the nominal efficiencies which are determined assuming zero signal contribution. For \( B(t \rightarrow Hq) = 0.2\% \), the FCNC process would contribute approximately 30% of the prompt lepton contribution in the low-jet-multiplicity control regions with \( T \) leptons. This effect is accounted for in two ways. First, the nonprompt efficiencies are derived under the two hypotheses \( B(t \rightarrow Hq) = 0 \) and \( B(t \rightarrow Hq) = 0.2\% \) and both values are used to predict the yield of nonprompt lepton in the signal categories; the two hypotheses result in nonprompt yields differing by \( \approx 40\% \) for the 2\( e \)SS and \( \approx 30\% \) for the 3\( e \) category. This overall normalization correction from possible signal contamination is then scaled proportionally to the FCNC branching fraction in the fit. Second, the change in the shape of the FCNC discriminant response for the nonprompt background in the signal regions under the two hypotheses is derived. The difference is assigned as a systematic uncertainty on the nonprompt background discriminant shape.

The separation of FCNC signal from nonprompt lepton background by the BDT\( (t\bar{t}, X) \) discriminants is sufficiently strong that the impact of these systematic uncertainties in the nonprompt background estimate on the signal extraction is small. Tests with MC simulation indicate that the procedure correctly recovers the branching fraction of injected FCNC signals.

V. SYSTEMATIC UNCERTAINTIES

The same model of systematic uncertainties in background processes (including \( t\bar{t}H \)) is used as in Ref. [22], with the additional normalization and BDT shape uncertainties in nonprompt lepton backgrounds described in Sec. IV. As the measured \( t\bar{t}H \) cross section is compatible with the SM predictions, the SM rate is assumed with appropriate theoretical uncertainties. Acceptance uncertainties from the choice of parton distribution functions and QCD scale for the major backgrounds simulated with MADGRAPH5_AMC@NLO are calculated using SysCalc [58].

The \( t \rightarrow Hq \) signal processes are subject to their own theoretical uncertainties, primarily in the modeling of the parent \( t\bar{t} \) system. Systematic uncertainties are assigned for the \( t\bar{t} \) cross section, the variation of BDT response with the choice of renormalization and factorization scale, the modeling of parton showers, the event generator, and the amount of initial/final-state radiation.

The systematic uncertainty model includes components from

(i) light lepton, \( \tau_{had} \), and jet selection and energy/momentum scale and \( E_T^{miss} \) modeling;

(ii) \( b \)-jet tagging efficiency and the probability for \( c \)-jets and light-quark or gluon jets to be misidentified as \( b \)-jets;

(iii) the cross section and MC modeling of simulated backgrounds and signals;

(iv) the statistical uncertainties in the control regions for nonprompt lepton backgrounds, the matrix method efficiencies, and the applicability to the 2\( e \)SS and 3\( e \) category events of the matrix method efficiencies derived at low jet multiplicity in same-charge dilepton events;

(v) electron charge misassignment;

(vi) \( pp \) integrated luminosity (determined using a methodology similar to that described in Ref. [59]).
(vii) modeling of multiple $pp$ interactions per bunch crossing.

The background-related systematic uncertainties with the largest impact on the final result are found to be those associated with the statistical uncertainty in the nonprompt lepton background estimation, the nonprompt lepton efficiencies used in the matrix method, and the cross section for diboson production in association with $b$-quarks. Excluding the correction for signal contributions to nonprompt lepton control regions, systematic uncertainties on the background lead to an uncertainty in the determined signal decay branching fractions of 0.04%. Systematic uncertainties in the signal processes are primarily associated with the matching of matrix element calculations with parton shower algorithms. The relative systematic uncertainty in the signal yield prediction for a given signal branching fraction value is set to zero while the other is permitted to float. Excluding the correction for signal contributions to nonprompt lepton control regions depends on the signal decay branching fraction; for a true branching fraction of 0.2%, the corresponding systematic uncertainty on the determined branching fraction is 0.02%.

