

# Search for pair-produced heavy quarks decaying to $Wq$ in the two-lepton channel at $\sqrt{s} = 7$ TeV with the ATLAS detector

The ATLAS Collaboration

A search is presented for heavy-quark pair production ( $Q\bar{Q}$ ) under the decay hypothesis  $Q\bar{Q} \rightarrow W^+qW^-\bar{q}$  with  $q = d, s, b$  for up-type  $Q$  or  $q = u, c$  for down-type  $Q$ . The search is performed with  $1.04 \text{ fb}^{-1}$  of integrated luminosity from  $pp$  collisions at  $\sqrt{s} = 7$  TeV collected by the ATLAS detector at the CERN LHC. Dilepton final states are selected, requiring large missing transverse momentum and at least two jets. Mass reconstruction of heavy quark candidates is performed by assuming that the  $W$  boson decay products are nearly collinear. The data are in agreement with Standard Model expectations; a heavy quark with mass less than 350 GeV is excluded at 95% confidence level.

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The addition of one or more heavy quarks is a natural extension to the Standard Model, capable of providing an additional source of CP violation in  $B_s$  decays and accommodating a heavy Higgs boson [1, 2]. Searches for heavy quarks with the Collider Detector at Fermilab (CDF) constrain the mass of heavy quarks ( $Q$ ) that decay as  $Q \rightarrow Wq$ , where  $q = d, s, b$  for up-type  $Q$  or  $q = u, c$  for down-type  $Q$ , to be  $m_Q > 340$  GeV [3]. More specific searches have also constrained the mass of up-type heavy quarks ( $t'$ ) that decay as  $t' \rightarrow Wb$  to be  $m_{t'} > 358$  GeV [3] and the mass of down-type heavy quarks ( $b'$ ) decaying via  $b' \rightarrow Wt$  to be  $m_{b'} > 372$  GeV [4]. The D0 experiment at Fermilab has set a mass limit of  $m_Q > 285$  GeV [5] on heavy quarks that decay as  $Q \rightarrow Wq$ . All previous searches used the “lepton+jets” channel, where only one of the produced  $W$  bosons decays hadronically.

In this Article, a search is presented for pair production of a heavy quark ( $Q\bar{Q}$ ) in data corresponding to an integrated luminosity of  $1.04 \text{ fb}^{-1}$  from proton-proton collisions at  $\sqrt{s} = 7$  TeV collected by the ATLAS experiment. The heavy quark is assumed to decay via  $Q \rightarrow Wq$  where  $q = d, s, b$  for up-type  $Q$  or  $q = u, c$  for down-type  $Q$ . This search does not include states with  $q = t$ , i.e.  $d' \rightarrow Wt$  decays are assumed not to happen. The search is performed in the dilepton channel, where both  $W$  bosons decay leptonically. Fourth-generation up-type quarks ( $t'$ ) decaying through weak charged currents ( $t' \rightarrow Wb$ ,  $t' \rightarrow Ws$ , and  $t' \rightarrow Wd$ ) are used as a benchmark.

Three complementary searches for fourth-generation quarks were performed with the ATLAS detector using  $1.04 \text{ fb}^{-1}$  of 2011 data. These searches all implement  $b$ -quark identification algorithms and are thus targeted towards more specific heavy quark decay modes. The channels considered are  $t'\bar{t}' \rightarrow W^+W^-b\bar{b}$  in the lepton plus jets channel (setting a limit  $m_{t'} > 404$  GeV [6]),  $b'\bar{b}' \rightarrow W^+W^-t\bar{t} \rightarrow W^+W^-W^+W^-b\bar{b}$  in the lepton plus jets channel ( $m_{b'} > 480$  GeV [7]), and  $b'\bar{b}' \rightarrow W^+W^-t\bar{t} \rightarrow W^+W^-W^+W^-b\bar{b}$  with two same sign leptons in the final state ( $m_{b'} > 450$  GeV [8]).

The dileptonic final state arises in a way similar to that

of pair-produced top quarks:  $Q\bar{Q} \rightarrow \ell^+\nu q\ell^-\bar{\nu}\bar{q}$ , where  $\ell$  is either  $e$  or  $\mu$ . Leptonically-decaying intermediary  $\tau$  leptons are able to contribute to this final state if additional neutrinos are considered. The signature is at least two jets, two oppositely charged leptons, and missing transverse momentum ( $E_{\text{T}}^{\text{miss}}$ ) from undetected neutrinos. Top quark pair production is the dominant source of background. To distinguish a potential heavy-quark signal, heavy-quark mass reconstruction is performed by taking advantage of the larger boost each  $W$  boson receives from the decay of a heavy quark compared to the decay of a top quark. This large boost makes each undetected neutrino approximately collinear with an observed charged lepton.

