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G. Aad ... P. Jackson ... L. Lee ... A. Petridis ... N. Soni ... M.J. White ... et al. (ATLAS Collaboration)

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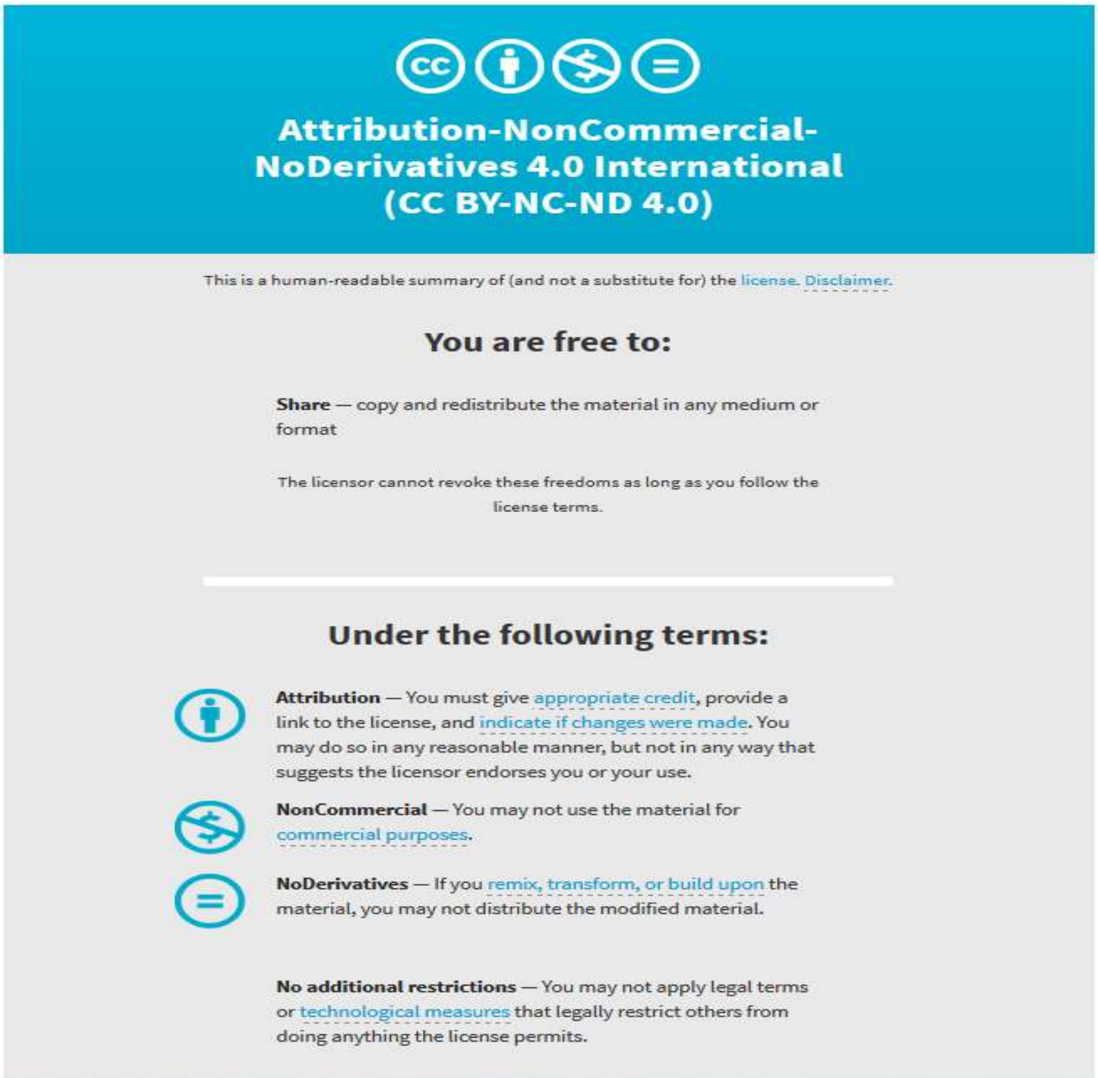

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Search for heavy vector-like quarks coupling to light quarks in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector ☆

ATLAS Collaboration ⋆

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ABSTRACT

This Letter presents a search for singly produced vector-like quarks, Q, coupling to light quarks, q. The search is sensitive to both charged current (CC) and neutral current (NC) processes, $pp \to Qq \to Wqq'$ and $pp \to Qq \to Zqq'$ with a leptonic decay of the vector gauge boson. In 1.04 fb^{-1} of data taken in 2011 by the ATLAS experiment at a center-of-mass energy $\sqrt{s} = 7$ TeV, no evidence of such heavy vector-like quarks is observed above the expected Standard Model background. Limits on the heavy vector-like quark production cross section times branching ratio as a function of mass m_Q are obtained. For a coupling $\kappa_{qQ} = v/m_Q$, where v is the Higgs vacuum expectation value, 95% C.L. lower limits on the mass of a vector-like quark are set at 900 GeV and 760 GeV from CC and NC processes, respectively.

1. Introduction

Vector-like quarks (VLQ), defined as quarks for which both chiralities have the same transformation properties under the electroweak group $SU(2) \times U(1)$, are predicted by many extensions of the SM, relating to Grand Unification, dynamical electroweak symmetry breaking scenarios or theories with extra dimensions [1–10]. Since the couplings of the light quarks are well constrained, if VLQs exist they are generally expected to only couple sizably to the third generation. However, in certain scenarios, corrections to quark mixings can cancel, relaxing these constraints. The motivation and phenomenology of heavy VLQs coupling to light generations is discussed for the Tevatron [11], where a baseline model is introduced which considers two degenerate VLQ doublets having hypercharges 1/6 and 7/6 and mixing only with the up quark. This scenario can occur naturally in certain models [12]. Because the doublets are degenerate, cancellations occur which allow VLQ coupling to the first two generations, leading to a potentially strong signal at the Large Hadron Collider (LHC).

Following the notation of more recent work [13] which describes a model-independent approach to VLQ sensitivity at the LHC, a coupling $\kappa_{qQ} = (v/m_Q)\tilde{\kappa}_{qQ}$ is defined here, where q stands for any light quark, Q is the VLQ, m_Q is the VLQ mass, v is the Higgs vacuum expectation value and $\tilde{\kappa}_{qQ}$ encodes all the model dependence of the qVQ vertex ($V = W$ or Z). Electroweak precision measurements constrain the contribution of heavy quarks to loop diagrams, but under certain conditions, as for the degenerate VLQ doublet model above, mild bounds apply on the dimensionless coupling κ, allowing it to be as large as ~ 1 [13]. The masses of VLQs are not constrained by vacuum stability in the SM [14].