**VI. RESULTS**

Binned maximum-likelihood fits to the distributions of the $2\ell$/$SS$ and $3\ell$/$C6$ FCNC discriminants are performed to extract the best-fit values of the $t \rightarrow Hq$ branching fractions. The profile likelihood technique is used, in which systematic uncertainties are modeled as nuisance parameters which are allowed to vary in the fit, constrained by Gaussian or log-normal probability density penalty functions multiplying the likelihood function $L$. The test statistic $q_{B}$ is obtained from the profile log-likelihood ratio as $q_{B} = -2 \ln \Lambda_{B} = -2 \ln \left[ L(\hat{B}, \hat{\theta}) / L(\hat{B}, \hat{\theta}) \right]$, where $\hat{B}$ and $\hat{\theta}$ are the best-fit branching fraction and nuisance parameter values that give the global maximum likelihood and $\hat{\theta}$ are the nuisance parameter values which maximize $L$ for a given branching fraction $B$. The uncertainties in the best-fit branching fraction value $\hat{B}$ are determined by the variation of $q_{B}$ by one unit from its minimum, and the distribution of $q_{B}$ is used to set $95\%$ C.L. upper limits on the branching fractions $B(t \rightarrow Hq)$ using the CL$_s$ method [60]. Due to the near-degeneracy of the BDT response to $t \rightarrow Hu$ and $t \rightarrow Hc$ signals, during the fits, one of these branching fractions is set to zero while the other is permitted to float. Expected and observed yields of events in the signal categories, before and after the nuisance parameters are adjusted in the fits, are shown in Table II. The distributions of the FCNC discriminant for the data and the best-fit signal-plus-background models are shown in Fig. 2.

The results of the fits are shown in Tables III and IV. The best-fit branching fractions are compatible with zero, and $95\%$ C.L. upper limits are set, as shown in Fig. 3. Statistical uncertainties are dominant in the result. No variations of the nuisance parameters by more than $1\sigma$ of the prior systematic uncertainty are observed; the largest variations are observed in the nuisance parameters associated with statistical uncertainties in the nonprompt lepton background estimate and in one of the normalization systematic uncertainties in the $3\ell$/$C6$ nonprompt lepton background.

To confirm the self-consistency of the nonprompt lepton background estimate, a number of checks were performed. There is no evidence of a BDT response shape distortion in the nonprompt lepton background estimate during the fit.
FIG. 2. Distributions of the FCNC signal discriminants for (top) $t \to Hu$, (bottom) $t \to Hc$ signals in (left) 2$\ell$ SS, (right) 3$\ell$ categories. In the $t \to Hu$ fit, $B(t \to Hc)$ is set to zero, and vice versa. The binning, which is that used in the fit, is chosen so as to have roughly equal signal yields in each bin. The FCNC signals, normalized to their best-fit branching fractions from the combined fit to the 2$\ell$ SS and 3$\ell$ categories, are shown as filled red histograms stacked above the background components; only $t \to Hu$ is large enough to be visible. The hashed band indicates the total uncertainty in the signal-plus-background prediction, including the statistical uncertainty in the best-fit FCNC signal. The dashed red lines show the expected contribution of the respective FCNC decay with the 95% C.L. upper limit branching fraction (0.19% for $t \to Hu$, 0.16% for $t \to Hc$).

TABLE III. Best-fit values and 95% C.L. upper limits for $B(t \to Hu)$, assuming $B(t \to Hc) = 0$. The “stat + syst” columns show the full result allowing all systematic uncertainty nuisance parameters to float in the fit, while the “stat” columns show the result with systematic uncertainty nuisance parameters fixed to their values at the global best-fit point.

<table>
<thead>
<tr>
<th></th>
<th>Best-fit</th>
<th>Observed (expected)</th>
<th>Upper Limit on $B(t \to Hu)$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$B(t \to Hu)$ [%]</td>
<td>stat</td>
<td>stat + syst</td>
</tr>
<tr>
<td>2$\ell$ SS</td>
<td>0.08$^{+0.08}_{-0.08}$</td>
<td>0.08$^{+0.11}_{-0.10}$</td>
<td>0.23 (0.15)</td>
</tr>
<tr>
<td>3$\ell$</td>
<td>0.01$^{+0.09}_{-0.08}$</td>
<td>0.01$^{+0.10}_{-0.09}$</td>
<td>0.20 (0.18)</td>
</tr>
<tr>
<td>Combined</td>
<td>0.04$^{+0.06}_{-0.06}$</td>
<td>0.04$^{+0.08}_{-0.07}$</td>
<td>0.17 (0.12)</td>
</tr>
</tbody>
</table>

TABLE IV. Best-fit values and 95% C.L. upper limits for $B(t \to Hc)$, assuming $B(t \to Hu) = 0$. The “stat + syst” columns show the full result allowing all systematic uncertainty nuisance parameters to float in the fit, while the “stat” columns show the result with systematic uncertainty nuisance parameters fixed to their values at the global best-fit point.