The following sections contain descriptions of the ATLAS detector (Section I), simulated samples (Section II), object reconstruction (Section III), baseline event selection (Section IV), data-driven background estimates (Section V), mass reconstruction strategy (Section VI), validation of background modeling (Section VII), final event selection (Section VIII), binned maximum-likelihood ratio fit using the reconstructed mass (Section IX and Section X), and final results (Section XI).

## I. THE ATLAS DETECTOR

The ATLAS detector [9] is a multi-purpose particle detector with precision trackers, calorimeters and muon spectrometers. The momenta of charged particles with pseudorapidity  $|\eta| < 2.5^1$  are measured by the inner detector (ID), which is a combination of silicon pixels, sili-

<sup>1</sup> 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 Large Hadron Collider (LHC) ring and the  $y$ -axis points upward. Cylindrical coordinates ( $r, \phi$ ) are used in the transverse plane,  $\phi$  being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ .

con microstrips and a straw-tube tracker. The ID operates in a uniform 2 T axial magnetic field produced by a superconducting solenoid. The pixel detector measurements enable precise determination of production vertices.

Electromagnetic (EM) calorimetry for electron and photon reconstruction is provided by a high-granularity, three layer liquid argon (LAr) sampling calorimeter with lead absorbers in the region  $|\eta| < 3.2$ . A presampler is used to correct for energy lost by electrons and photons in material in front of the calorimeter for  $|\eta| < 1.8$ . Hadronic calorimetry for  $|\eta| < 1.7$  is provided by a scintillating tile sampling calorimeter with steel absorbers, and for  $1.5 < |\eta| < 3.2$  it is provided by a LAr sampling calorimeter with copper-plate absorbers.

Muons are detected with a multi-system muon spectrometer (MS). Precision measurements in the  $\eta$  coordinate are provided by monitored drift tubes for  $|\eta| < 2.7$ . These are supplemented by cathode-strip chambers measuring both the  $\eta$  and azimuth ( $\phi$ ) coordinates for  $2.0 < |\eta| < 2.7$ . Fast measurements required for initiating trigger logic are provided by resistive-plate chambers for  $|\eta| < 1.05$  and then by thin-gap chambers for  $1.05 < |\eta| < 2.4$ . The muon detectors operate in a non-uniform toroidal magnetic field generated by a superconducting air-core magnet system.

The ATLAS detector uses a three-level trigger system to select events for offline analysis. For this search, events are required to have at least one lepton satisfying trigger requirements. Electron trigger candidates must have transverse energy  $E_T > 20$  GeV, must satisfy shower-shape requirements [10] and must have an ID track matched to the EM shower. Muon trigger candidates must have transverse momentum  $p_T > 18$  GeV and matching tracks in the ID and MS.

## II. SIMULATED SIGNAL AND BACKGROUND SAMPLES

Simulated samples are used to evaluate the contributions from the  $Q\bar{Q}$  signal (assuming an up-type heavy quark) and most background processes. Unless otherwise noted, all events are showered and hadronized with HERWIG v6.5 [11, 12], using JIMMY [13] for the underlying event model. After event generation, all samples are processed with the GEANT4-based [14] simulation of the ATLAS detector [15] and subject to the same reconstruction algorithms as the data.

The CERN LHC instantaneous luminosity varied during data-taking from about  $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$  to  $1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$  [16, 17]. At maximum luminosity numerous proton-proton ( $pp$ ) interactions were superimposed in each bunch crossing. This pileup background produces additional activity in the detector, affecting variables such as jet reconstruction and isolation energies. Monte Carlo (MC) events simulate the pileup background by adding minimum bias events on top of the

hard scatter. The MC events are later reweighted such that the simulated instantaneous luminosity distribution matches that in data.