It has been shown that single production provides a favorable process to probe for the existence of these heavy quarks if the coupling to light quarks is large, and that a significant mass reach could be achieved at the LHC with early data [11,13]. Single production of a VLQ occurs via the process $qq' \xrightarrow{V^*} q''Q$ (Fig. 1). A quark produced by this process of gauge boson exchange can have a charge of 5/3, 2/3, −1/3 or −4/3. As a benchmark, we consider theories with only VLQs U of charge +2/3 or only with D of charge −1/3, without regard to the multiplet structure of the model. The experimental limits obtained on cross section times branching ratio can then be interpreted as limits on the couplings for different VLQ models [13]. The contribution from the s-channel diagram is negligible compared to that of the t-channel process. Therefore one characteristic of the signal is the presence of a forward jet: after one of the initial state quarks emits the electroweak gauge boson, it will continue in the forward direction with little transverse momentum (p_T), while the other quark couples to the W or Z to produce the heavy quark. Because the LHC is a proton–proton collider, the charged current (CC) production of a D quark is expected to have a higher cross section than that of a U quark. Similarly, for the neutral current (NC) process, U quarks are expected to be produced more abundantly. Anti-quark production is suppressed since it involves anti-quarks in the initial state.

Bounds on the mass of new heavy quarks were obtained previously from a search in the pair production process at the Tevatron [15,16] and LHC [17,18]. Limits have also been obtained at the Tevatron [19,20] on single production processes $\sigma(p\bar{p} \to qQ) \times \text{BR}(Q \to qW)$, which in the model [11] of degenerate doublets

⋆ *E-mail address:* atlas.publications@cern.ch.

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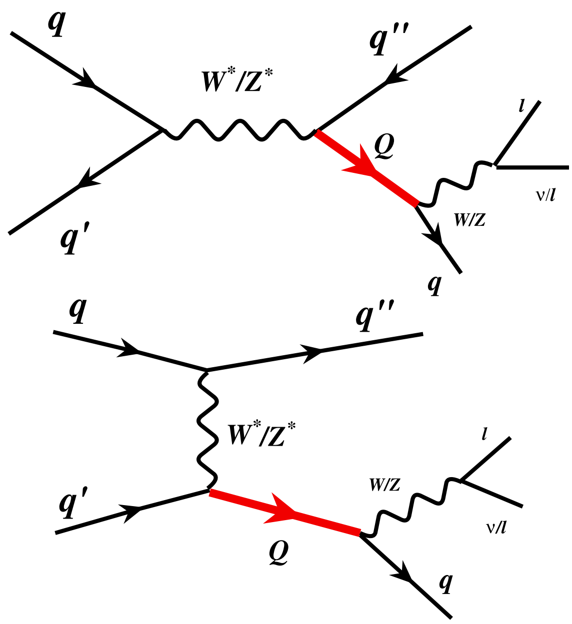

Fig. 1. Vector-like quark production and decay diagrams for s-channel (top) and t-channel (bottom). The thick line indicates the vector-like quark.

with $\tilde{\kappa}_{uD} = 1$ and decaying 100% via CC gives a 95% confidence level (C.L.) upper limit exclusion for D quarks with masses up to 690 GeV. Limits at 95% C.L. on $\sigma(p\bar{p} \to qQ) \times \mathrm{BR}(Q \to qZ)$ in the same model yield an exclusion of a U quark with $\tilde{\kappa}_{uU} = \sqrt{2}$ and 100% branching ratio via NC up to a mass of 550 GeV.

This Letter reports on a search for singly produced VLQs in the ATLAS detector at the LHC. The search is conducted in events with at least two jets and a vector boson, indicated by either two high-p_T leptons (electrons or muons) in the case of a Z, or a single lepton and missing transverse momentum (E_T^{miss}) in the case of a W. The data used in this analysis were collected from March to June 2011, at a center-of-mass energy $\sqrt{s} = 7$ TeV and correspond to an integrated luminosity of $\mathcal{L} = (1.04 \pm 0.04)$ fb^{-1} [21].

2. The ATLAS detector

The ATLAS detector is a multi-purpose particle physics detector system optimized to record information coming from pp collisions [22]. Closest to the interaction point is the inner detector (ID) for charged particle tracking, which is performed by silicon pixel and microstrip detectors in addition to a straw-tube tracker with radiators to produce transition radiation. The tracking system is embedded in a 2 T axial magnetic field. Surrounding the solenoid are the lead and liquid argon electromagnetic (EM) calorimeter and hadronic tile calorimeter subsystems. Forward calorimetry is accomplished with liquid argon detectors and copper and tungsten absorbers. These systems allow the reconstruction of electrons and jets, both essential for this analysis. Surrounding the calorimeter systems is a muon spectrometer (MS) that uses drift chambers to record muon trajectories in a toroidal magnetic field. A three-level trigger is used to select events for subsequent offline analysis. Events recorded when a subsystem was not properly functioning are not used in this analysis.

3. Signal and background modeling

Signal Monte Carlo (MC) samples are generated using MadGraph [23] based on Refs. [11,13], then hadronized and showered through PYTHIA [24]. The CTEQ6L1 parton distribution function (PDF) [25] is used, with factorization and renormalization scales of m_W (m_Z) for the CC (NC) channel. Nine reference masses are generated for both CC and NC decays: 225 GeV, 300 GeV, then continuing in steps of 100 GeV up to 1 TeV. The production cross section times branching ratio to a vector boson and jets ranges from 194 pb to 0.47 pb for CC and from 88 pb to 0.28 pb for NC, assuming $\tilde{\kappa}_{qQ} = 1$.

The dominant SM backgrounds are $W \to \ell\nu +$ jets and $Z \to \ell\ell +$ jets for the CC and NC channels, respectively. Other sources of background are from multijet events, $t\bar{t}$, single top, and diboson processes, which can have electrons or muons and jets in the final states. With the exception of multijets, the contributions of these backgrounds are estimated using MC samples. $W+$jets and $Z+$jets samples are generated by ALPGEN [26] using CTEQ6L1 PDFs with parton showering performed by HERWIG [27] and using JIMMY [28] for simulation of the underlying event model. The cross section times leptonic branching ratios are 10.3 pb and 1.06 pb per lepton flavor for W and Z's, respectively, with p_T of the leptons > 20 GeV. This includes K-factors of 1.22 and 1.25, respectively, to reproduce the inclusive cross sections at next-to-leading order in QCD [29]. MC@NLO [30] is used to simulate $t\bar{t}$ production, giving a cross section of 165 pb. Single top quark events decaying leptonically ($\sigma = 37.5$ pb) are generated with AcerMC [31] combined with parton showering and hadronization by PYTHIA. Diboson backgrounds are simulated with ALPGEN and HERWIG parton shower for the NC channel ($\sigma \times \mathrm{BR} = 5.97$ pb), which requires two leptons in the final state, and standalone HERWIG (with a K-factor of 1.52 to reproduce the inclusive cross section at next-to-leading order in QCD [32]) for the CC channel ($\sigma \times \mathrm{BR} = 69.1$ pb) where a single lepton is required. Multijet backgrounds from QCD processes are derived both from PYTHIA and data samples, described below.

The detector response simulation [33] is based on GEANT4 [34,35]. The MC samples are generated with superimposed minimum bias events to simulate the conditions that occur in data. In order to improve the modeling of both signal and backgrounds, lepton reconstruction and identification efficiencies, energy scales and resolutions in the MC are corrected to correspond to the values measured in the data.