<table>
<thead>
<tr>
<th></th>
<th>Best-fit</th>
<th>Observed (expected)</th>
<th>Upper Limit on $B(t \to Hc)$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$B(t \to Hc)$ [%]</td>
<td>stat</td>
<td>stat + syst</td>
</tr>
<tr>
<td>2$\ell$ SS</td>
<td>0.05$^{+0.08}_{-0.10}$</td>
<td>0.05$^{+0.11}_{-0.10}$</td>
<td>0.22 (0.15)</td>
</tr>
<tr>
<td>3$\ell$</td>
<td>$-0.09^{+0.10}_{-0.09}$</td>
<td>$-0.09^{+0.11}_{-0.10}$</td>
<td>0.19 (0.23)</td>
</tr>
<tr>
<td>Combined</td>
<td>$-0.01^{+0.06}_{-0.01}$</td>
<td>$-0.01^{+0.08}_{-0.08}$</td>
<td>0.15 (0.13)</td>
</tr>
</tbody>
</table>
which would be consistent with a FCNC signal. In addition, a second fit that decorrelates FCNC contributions in the signal categories from their impact on the nonprompt lepton efficiency estimates finds best-fit branching fractions consistent with those of the nominal fit.

VII. CONCLUSION

Any observable branching fraction for the FCNC decays $t \rightarrow Hq$ would indicate new physics beyond the Standard Model. A search for $t \bar{t}$ production events in which one top quark or antiquark undergoes a $t \rightarrow Hq$ decay was carried out with an integrated luminosity of 36.1 fb$^{-1}$ of $pp$ collision data with $\sqrt{s} = 13$ TeV collected in 2015 and 2016 using the ATLAS detector at the LHC. Two final states are targeted: two same-charge light leptons with four or more jets, and three light leptons with two or more jets. These are sensitive primarily to $H \rightarrow WW^*$ decays, with subleading contributions from $H \rightarrow \tau\tau$ and $H \rightarrow ZZ^*$. Specialized boosted decision trees using the kinematic properties of the final-state particles are used to distinguish FCNC signals from nonprompt lepton backgrounds and from $t\bar{t}W$ and $t\bar{t}Z$ production. Potential contamination from FCNC signal in the nonprompt lepton background control regions is treated in a self-consistent manner. No evidence of FCNC decays is found and the upper limits set on the branching fractions are $B(t \rightarrow Hc) < 0.16\%$ and $B(t \rightarrow Hu) < 0.19\%$ at 95% C.L.

ACKNOWLEDGMENTS

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; STSC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MINE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, the Canada Council, CANARIE, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, ERDF, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; CERCA Programme Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/ GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [61].


[18] ATLAS Collaboration, Search for top quark decays $t \rightarrow qH$ with $H \rightarrow \gamma\gamma$ using the ATLAS detector, J. High Energy Phys. 06 (2014) 008.


[56] DØ Collaboration, Extraction of the angular distribution of $W$ bosons from measurements of $\sigma(p\bar{p} \rightarrow W + X) \times B(W \rightarrow e\nu)$ and $\sigma(p\bar{p} \rightarrow Z + X) \times B(Z \rightarrow ee)$ and their ratio, Phys. Rev. D 61, 072001 (2000).


SEARCH FOR FLAVOR-CHANGING NEUTRAL CURRENTS … 

**PHYS. REV. D** 98, 032002 (2018)
SEARCH FOR FLAVOR-CHANGING NEUTRAL CURRENTS …

PHYS. REV. D 98, 032002 (2018)
Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
Physics Department, Tsinghua University, Beijing
University of Chinese Academy of Science (UCAS), Beijing, China
Institute of Physics, University of Belgrade, Belgrade, Serbia
Department for Physics and Technology, University of Bergen, Bergen, Norway
Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
Department of Physics, Humboldt University, Berlin, Germany
Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna
INFN Sezione di Bologna, Italy
Physikalisches Institut, University of Bonn, Bonn, Germany
Department of Physics, Brandeis University, Waltham, Massachusetts, USA
Transylvania University of Brașov, Brașov
Horia Hulubei National Institute of Physics and Nuclear Engineering
Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi
National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca
University Politehnica Bucharest, Bucharest
West University in Timisoara, Timisoara, Romania
Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava
Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
Physics Department, Brookhaven National Laboratory, Upton, New York, USA
Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
Department of Physics, University of Cape Town, Cape Town, South Africa
Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa
School of Physics, University of the Witwatersrand, Johannesburg, South Africa
Department of Physics, Carleton University, Ottawa, Ontario, Canada
Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca
Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat
Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech
Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda
Faculté des sciences, Université Mohammed V, Rabat, Morocco
CERN, Geneva, Switzerland
Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
Nevis Laboratory, Columbia University, Irvington, New York, USA
Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
Dipartimento di Fisica, Università della Calabria, Rende
INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow
Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
Physics Department, Southern Methodist University, Dallas, Texas, USA
Physics Department, University of Texas at Dallas, Richardson, Texas, USA
SEARCH FOR FLAVOR-CHANGING NEUTRAL CURRENTS ...