### A. Heavy-quark pair production

Production and decay of heavy-quark pairs ( $Q\bar{Q}$ ) is modeled with the leading-order (LO) generator PYTHIA 6.421 [18] using MRST 2007 LO\* [19] parton distribution functions (PDFs). The production cross-section is calculated using HATHOR [20] with approximate next-to-next-to-leading-order (NNLO) QCD calculations with CTEQ6.6 PDFs [21] for several heavy-quark masses ( $m_Q$ ). In addition, scale uncertainties are evaluated in the range  $m_Q/2$  to  $2 \times m_Q$  and PDF uncertainties are calculated from the CTEQ6.6 error eigenvectors. The cross-sections and uncertainties for each heavy-quark mass considered in this analysis are shown in Table I. Samples are generated with either  $t' \rightarrow Wb$ ,  $t' \rightarrow Ws$ , or  $t' \rightarrow Wd$  final states; final results are verified with all three decay modes.

TABLE I. NNLO cross-sections, scale uncertainties and PDF uncertainties calculated using HATHOR for  $Q\bar{Q}$  production in  $\sqrt{s} = 7$  TeV  $pp$  collisions with CTEQ6.6 PDFs for different heavy-quark mass assumptions. Other uncertainties related to the cross-sections are neglected. The  $1\sigma$  uncertainties are each represented by  $\Delta$ .

$m_Q$ (GeV)	$\sigma_{Q\bar{Q}}$ (pb)	Scale $\Delta$ (pb)	PDF $\Delta$ (pb)
300	8.0	+0.2	+1.0
		-0.5	-0.8
350	3.2	+0.1	+0.4
		-0.2	-0.4
400	1.4	+0.1	+0.2
		-0.1	-0.2
450	0.68	+0.02	+0.11
		-0.04	-0.09
500	0.34	+0.01	+0.06
		-0.02	-0.04

### B. Top quark pair production

The background due to  $t\bar{t}$  production is modeled using the next-to-leading-order (NLO) generator MC@NLO v3.41 [22] with an assumed top quark mass of 172.5 GeV and the NLO PDF set CTEQ6.6. The cross-section for  $t\bar{t}$  production is normalized to the value obtained from an approximate NNLO calculation [20].

### C. Z boson, diboson and single-top quark production

The background from  $Z/\gamma^*$  boson production in association with jets is modeled with the LO generator ALPGEN v2.13 [23]. The LO PDF set CTEQ6.1 [21] is used to generate  $Z/\gamma^*$ +jets events with dilepton invariant mass  $m_{\ell\ell} > 10$  GeV. For  $WW$ ,  $WZ$  and  $ZZ$  production, events are generated with the LO generator HERWIG v6.5 and the LO PDF set CTEQ6.1. For the small background from single-top production, MC@NLO is used with the NLO PDF set CTEQ6.6, invoking the diagram removal scheme [24, 25] to remove overlaps between the single-top and  $t\bar{t}$  final states. The cross-sections for  $Z/\gamma^*$ +jets samples are determined using NNLO inclusive calculations from FEWZ [26, 27] and from a data-driven technique where possible, while the cross-sections for diboson samples are determined using NLO calculations with MC@NLO. The cross-sections for single-top samples are normalized to an approximate NNLO prediction [28, 29].

### III. OBJECT SELECTION

Electrons are found by a calorimeter-seeded reconstruction algorithm and must have a track that matches an energy deposit in the calorimeter. They are required to satisfy  $E_{\text{cluster}}/\cosh(\eta_{\text{track}}) > 25$  GeV, where  $E_{\text{cluster}}$  is the energy deposited in the calorimeter cluster and  $\eta_{\text{track}}$  is the pseudorapidity of the matching track. Electrons are required to be in a pseudorapidity range  $|\eta_{\text{cluster}}| < 2.47$ , excluding the transition region  $1.37 < |\eta_{\text{cluster}}| < 1.52$  between the EM calorimeter barrel and endcap. They must also satisfy a calorimeter isolation  $I_{\text{cal}} < 3.5$  GeV requirement in  $\Delta R < 0.2$ , where  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ . Calorimeter isolation is defined as the energy reconstructed within a cone of a certain radius around the lepton that is not associated with that lepton, and it is represented by  $I_{\text{cal}}$ . The calorimeter shower shape is required to closely resemble what is expected for electrons [10].

Jets are reconstructed from topological clusters of energy deposits in the calorimeter [30] using the anti- $k_t$  algorithm with distance parameter  $R = 0.4$  [31, 32]. These jets are calibrated to the hadronic energy scale using a correction factor obtained from simulation which depends on  $p_T$  and  $\eta$  [33]. They are required to satisfy  $p_T > 25$  GeV and  $|\eta| < 2.5$ . Jets that fall within  $\Delta R < 0.2$  of accepted electrons are rejected.