4. Analysis

The analysis is subdivided into four channels: charged and neutral current, each with either electrons or muons in the final state. Particle definitions and selections are identical in all channels, but signal and control regions for the CC and NC channels are defined independently.

Events are selected in which there is at least one vertex reconstructed with at least three tracks. The vertex with the greatest total transverse momentum, $\sum |p_T|$, of the associated tracks is designated as the primary vertex. The trigger requires at least one cluster in the EM calorimeter with $p_T > 20$ GeV or at least one muon candidate in the MS with a track originating from the primary vertex with $p_T > 18$ GeV. In both cases, the trigger requires a matching ID track.

Electron candidates are required to pass tight quality selection criteria based on the calorimeter shower shape, track quality and track matching with the calorimeter cluster [36]. They must have $p_T > 25$ GeV and lie in the pseudorapidity[1] region $|\eta| < 2.47$, excluding the regions of transition between the central and forward detector sub-elements, $1.37 < |\eta| < 1.52$. During most run periods

[1] ATLAS uses a right-handed coordinate system with the z-axis along the beam pipe. The x-axis points to the center of the LHC ring, and the y-axis points upward. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

of the data set, a region of the EM calorimeter corresponding to about 1% of channels was less efficient than the rest of the detector. An exclusion window around the affected area was defined as $-0.1 < \eta < +1.5$ in pseudorapidity and $-0.9 < \phi < -0.5$ in azimuth. Electrons in this region are removed from data collected during these periods. The same procedure is applied to simulated events corresponding to the fraction of data covered by these run periods. Finally, no more than 4 GeV of transverse energy is allowed outside the core of the electron defined by a cone of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$.

Muon candidates are reconstructed by combining tracks from both the ID and the MS. They are required to pass ID quality requirements [37] and have $p_T > 25$ GeV and $|\eta| < 2.4$. To suppress cosmic rays, muon candidates must have a distance of closest approach to the primary vertex in the longitudinal direction $|z_0| < 5$ mm and in the transverse plane $|d_0| < 0.1$ mm. Isolated muons are selected by requiring that the sum of ID track transverse momentum around the muon track, in a cone of $\Delta R = 0.2$ divided by the p_T of the muon itself be less than 0.1.

Jet four-vectors are reconstructed from calorimeter clusters using the anti-k_T algorithm [38] with a radius parameter of 0.4. After correcting for calorimeter non-compensation and inhomogeneities by using p_T- and η-dependent calibration factors [39], jets are required to have $p_T > 25$ GeV and $|\eta| < 4.5$. Events containing jets that fail quality criteria [40] are rejected to ensure an accurate E_T^{miss} measurement. Furthermore, events containing jets passing through the inefficient region of the EM calorimeter are vetoed. To remove jets originating from other pp interactions within an event, the selected jets are required to have more than 75% of p_T-weighted ID tracks associated to the primary vertex. Finally, to avoid counting electrons as jets, any jet candidate within $\Delta R < 0.2$ of a selected electron is removed.

The E_T^{miss} is calculated as the negative vector of the transverse components of energy deposits in the calorimeters within $|\eta| < 4.5$. For events containing muons, any calorimeter energy deposit from a muon is ignored and the muon energy measured in the MS is used instead [41].

The CC candidates are required to have (i) exactly one electron or muon, (ii) missing transverse momentum $E_T^{\text{miss}} > 50$ GeV, (iii) one jet with $p_T > 50$ GeV and at least one more jet with $p_T > 25$ GeV, (iv) a minimum pseudorapidity separation $|\Delta\eta| > 1.0$ between the highest-p_T (leading) jet and second or third-leading jet, since the presence of a forward jet is expected in signal events, (v) $m_T(\ell, E_T^{\text{miss}}) > 40$ GeV, where $m_T(\ell, E_T^{\text{miss}}) = \sqrt{2E_T^{\ell} E_T^{\text{miss}}(1 - \cos\Delta\phi_{\ell, E_T^{\text{miss}}})}$ is the transverse mass of the W candidate, and (vi) an azimuthal angle separation between the lepton and E_T^{miss} vector $\Delta\phi_{\ell, E_T^{\text{miss}}} < 2.4$ rad since the W in the signal is expected to be boosted. To reconstruct the mass of the VLQ candidate, the longitudinal momentum p_z of the neutrino is calculated such that the invariant mass of the lepton and E_T^{miss} equals the mass of the W. Of the two solutions, the one which leads to the larger value of $|\Delta\eta|$ between the reconstructed neutrino four-vector and the leading jet is chosen, since the simulation shows it to be the correct solution about 60% of the time. If no real solution is found, the real part of the complex solutions is taken. The system composed of the leading jet and the reconstructed W is taken to be the VLQ candidate.

The NC candidates are required to have exactly two oppositely charged same-flavor leptons with an invariant mass in the range $66 < M(\ell, \ell) < 116$ GeV and a transverse momentum $p_T(\ell, \ell) > 50$ GeV. At least two jets of $p_T > 25$ GeV are required, with the same $|\Delta\eta| > 1.0$ requirement as described for the CC selection. The invariant mass of the system composed of the two leptons and the leading jet is taken to be the VLQ candidate mass.

Table 1
Expected and observed event counts in the kinematically allowed VLQ mass range after the final selection in the CC channel with an integrated luminosity of 1.04 fb^{-1}. Uncertainties are statistical and systematic, respectively. The signal predictions assume a coupling $\tilde{\kappa}_{uD} = 1$.

Process	Electron channel	Muon channel
W + jets	$14500 \pm 100 \pm 4400$	$16600 \pm 100 \pm 5000$
$t\bar{t}$	$2360 \pm 50 \pm 270$	$2530 \pm 50 \pm 290$
Single top	$700 \pm 30 \pm 120$	$740 \pm 27 \pm 120$
Multijet	$670 \pm 30 \pm 270$	$340 \pm 20 \pm 410$
Z + jets	$128 \pm 11 \pm 90$	$432 \pm 21 \pm 170$
Diboson	$174 \pm 13 \pm 53$	$198 \pm 14 \pm 62$
Expected total background	$18500 \pm 100 \pm 4400$	$20900 \pm 100 \pm 5100$
Data	17302	20668
Expected signal, D(225 GeV)	$2360 \pm 50 \pm 350$	$2380 \pm 50 \pm 400$
Expected signal, D(600 GeV)	$133 \pm 12 \pm 10$	$133 \pm 12 \pm 11$
Expected signal, D(1000 GeV)	$14 \pm 4 \pm 1$	$14 \pm 4 \pm 1$

To evaluate the level of multijet background in the CC analysis, a procedure is used based on a fit to the E_T^{miss} distribution in the range $0 < E_T^{\text{miss}} < 100$ GeV. For this purpose, only selection criteria (i) and (v) above are required. For both the electron and muon modes, template shapes for the non-multijet backgrounds are taken from the MC samples described earlier and summed according to their relative cross sections. The overall normalization of this non-multijet template is left floating. In the electron mode, a sample enriched in objects misidentified as electrons (fakes) is selected from data using *medium* quality electrons, excluding *tight* electrons, as defined in [36]. The E_T^{miss} distribution of this sample serves as the electron multijet template shape. For the muon mode, multijet background is primarily expected to come from heavy-flavor decays. Therefore, the multijet template shape is taken from a PYTHIA sample of $b\bar{b}$ events. For both lepton flavors, a fit to the E_T^{miss} distribution is performed using the multijet and non-multijet templates to determine the normalization of the multijet component. The modeling of the multijet background was tested in a control region defined by the range of $10 < E_T^{\text{miss}} < 30$ GeV. The modeling of the kinematic variable distributions, and in particular of the VLQ candidate mass, was found to agree with data within statistics.