PHYS. REV. D 98, 032002 (2018)

45a Department of Physics, Stockholm University
45b The Oskar Klein Centre, Stockholm, Sweden
46 DESY, Hamburg and Zeuthen, Germany
47 Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
48 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
49 Department of Physics, Duke University, Durham, North Carolina, USA
50 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
51 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
52 INFN e Laboratori Nazionali di Frascati, Frascati, Italy
53 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
55 Departement de Physique Nucléaire et Corpusculaire, Université de Genève, Geneva, Switzerland
56a Dipartimento di Fisica, Università di Genova, Genova
56b INFN Sezione di Genova, Italy
57 II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
58 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
59 LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
60 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
61 Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Anhui
62 School of Physics, Shandong University, Shandong
63 School of Physics and Astronomy, Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University
64a Dipartimento di Fisica, Università di Pavia, Pavia, Italy
64b Dipartimento di Fisica E. Fermi, Università di Roma, Roma, Italy
64c Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
65 Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
66 Department of Physics, Indiana University, Bloomington, Indiana, USA
66a INFN Sezione di Pavia, Pavia, Italy
66b INFN Sezione di Roma Tor Vergata, Roma, Italy
67a INFN-TIFPA, Italy
67b University of Trento, Trento, Italy
68a INFN Sezione di Trieste, Trieste, Italy
68b INFN Sezione di Udine, Sezione di Trieste, Udine
69a INFN Sezione di Lecce, Lecce, Italy
69b INFN Sezione di Milano, Milano, Italy
70a INFN Sezione di Napoli, Napoli, Italy
70b Dipartimento di Fisica, Università di Napoli, Napoli, Italy
71a INFN Sezione di Pavia, Pavia, Italy
71b Dipartimento di Fisica, Università di Pavia, Pavia, Italy
72a INFN Sezione di Pisa, Pisa, Italy
72b Dipartimento di Fisica E. Fermi, Università di Roma, Roma, Italy
73a INFN Sezione di Roma, Roma, Italy
73b Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
74a INFN Sezione di Roma Tor Vergata, Roma, Italy
75a INFN Sezione di Roma Tre, Roma, Italy
76a INFN-Sezione di Trieste, Trieste, Italy
77 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
78 University of Iowa, Iowa City, Iowa, USA
Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
Graduate School of Science, Kobe University, Kobe, Japan
Faculty of Science, Kyoto University, Kyoto, Japan
Kyoto University of Education, Kyoto, Japan
Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
Physics Department, Lancaster University, Lancaster, United Kingdom
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
Department of Physics and Astronomy, University College London, London, United Kingdom
Louisiana Tech University, Ruston, Louisiana, USA
Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
Fysiska institutionen, Lunds universitet, Lund, Sweden
Departamento de Física Teórica C-15 and CIAFF, Universidad Autonoma de Madrid, Madrid, Spain
Institut für Physik, Universität Mainz, Mainz, Germany
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
Department of Physics, McGill University, Montreal, Quebec, Canada
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA
Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Republic of Belarus
Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada
P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
National Research Nuclear University MEPhI, Moscow, Russia
D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
Nagasaki Institute of Applied Science, Nagasaki, Japan
Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
Budker Institute of Nuclear Physics, SB RAS, Novosibirsk
Novosibirsk State University Novosibirsk, Russia
Department of Physics, New York University, New York, New York, USA
The Ohio State University, Columbus, Ohio, USA
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
Palacký University, RCPTM, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
Graduate School of Science, Osaka University, Osaka, Japan
SEARCH FOR FLAVOR-CHANGING NEUTRAL CURRENTS . . .

PHYS. REV. D 98, 032002 (2018)

Department of Physics, University of Oslo, Oslo, Norway

Department of Physics, Oxford University, Oxford, United Kingdom

Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA

Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg, Russia

Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA

Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa

Faculdade de Ciências, Universidade de Lisboa, Lisboa

Department of Physics, University of Coimbra, Coimbra

Centro de Física Nuclear da Universidade de Lisboa, Lisboa

Departamento de Física, Universidade do Minho, Braga

Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain)

Dep Física and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal

Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic

Czech Technical University in Prague, Praha, Czech Republic

Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic

State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia

Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom

Unividade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro

Electrical Circuits Department, Federal University of Juiz de Fora (UFJJ), Juiz de Fora

Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei

Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil

Institut de Recherches sur les Lois Fondamentales de l’Univers, DSM/IRFU, CEA Saclay, Gif-sur-Yvette, France

Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA

Departamento de Física, Pontificia Universidad Católica de Chile, Santiago

Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

Department of Physics, University of Washington, Seattle, Washington, USA

Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom

Department of Physics, Shinshu University, Nagano, Japan

Department Physik, Universität Siegen, Siegen, Germany

Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada

SLAC National Accelerator Laboratory, Stanford, California, USA

Physics Department, Royal Institute of Technology, Stockholm, Sweden

Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA

Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom

School of Physics, University of Sydney, Sydney, Australia

Institute of Physics, Academia Sinica, Taipei, Taiwan

E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi

High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel

Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan

Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan

Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

Tomsk State University, Tomsk, Russia

Department of Physics, University of Toronto, Toronto, Ontario, Canada

TRIUMF, Vancouver, British Columbia, Canada

Department of Physics and Astronomy, York University, Toronto, Ontario, Canada

Division of Physics and Tonomaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA

Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA

Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
† Deceased.

a Also at Borough of Manhattan Community College, City University of New York, New York City, New York, USA.
b Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.
c Also at CERN, Geneva, Switzerland.
da Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
e Also at Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain.
f Also at Departamento de Física de la Universidad Autónoma de Barcelona, Barcelona, Spain.
g Also at Departamento de Física, University of Barcelona, Barcelona, Spain.
h Also at Department of Physics, University of Warwick, Coventry, United Kingdom.
i Also at Department of Physics, Royal Holloway, University of London, Egham, United Kingdom.
j Also at Dipartimento di Fisica E. Fermi, Università di Roma, Rome, Italy.
k Also at Dipartimento di Scienze della Terra, Università di Torino, Turin, Italy.
l Also at Dipartimento di Fisica E. Fermi, Università di Roma, Rome, Italy.
m Also at Dipartimento di Fisica, Università di Bologna, Bologna, Italy.

Also at Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada.

Also at Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada.

Also at Department of Physics, Waseda University, Tokyo, Japan.

Also at Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel.

Also at Department of Physics, University of Wisconsin, Madison, Wisconsin, USA.

Also at Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany.

Also at Department of Physics, Yale University, New Haven, Connecticut, USA.

Also at Yerevan Physics Institute, Yerevan, Armenia.

Also at Department of Physics, University of Illinois, Urbana, Illinois, USA.

Also at Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Spain.

Also at Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada.

Also at Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada.

Also at Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany.

Also at Department of Physics, University of Warwick, Coventry, United Kingdom.

Also at Waseda University, Tokyo, Japan.

Also at Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel.

Also at Department of Physics, University of Wisconsin, Madison, Wisconsin, USA.

Also at Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany.

Also at Department of Physics, Yale University, New Haven, Connecticut, USA.

Also at Yerevan Physics Institute, Yerevan, Armenia.

Also at Department of Physics, University of Illinois, Urbana, Illinois, USA.

Also at Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Spain.

Also at Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada.

Also at Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada.

Also at Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany.

Also at Department of Physics, University of Warwick, Coventry, United Kingdom.

Also at Waseda University, Tokyo, Japan.

Also at Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel.

Also at Department of Physics, University of Wisconsin, Madison, Wisconsin, USA.

Also at Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany.

Also at Department of Physics, Yale University, New Haven, Connecticut, USA.

Also at Yerevan Physics Institute, Yerevan, Armenia.

Also at Department of Physics, University of Illinois, Urbana, Illinois, USA.

Also at Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Spain.

Also at Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada.

Also at Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada.

Also at Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany.

Also at Department of Physics, University of Warwick, Coventry, United Kingdom.

Also at Waseda University, Tokyo, Japan.

Also at Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel.

Also at Department of Physics, University of Wisconsin, Madison, Wisconsin, USA.

Also at Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany.

Also at Department of Physics, Yale University, New Haven, Connecticut, USA.

Also at Yerevan Physics Institute, Yerevan, Armenia.

Also at Department of Physics, University of Illinois, Urbana, Illinois, USA.

Also at Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Spain.

Also at Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada.

Also at Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada.

Also at Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany.

Also at Department of Physics, University of Warwick, Coventry, United Kingdom.

Also at Waseda University, Tokyo, Japan.

Also at Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel.

Also at Department of Physics, University of Wisconsin, Madison, Wisconsin, USA.

Also at Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany.

Also at Department of Physics, Yale University, New Haven, Connecticut, USA.

Also at Yerevan Physics Institute, Yerevan, Armenia.
Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
Also at TRIUMF, Vancouver, British Columbia, Canada.
Also at Universita di Napoli Parthenope, Napoli, Italy.
Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.