Muons are found by requiring that a track reconstructed in the MS has a matching track in the ID. A loose cosmic ray rejection is applied by removing all muon pairs that are back-to-back azimuthally ( $\Delta\phi(\mu, \mu') > 3.1$ ) and whose transverse impact parameter with respect to the beam line is greater than 0.5 mm. Muon candidates must satisfy  $p_T > 20$  GeV and  $|\eta| < 2.5$ . The muon must be isolated, satisfying calorimeter isolation  $I_{\text{cal}} < 4$  GeV in  $\Delta R < 0.3$  and tracking isolation

$I_{\text{trk}} < 4$  GeV in  $\Delta R < 0.3$ . Tracking isolation is defined as the sum of track momenta within a cone of a certain radius around the lepton vertex, and it is represented by  $I_{\text{trk}}$ . The muon must also not fall within  $\Delta R < 0.4$  of any jet with  $p_T > 20$  GeV.

The  $E_T^{\text{miss}}$  is constructed from the vector sum of calorimeter topological cluster energies projected onto the transverse plane [34]. Calorimeter deposits not associated to a jet are calibrated at the EM energy scale. Deposits associated with selected jets contribute at the corrected hadronic energy scale. Muon transverse momenta are included after correcting for muon energy losses in the calorimeters.

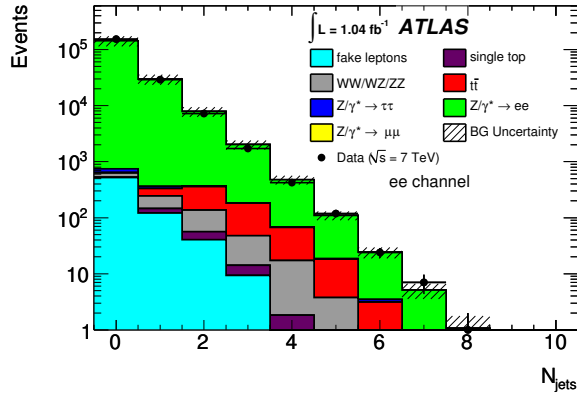
### IV. BASELINE EVENT SELECTION

The  $Q\bar{Q}$  pair decay yields two charged leptons, two jets and  $E_T^{\text{miss}}$  from the undetected neutrinos. An initial dilepton selection is applied to validate the modeling of the  $Z/\gamma^*$  boson production background as well as the identification of leptons, reconstruction of jets and measurement of  $E_T^{\text{miss}}$ .

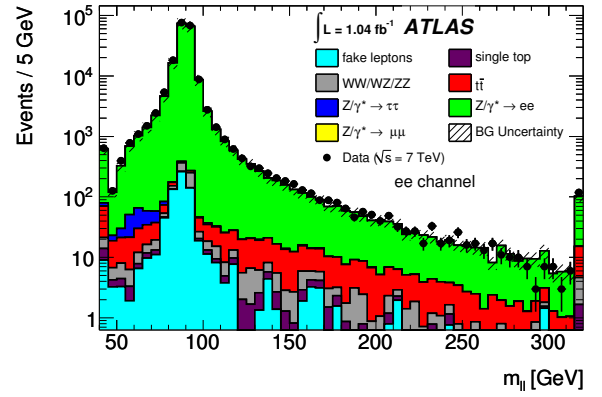
The initial dilepton selection [35, 36] first requires that an event contains a high-quality reconstructed primary vertex. The event must also have exactly two leptons ( $e$  or  $\mu$ ) with opposite charges, at least one of which must be associated with the object that triggered the event. The two leptons must not share a track in the ID. At this stage, the data sample is dominated by  $Z/\gamma^* \rightarrow \ell\ell$  decays (the Drell-Yan process), although the contribution from  $t\bar{t}$  production is evident at large jet multiplicity, as can be seen in Figures 1 and 2. These figures show good agreement between the data and background expectation.

To reduce the background from  $Z/\gamma^* \rightarrow \ell\ell$  decays, the baseline selection requires:

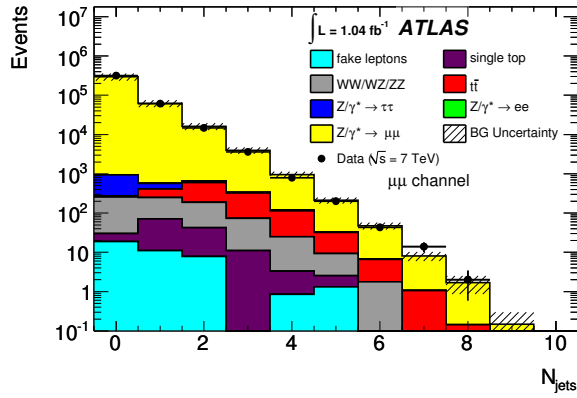
- All events must have at least two jets, each with  $p_T > 25$  GeV and  $|\eta| < 2.5$ ;
- Same-flavor events ( $ee$  and  $\mu\mu$ ) must satisfy a missing transverse momentum requirement,  $E_T^{\text{miss}} > 60$  GeV;
- The dilepton invariant mass of same-flavor events ( $ee$  and  $\mu\mu$ ) must be greater than 15 GeV and must fall outside a window around the  $Z$  boson mass, defined as  $81 \text{ GeV} < m_{\ell\ell} < 101 \text{ GeV}$ ;
- In different-flavor events ( $e\mu$ ),  $H_T$ , defined as the scalar sum of  $E_T$  from every lepton and jet passing the object selection criteria, must exceed 130 GeV. The  $H_T$  requirement reduces the  $Z/\gamma^* \rightarrow \tau\tau$  background, where a  $E_T^{\text{miss}}$  requirement is insufficient due to the presence of neutrinos.



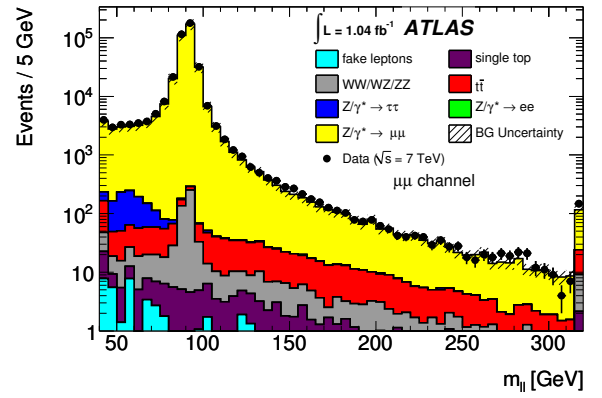
(a)



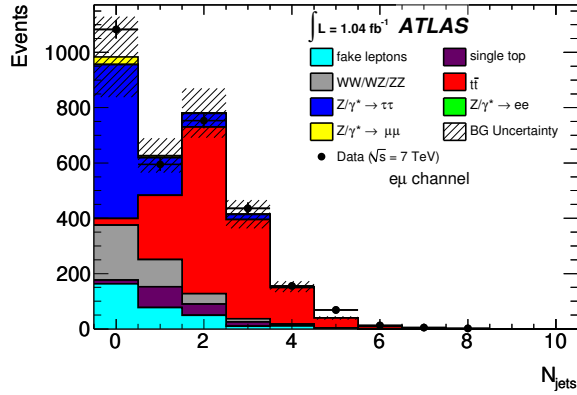
(a)



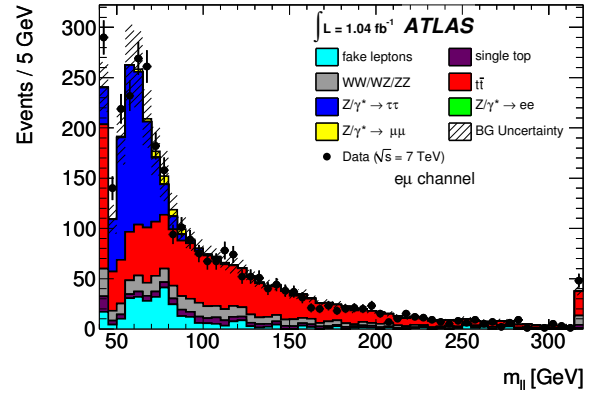
(b)



(b)



(c)



(c)

FIG. 1. Jet multiplicity after initial dilepton selection in (a)  $ee$ , (b)  $\mu\mu$ , and (c)  $e\mu$  channels. The shaded region indicates the magnitude of cross-section and luminosity uncertainties. Samples are stacked in the same order as they are presented in the legend, from left to right; the first entry in the legend is at the bottom of the stack. The data-driven Drell-Yan estimate defined in Section V A has not been applied here.

FIG. 2. Dilepton mass after initial dilepton selection in (a)  $ee$ , (b)  $\mu\mu$ , and (c)  $e\mu$  channels. The shaded region indicates the magnitude of cross-section and luminosity uncertainties. The last bin contains overflow events, and the first bin contains underflow events. Samples are stacked in the same order as they are presented in the legend, from left to right; the first entry in the legend is at the bottom of the stack. The data-driven Drell-Yan estimate defined in Section V A has not been applied here.