In the case of the NC selection, the multijet background is estimated from data-driven studies to be negligible. In the electron channel the selection for electron candidates is changed to require the medium criteria, excluding tight electrons, to obtain a fake di-electron template shape in m_{ee}, which is then scaled to make the total background expectation match the data with the same selection. In the muon channel the isolation requirement is inverted, and the $m_{\mu\mu}$ template scaled to the data in the same way.

With the above selections, the observed event yields and corresponding predictions are given in Tables 1 and 2. From these yields, no significant excess is observed in the data that can be accounted for by a VLQ signal. Fig. 2 shows the invariant mass distributions of the reconstructed VLQ candidate in the signal regions for both channels. These distributions are used in a binned likelihood fit to extract signal yields and production cross section upper limits. A slight shape discrepancy between data and MC is apparent in Fig. 2. Before extracting an upper limit, a correction is applied to the MC background shape, as described in Section 6.

5. Systematic uncertainties

Systematic uncertainties on the simulation of the signal arise from uncertainties in PDFs and the factorization and renormalization scales. In order to estimate the uncertainty due to the parton

Table 2
Expected and observed event counts in the kinematically allowed VLQ mass range after the final selection in the NC channel with an integrated luminosity of 1.04 fb^{-1}. Uncertainties are statistical and systematic, respectively. The signal predictions assume a coupling $\tilde{\kappa}_{uU} = 1$.

Process	Electron channel	Muon channel
$Z+$jets	$3250 \pm 60 \pm 430$	$5350 \pm 70 \pm 700$
$t\bar{t}$	$58 \pm 8 \pm 3$	$90 \pm 9 \pm 5$
Diboson	$38 \pm 6 \pm 4$	$58 \pm 8 \pm 4$
Expected total background	$3350 \pm 60 \pm 430$	$5500 \pm 70 \pm 700$
Data	3105	5070
Expected signal, U(225 GeV)	$192 \pm 14 \pm 9$	$339 \pm 18 \pm 19$
Expected signal, U(600 GeV)	$15 \pm 3.9 \pm 0.6$	$23 \pm 4.8 \pm 0.7$
Expected signal, U(1000 GeV)	$1.9 \pm 1.4 \pm 0.1$	$2.7 \pm 1.6 \pm 0.1$

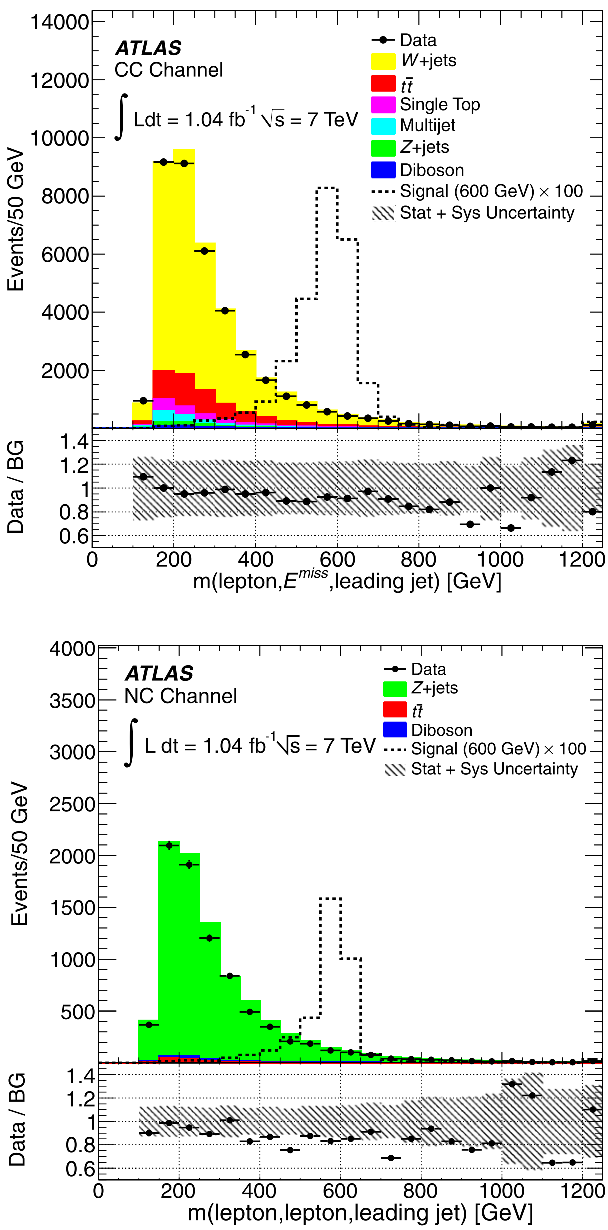

Fig. 2. Invariant mass distribution of VLQ candidates in both the CC (top) and NC (bottom) channels, summed over both the electron and muon final states. The dashed line shows the signal shape, normalized by 100 times the leading-order theoretical cross section. The bottom part of each plot shows the ratio of the data to the background model. The last bin contains events with invariant mass candidates equal to or higher than 1200 GeV.

distributions, the CTEQ66 [42] PDF set is used, for which the eigenvectors of the Hessian matrix are known. The difference in signal cross section due to the PDF uncertainty is found to range from 3.0% at a signal mass of 225 GeV to 4.4% at 1000 GeV. The uncertainty due to the factorization and renormalization scales is estimated by taking the difference between signal cross sections at the nominal value of the scales, and at values of one-half and twice the nominal. The uncertainty is found to vary between 4% and 12% for the same mass range. Uncertainties due to the simulation of initial and final state radiation are found to be about 1%. These uncertainties on the theoretical cross section are added in quadrature.

For signal and background events, the jet-energy-scale uncertainty is calculated by shifting the p_T of all jets up and down by factors that vary as a function of p_T and η. The factors range from 4.6% for jets with $p_T = 20$ GeV to 2.5% for jets with p_T above 60 GeV [39]. This procedure results in an uncertainty of about 20% on the background normalization, and about 5% on the signal efficiency. The jet-energy-resolution uncertainty is calculated by smearing the p_T of each jet depending on the jet p_T and η, typically by around 10%. This source of uncertainty is found to impact both the background normalization and signal efficiency by about 1%. The lepton-energy-scale uncertainty is evaluated and found to be much less than 1% for both signal and background. The effect of the previously mentioned EM calorimeter inefficiency is also found to be much less than 1%. Uncertainties also arise from the trigger, identification, and reconstruction efficiency corrections applied to the MC simulation. They affect the signal efficiency uncertainty by 1–2% depending on the mass. The rate uncertainty from MC statistics after event selection is 3–5%. Finally, the uncertainty on the luminosity is 3.7% [21]. None of the systematics studied have been found to significantly affect the shape of the VLQ candidate mass distribution.

6. Results

To determine signal yields, a binned maximum likelihood fit is performed using template histograms of the VLQ candidate mass distribution. The fit is performed separately for each signal mass. The electron and muon final states are fitted simultaneously. The overall signal and background normalizations are left floating in the fit. Systematic uncertainties on the template normalizations are incorporated as Gaussian-distributed nuisance parameters, as are the signal efficiency systematics used in determining the cross section limits. Signal template shapes are taken from MC, while background templates are as shown in Fig. 2, with an additional correction described next.

A heavy VLQ signal would appear as a peak on top of a smooth background in the VLQ candidate invariant mass distribution. It is therefore important to have a good estimate of the background shape in the region around a signal mass hypothesis. The fit procedure described above makes use of the full range of mass, but the normalization is dominated by the lower mass region where the number of events is higher. A small shape difference between Monte Carlo and data can therefore yield a systematic bias in the fit at high mass. For that reason a correction is applied to the background model for each signal mass. It is obtained from linear fits to the reconstructed invariant mass of the ratio of data/MC after the full event selection, excluding bins in the range [−200, +100] GeV around each signal mass tested. The asymmetric choice in the excluded mass is motivated by the fact that the expected signal has a low mass tail. The 1σ uncertainty in the slope is taken as a systematic shape uncertainty. It was verified that no significant difference to the fit results arose from choosing a narrower excluded mass window, or even no exclusion at all.

Table 3
Observed upper limits at 95% confidence level on the cross section times branching ratio $\sigma(pp \to Qq) \times \mathrm{BR}(Q \to Vq)$ as a function of mass and the corresponding upper limit on a model-independent heavy-to-light quark coupling. The final column shows the limit on the CC process after selecting negatively charged leptons.

Mass [GeV]	CC $\sigma \times$ BR [pb]	NC $\sigma \times$ BR [pb]	$\tilde{\kappa}^2_{uD}$	$\tilde{\kappa}^2_{uU}$	CC$^-$ $\sigma \times$ BR [pb]
225	15	18	0.075	0.21	12
300	17	11	0.24	0.31	5.6
400	5.3	2.4	0.21	0.19	3.8
500	2.1	1.4	0.19	0.26	1.1
600	1.9	1.5	0.37	0.56	1.9
700	2.2	1.0	0.86	0.75	2.2
800	0.93	1.0	0.66	1.33	0.97
900	0.80	0.9	1.0	2.1	0.70
1000	0.91	1.1	1.9	4.0	0.50

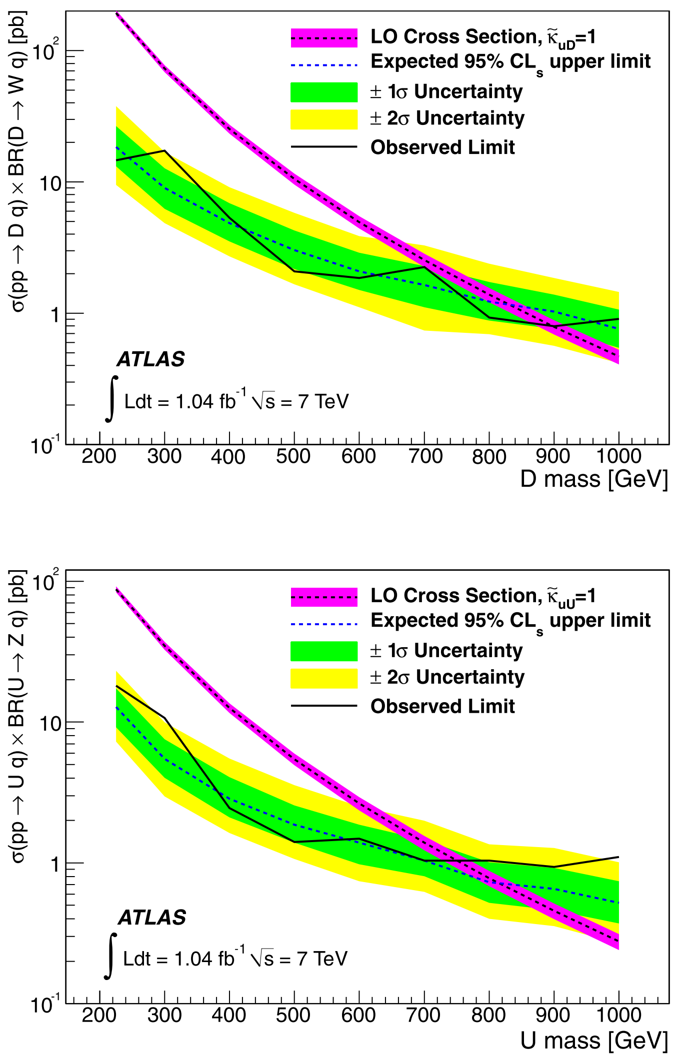

Fig. 3. Upper limits at 95% confidence level on the cross section times branching ratio $\sigma(pp \to Qq) \times \mathrm{BR}(Q \to Vq)$ for the CC (top) and NC (bottom) channels as a function of mass. The leading-order (LO) theoretical cross section assumes $\tilde{\kappa}_{uD} = 1$ and $\tilde{\kappa}_{uU} = 1$ on the top and bottom, respectively. The width of the dark band around it corresponds to the theoretical uncertainty described in the text. The expected cross section upper limit is determined by the median result of background-only pseudoexperiments, and is shown with its 1σ and 2σ uncertainties, respectively.

Since no significant excess of data over the background prediction is observed in either channel, limits as function of the VLQ mass are obtained based on the likelihood fits. Pseudoexperiments are generated by sampling the likelihood function to compute the expected limits, using a Gaussian prior for all nuisance parameters and including the shape uncertainty from the linear correction.

The 95% C.L. exclusion limits on $\sigma(pp \to Qq) \times \mathrm{BR}(Q \to Vq)$ as a function of the VLQ mass, based on the CL$_s$ method [43], are shown in Fig. 3. Taking the intersection of the observed (expected) cross section limits with the central value of the theoretical cross section, masses below 900 GeV (840 GeV) are excluded for the CC channel and 760 GeV (820 GeV) for the NC channel, assuming a coupling $\tilde{\kappa}^2_{qQ} = 1$ and a 100% branching ratio for VLQs to decay to a vector boson and a jet. Within the $\pm 1\sigma$ theoretical uncertainties, the observed CC mass limit ranges from 870–920 GeV. The corresponding range for the NC limit is 730–770 GeV. Limits for each mass tested are given in Table 3. The fourth and fifth columns show an interpretation of the cross section limits in terms of limits on the couplings $\tilde{\kappa}^2_{uD}$ and $\tilde{\kappa}^2_{uU}$, in each case assuming only D production or only U production, respectively, and 100% branching fraction to a vector boson and jet.

A stronger limit in the CC channel may be obtained by repeating the CC analysis, requiring a negatively charged lepton because the SM background from $W^- +$ jets is lower than for $W^+ +$ jets. The upper limits on $\sigma(pp \to D^{-\frac{1}{3}} q) \times \mathrm{BR}(D^{-\frac{1}{3}} \to W^- u)$ are given in the sixth column of Table 3.

7. Conclusion

A search for single production of vector-like quarks coupling to light generations has been presented. No evidence is found for such quarks above the expected background in either the CC or NC channel. Upper limits on the production cross section times branching ratio to a vector boson and a jet were determined at 95% confidence level. Assuming couplings $\tilde{\kappa}^2_{uD} = 1$ and $\tilde{\kappa}^2_{uU} = 1$, the upper bounds obtained for the mass of vector-like quarks are 900 GeV for the CC channel and 760 GeV for the NC channel. These limits, which can be used to constrain different models of vector-like quarks [13], are the most stringent to date on this benchmark model.

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Shao [86], M. Shapiro [14], P.B. Shatalov [95], L. Shaver [6], K. Shaw [164a,164c], D. Sherman [175], P. Sherwood [77], A. Shibata [108], H. Shichi [101], S. Shimizu [29], M. Shimojima [100], T. Shin [56], M. Shiyakova [65], A. Shmeleva [94], M.J. Shochet [30], D. Short [118], S. Shrestha [64], E. Shulga [96], M.A. Shupe [6], P. Sicho [125], A. Sidoti [132a], F. Siegert [48], Dj. Sijacki [12a], O. Silbert [171], J. Silva [124a,b], Y. Silver [153], D. Silverstein [143], S.B. Silverstein [146a], V. Simak [127], O. Simard [136], Lj. Simic [12a], S. Simion [115], B. Simmons [77], R. Simoniello [89a,89b], M. Simonyan [35], P. Sinervo [158], N.B. Sinev [114], V. Sipica [141], G. Siragusa [173], A. Sircar [24], A.N. Sisakyan [65], S.Yu. Sivoklokov [97], J. Sjölin [146a,146b], T.B. Sjursen [13], L.A. Skinnari [14], H.P. Skottowe [57], K. Skovpen [107], P. Skubic [111], N. Skvorodnev [22], M. Slater [17], T. Slavicek [127], K. Sliwa [161], J. Sloper [29], V. Smakhtin [171], B.H. Smart [45], S.Yu. Smirnov [96], Y. Smirnov [96], L.N. Smirnova [97], O. Smirnova [79], B.C. Smith [57], D. Smith [143], K.M. Smith [53], M. Smizanska [71], K. Smolek [127], A.A. Snesarev [94], S.W. Snow [82], J. Snow [111], J. Snuverink [105], S. Snyder [24], M. Soares [124a], R. Sobie [169,j], J. Sodomka [127], A. Soffer [153], C.A. Solans [167], M. Solar [127], J. Solc [127], E. Soldatov [96], U. Soldevila [167], E. Solfaroli Camillocci [132a,132b], A.A. Solodkov [128], O.V. Solovyanov [128], J. Sondericker [24], N. Soni [2], V. Sopko [127], B. Sopko [127], M. Sosebee [7], R. Soualah [164a,164c], A. Soukharev [107], S. Spagnolo [72a,72b], F. Spanò [76], R. Spighi [19a], G. Spigo [29], F. Spila [132a,132b], R. Spiwoks [29], M. Spousta [126], T. Spreitzer [158], B. Spurlock [7], R.D. St. Denis [53], T. Stahl [141], J. Stahlman [120], R. Stamen [58a], E. Stanecka [38], R.W. Stanek [5], C. Stanescu [134a], M. Stanescu-Bellu [41], S. Stapnes [117], E.A. Starchenko [128], J. Stark [55], P. Staroba [125], P. Starovoitov [91], A. Staude [98], P. Stavina [144a], G. Stavropoulos [14], G. Steele [53], P. Steinbach [43], P. Steinberg [24], I. Stekl [127], B. Stelzer [142], H.J. Stelzer [88], O. Stelzer-Chilton [159a], H. Stenzel [52], S. Stern [99], K. Stevenson [75], G.A. Stewart [29], J.A. Stillings [20], M.C. Stockton [29], K. Stoerig [48], G. Stoicea [25a], S. Stonjek [99], P. Strachota [126], A.R. Stradling [7], A. Straessner [43], J. Strandberg [147], S. Strandberg [146a,146b], A. Strandlie [117], M. Strang [109], E. Strauss [143], M. Strauss [111], P. Strizenec [144b], R. Ströhmer [173], D.M. Strom [114], J.A. Strong [76,*], R. Stroynowski [39], J. Strube [129], B. Stugu [13], I. Stumer [24,*], J. Stupak [148], P. Sturm [174], N.A. Styles [41], D.A. Soh [151,u], D. Su [143], H.S. Subramania [2], A. Succurro [11], Y. Sugaya [116], T. Sugimoto [101], C. Suhr [106], K. Suita [67], M. Suk [126], V.V. Sulin [94], S. Sultansoy [3d], T. Sumida [68], X. Sun [55], J.E. Sundermann [48], K. Suruliz [139], S. Sushkov [11], G. Susinno [36a,36b], M.R. Sutton [149], Y. Suzuki [66], Y. Suzuki [67], M. Svatos [125], Yu.M. Sviridov [128], S. Swedish [168], I. Sykora [144a], T. Sykora [126], B. Szeless [29], J. Sánchez [167], D. Ta [105], K. Tackmann [41], A. Taffard [163], R. Tafirout [159a], N. Taiblum [153], Y. Takahashi [101], H. Takai [24], R. Takashima [69], H. Takeda [67], T. Takeshita [140], Y. Takubo [66], M. Talby [83], A. Talyshev [107,f], M.C. Tamsett [24], J. Tanaka [155], R. Tanaka [115], S. Tanaka [131], S. Tanaka [66], Y. Tanaka [100], A.J. Tanasijczuk [142], K. Tani [67], N. Tannoury [83], G.P. Tappern [29], S. Tapprogge [81], D. Tardif [158], S. Tarem [152], F. Tarrade [28], G.F. Tartarelli [89a], P. Tas [126], M. Tasevsky [125], E. Tassi [36a,36b], M. Tatarkhanov [14], Y. Tayalati [135d], C. Taylor [77], F.E. Taylor [92], G.N. Taylor [86], W. Taylor [159b], M. Teinturier [115], M. Teixeira Dias Castanheira [75], P. Teixeira-Dias [76], K.K. Temming [48], H. Ten Kate [29], P.K. Teng [151], S. Terada [66], K. Terashi [155], J. Terron [80], M. Testa [47], R.J. Teuscher [158,j], J. Thadome [174], J. Therhaag [20], T. Theveneaux-Pelzer [78], M. Thioye [175], S. Thoma [48], J.P. Thomas [17], E.N. Thompson [34], P.D. Thompson [17], P.D. Thompson [158], A.S. Thompson [53], L.A. Thomsen [35], E. Thomson [120], M. Thomson [27], R.P. Thun [87], F. Tian [34], M.J. Tibbetts [14], T. Tic [125], V.O. Tikhomirov [94], Y.A. Tikhonov [107,f], S. Timoshenko [96], P. Tipton [175], F.J. Tique Aires Viegas [29], S. Tisserant [83], B. Toczek [37], T. Todorov [4], S. Todorova-Nova [161], B. Toggerson [163], J. Tojo [66], S. Tokár [144a], K. Tokunaga [67], K. Tokushuku [66], K. Tollefson [88], M. Tomoto [101], L. Tompkins [30], K. Toms [103], G. Tong [32a], A. Tonoyan [13], C. Topfel [16], N.D. Topilin [65], I. Torchiani [29], E. Torrence [114], H. Torres [78], E. Torró Pastor [167], J. Toth [83,aa], F. 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S. Tsuno[66], D. Tsybychev[148], A. Tua[139], A. Tudorache[25a], V. Tudorache[25a], J.M. Tuggle[30], M. Turala[38], D. Turecek[127], I. Turk Cakir[3e], E. Turlay[105], R. Turra[89a,89b], P.M. Tuts[34], A. Tykhonov[74], M. Tylmad[146a,146b], M. Tyndel[129], G. Tzanakos[8], K. Uchida[20], I. Ueda[155], R. Ueno[28], M. Ugland[13], M. Uhlenbrock[20], M. Uhrmacher[54], F. Ukegawa[160], G. Unal[29], D.G. Underwood[5], A. Undrus[24], G. Unel[163], Y. Unno[66], D. Urbaniec[34], G. Usai[7], M. Uslenghi[119a,119b], L. Vacavant[83], V. Vacek[127], B. Vachon[85], S. Vahsen[14], J. Valenta[125], P. Valente[132a], S. Valentinetti[19a,19b], S. Valkar[126], E. Valladolid Gallego[167], S. Vallecorsa[152], J.A. Valls Ferrer[167], H. van der Graaf[105], E. van der Kraaij[105], R. Van Der Leeuw[105], E. van der Poel[105], D. van der Ster[29], N. van Eldik[84], P. van Gemmeren[5], Z. van Kesteren[105], I. van Vulpen[105], M. Vanadia[99], W. Vandelli[29], G. Vandoni[29], A. Vaniachine[5], P. Vankov[41], F. 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[1] University at Albany, Albany, NY, United States
[2] Department of Physics, University of Alberta, Edmonton, AB, Canada
[3] [(a)] Department of Physics, Ankara University, Ankara; [(b)] Department of Physics, Dumlupinar University, Kutahya; [(c)] Department of Physics, Gazi University, Ankara; [(d)] Division of Physics, TOBB University of Economics and Technology, Ankara; [(e)] Turkish Atomic Energy Authority, Ankara, Turkey
[4] LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
[5] High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States
[6] Department of Physics, University of Arizona, Tucson, AZ, United States
[7] Department of Physics, The University of Texas at Arlington, Arlington, TX, United States
[8] Physics Department, University of Athens, Athens, Greece
[9] Physics Department, National Technical University of Athens, Zografou, Greece
[10] Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[11] Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
[12] [(a)] Institute of Physics, University of Belgrade, Belgrade; [(b)] Vinca Institute of Nuclear Sciences, Belgrade, Serbia
[13] Department for Physics and Technology, University of Bergen, Bergen, Norway
[14] Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States
[15] Department of Physics, Humboldt University, Berlin, Germany
[16] Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
[17] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[18] [(a)] Department of Physics, Bogazici University, Istanbul; [(b)] Division of Physics, Dogus University, Istanbul; [(c)] Department of Physics Engineering, Gaziantep University, Gaziantep; [(d)] Department of Physics, Istanbul Technical University, Istanbul, Turkey
[19] [(a)] INFN Sezione di Bologna; [(b)] Dipartimento di Fisica, Università di Bologna, Bologna, Italy
[20] Physikalisches Institut, University of Bonn, Bonn, Germany
[21] Department of Physics, Boston University, Boston, MA, United States
[22] Department of Physics, Brandeis University, Waltham, MA, United States
[23] [(a)] Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; [(b)] Federal University of Juiz de Fora (UFJF), Juiz de Fora; [(c)] Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; [(d)] Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
[24] Physics Department, Brookhaven National Laboratory, Upton, NY, United States
[25] [(a)] National Institute of Physics and Nuclear Engineering, Bucharest; [(b)] University Politehnica Bucharest, Bucharest; [(c)] West University in Timisoara, Timisoara, Romania
[26] Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
[27] Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
[28] Department of Physics, Carleton University, Ottawa, ON, Canada
[29] CERN, Geneva, Switzerland
[30] Enrico Fermi Institute, University of Chicago, Chicago, IL, United States
[31] [(a)] Departamento de Fisica, Pontificia Universidad Católica de Chile, Santiago; [(b)] Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
[32] [(a)] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; [(b)] Department of Modern Physics, University of Science and Technology of China, Anhui; [(c)] Department of Physics, Nanjing University, Jiangsu; [(d)] School of Physics, Shandong University, Shandong, China
[33] Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France
[34] Nevis Laboratory, Columbia University, Irvington, NY, United States
[35] Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
[36] [(a)] INFN Gruppo Collegato di Cosenza; [(b)] Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
[37] AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
[38] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
[39] Physics Department, Southern Methodist University, Dallas, TX, United States
[40] Physics Department, University of Texas at Dallas, Richardson, TX, United States
[41] DESY, Hamburg and Zeuthen, Germany
[42] Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
[43] Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
[44] Department of Physics, Duke University, Durham, NC, United States
[45] SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[46] Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 3, 2700 Wiener Neustadt, Austria
[47] INFN Laboratori Nazionali di Frascati, Frascati, Italy
[48] Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
[49] Section de Physique, Université de Genève, Geneva, Switzerland
[50] [(a)] INFN Sezione di Genova; [(b)] Dipartimento di Fisica, Università di Genova, Genova, Italy
[51] [(a)] E.Andronikashvili Institute of Physics, Tbilisi State University, Tbilisi; [(b)] High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
[52] II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
[53] SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[54] II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
[55] Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
[56] Department of Physics, Hampton University, Hampton, VA, United States
[57] Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States
[58] [(a)] Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(b)] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(c)] ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
[59] Faculty of Science, Hiroshima University, Hiroshima, Japan
[60] Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
[61] Department of Physics, Indiana University, Bloomington, IN, United States
[62] Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
[63] University of Iowa, Iowa City, IA, United States
[64] Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
[65] Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
[66] KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
[67] Graduate School of Science, Kobe University, Kobe, Japan
[68] Faculty of Science, Kyoto University, Kyoto, Japan
[69] Kyoto University of Education, Kyoto, Japan
[70] Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
[71] Physics Department, Lancaster University, Lancaster, United Kingdom
[72] [(a)] INFN Sezione di Lecce; [(b)] Dipartimento di Fisica, Università del Salento, Lecce, Italy
[73] Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[74] Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia

[75] School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
[76] Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
[77] Department of Physics and Astronomy, University College London, London, United Kingdom
[78] Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
[79] Fysiska Institutionen, Lunds Universitet, Lund, Sweden
[80] Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
[81] Institut für Physik, Universität Mainz, Mainz, Germany
[82] School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[83] CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
[84] Department of Physics, University of Massachusetts, Amherst, MA, United States
[85] Department of Physics, McGill University, Montreal, QC, Canada
[86] School of Physics, University of Melbourne, Victoria, Australia
[87] Department of Physics, The University of Michigan, Ann Arbor, MI, United States
[88] Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States
[89] [(a)] INFN Sezione di Milano; [(b)] Dipartimento di Fisica, Università di Milano, Milano, Italy
[90] B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
[91] National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
[92] Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, United States
[93] Group of Particle Physics, University of Montreal, Montreal, QC, Canada
[94] P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
[95] Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
[96] Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
[97] Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
[98] Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
[99] Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
[100] Nagasaki Institute of Applied Science, Nagasaki, Japan
[101] Graduate School of Science, Nagoya University, Nagoya, Japan
[102] [(a)] INFN Sezione di Napoli; [(b)] Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
[103] Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States
[104] Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
[105] Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
[106] Department of Physics, Northern Illinois University, DeKalb, IL, United States
[107] Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
[108] Department of Physics, New York University, New York, NY, United States
[109] Ohio State University, Columbus, OH, United States
[110] Faculty of Science, Okayama University, Okayama, Japan
[111] Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States
[112] Department of Physics, Oklahoma State University, Stillwater, OK, United States
[113] Palacký University, RCPTM, Olomouc, Czech Republic
[114] Center for High Energy Physics, University of Oregon, Eugene, OR, United States
[115] LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France
[116] Graduate School of Science, Osaka University, Osaka, Japan
[117] Department of Physics, University of Oslo, Oslo, Norway
[118] Department of Physics, Oxford University, Oxford, United Kingdom
[119] [(a)] INFN Sezione di Pavia; [(b)] Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[120] Department of Physics, University of Pennsylvania, Philadelphia, PA, United States
[121] Petersburg Nuclear Physics Institute, Gatchina, Russia
[122] [(a)] INFN Sezione di Pisa; [(b)] Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
[123] Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
[124] [(a)] Laboratorio de Instrumentacao e Fisica Experimental de Particulas – LIP, Lisboa, Portugal; [(b)] Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
[125] Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
[126] Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
[127] Czech Technical University in Prague, Praha, Czech Republic
[128] State Research Center Institute for High Energy Physics, Protvino, Russia
[129] Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[130] Physics Department, University of Regina, Regina, SK, Canada
[131] Ritsumeikan University, Kusatsu, Shiga, Japan
[132] [(a)] INFN Sezione di Roma I; [(b)] Dipartimento di Fisica, Università La Sapienza, Roma, Italy
[133] [(a)] INFN Sezione di Roma Tor Vergata; [(b)] Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
[134] [(a)] INFN Sezione di Roma Tre; [(b)] Dipartimento di Fisica, Università Roma Tre, Roma, Italy
[135] [(a)] Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; [(b)] Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; [(c)] Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; [(d)] Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; [(e)] Faculté des Sciences, Université Mohammed V-Agdal, Rabat, Morocco
[136] DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France
[137] Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States
[138] Department of Physics, University of Washington, Seattle, WA, United States
[139] Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[140] Department of Physics, Shinshu University, Nagano, Japan
[141] Fachbereich Physik, Universität Siegen, Siegen, Germany
[142] Department of Physics, Simon Fraser University, Burnaby, BC, Canada
[143] SLAC National Accelerator Laboratory, Stanford, CA, United States
[144] [(a)] Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; [(b)] Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
[145] [(a)] Department of Physics, University of Johannesburg, Johannesburg; [(b)] School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[146] [(a)] Department of Physics, Stockholm University; [(b)] The Oskar Klein Centre, Stockholm, Sweden
[147] Physics Department, Royal Institute of Technology, Stockholm, Sweden
[148] Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, United States
[149] Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom

[150] School of Physics, University of Sydney, Sydney, Australia
[151] Institute of Physics, Academia Sinica, Taipei, Taiwan
[152] Department of Physics, Technion: Israel Inst. of Technology, Haifa, Israel
[153] Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
[154] Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
[155] International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
[156] Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
[157] Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
[158] Department of Physics, University of Toronto, Toronto, ON, Canada
[159] [(a)] TRIUMF, Vancouver, BC; [(b)] Department of Physics and Astronomy, York University, Toronto, ON, Canada
[160] Institute of Pure and Applied Sciences, University of Tsukuba, 1-1-1 Tennodai,Tsukuba, Ibaraki 305-8571, Japan
[161] Science and Technology Center, Tufts University, Medford, MA, United States
[162] Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
[163] Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
[164] [(a)] INFN Gruppo Collegato di Udine; [(b)] ICTP, Trieste; [(c)] Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
[165] Department of Physics, University of Illinois, Urbana, IL, United States
[166] Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
[167] Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
[168] Department of Physics, University of British Columbia, Vancouver, BC, Canada
[169] Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
[170] Waseda University, Tokyo, Japan
[171] Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
[172] Department of Physics, University of Wisconsin, Madison, WI, United States
[173] Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
[174] Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
[175] Department of Physics, Yale University, New Haven, CT, United States
[176] Yerevan Physics Institute, Yerevan, Armenia
[177] Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

[a] Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas – LIP, Lisboa, Portugal.
[b] Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
[c] Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
[d] Also at TRIUMF, Vancouver, BC, Canada.
[e] Also at Department of Physics, California State University, Fresno, CA, United States.
[f] Also at Novosibirsk State University, Novosibirsk, Russia.
[g] Also at Fermilab, Batavia, IL, United States.
[h] Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
[i] Also at Università di Napoli Parthenope, Napoli, Italy.
[j] Also at Institute of Particle Physics (IPP), Canada.
[k] Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
[l] Also at Louisiana Tech University, Ruston, LA, United States.
[m] Also at Department of Physics and Astronomy, University College London, London, United Kingdom.
[n] Also at Group of Particle Physics, University of Montreal, Montreal, QC, Canada.
[o] Also at Department of Physics, University of Cape Town, Cape Town, South Africa.
[p] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[q] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
[r] Also at Manhattan College, New York, NY, United States.
[s] Also at School of Physics, Shandong University, Shandong, China.
[t] Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
[u] Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
[v] Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
[w] Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France.
[x] Also at Section de Physique, Université de Genève, Geneva, Switzerland.
[y] Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.
[z] Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.
[aa] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
[ab] Also at California Institute of Technology, Pasadena, CA, United States.
[ac] Also at Institute of Physics, Jagiellonian University, Krakow, Poland.
[ad] Also at Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China.
[ae] Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
[af] Also at Department of Physics, Oxford University, Oxford, United Kingdom.
[ag] Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
[ah] Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.
[ai] Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
* Deceased.