## V. DATA-DRIVEN ESTIMATES

### A. Drell-Yan events

The total number of Drell-Yan  $ee$  and  $\mu\mu$  events remaining after the baseline selection has been applied is estimated with a data-driven technique that extrapolates from a control region (CR) [37]. Events in the CR have dilepton invariant mass in the range 81 GeV – 101 GeV with at least two jets and  $E_T^{\text{miss}} > 30$  GeV. The number of data events in the control region, Data(CR), and MC  $Z/\gamma^*$ +jets events in the control region, MC<sub>DY</sub>(CR), are used to scale the prediction of  $Z/\gamma^*$ +jets events in the signal region, MC<sub>DY</sub>. Non- $Z/\gamma^*$  background processes in the control region, MC<sub>other</sub>(CR), are subtracted from the data using MC predictions. The estimated number of  $Z/\gamma^*$ +jets events in the signal region,  $N_{\text{DY}}$ , in the  $ee$  and  $\mu\mu$  channels is calculated with Equation 1:

$$N_{\text{DY}} = \frac{\text{Data}(\text{CR}) - \text{MC}_{\text{other}}(\text{CR})}{\text{MC}_{\text{DY}}(\text{CR})} \times \text{MC}_{\text{DY}}. \quad (1)$$

### B. Fake lepton events

A small fraction of the background consists of events in which a jet or a non-prompt lepton is misidentified as a prompt lepton from  $W$  boson decay. Prompt leptons and misidentified non-prompt leptons are referred to as real and fake leptons, respectively. Fake muons are predominantly produced from semi-leptonic  $b$  or  $c$  quark decays in which the muon passes the isolation requirements despite being produced in association with a jet. There are three principal mechanisms for producing fake electrons: heavy-flavor decay, light flavor jets with a leading  $\pi^0$  overlapping with a reconstructed track from a charged particle, and asymmetric conversion of photons into  $e^+e^-$ . The largest source of events with fake leptons is  $W$  boson production with associated jets, including lepton plus jets decays of top quark pairs.

A matrix method [36] is used to estimate the fraction of the sample that comes from fake lepton events. A looser lepton selection is defined, and the number of observed dilepton events with two tight leptons ( $N_{\text{TT}}$ ), one loose and one tight lepton ( $N_{\text{TL}}$ ,  $N_{\text{LT}}$ ) or two loose leptons ( $N_{\text{LL}}$ ) is counted. The leptons are ordered by  $p_T$  such that the leading lepton in  $N_{\text{TL}}$  is tight and the leading lepton in  $N_{\text{LT}}$  is loose. Tight leptons pass the selection criteria defined in Section III. Loose electrons need to pass the same selections as the electrons defined in Section III except for looser shower shape and calorimeter isolation requirements [10]. Loose muons only need to satisfy  $p_T > 20$  GeV,  $|\eta| < 2.5$  and the muon-jet overlap requirements defined in Section III.

The probabilities for real and fake leptons that pass the loose identification criteria to also pass the tight criteria are defined as  $r_\ell$  and  $f_\ell$ , respectively. These two probab-

ilities are measured separately for  $\ell = e$  and  $\ell = \mu$ . Using  $r_\ell$  and  $f_\ell$ , linear expressions are obtained for the observed yields as a function of the number of events with zero, one and two real leptons together with two, one and zero fake leptons ( $N_{\text{FF}}$ ,  $N_{\text{RF}}$  and  $N_{\text{FR}}$ ,  $N_{\text{RR}}$ ; in  $N_{\text{RF}}$  the real lepton has greater  $p_T$  than the fake lepton, and vice versa for  $N_{\text{FR}}$ ):

$$\begin{bmatrix} N_{\text{TT}} \\ N_{\text{TL}} \\ N_{\text{LT}} \\ N_{\text{LL}} \end{bmatrix} = M \begin{bmatrix} N_{\text{RR}} \\ N_{\text{RF}} \\ N_{\text{FR}} \\ N_{\text{FF}} \end{bmatrix}, \quad (2)$$

where  $M$  is a  $4 \times 4$  matrix containing terms proportional to  $r_\ell$  and  $f_\ell$ . The matrix is inverted in order to extract the real and fake content of the observed dilepton event sample. The method explicitly accounts for the presence of events with two fake leptons.

The probability ( $r_\ell$ ) for a real loose lepton to pass the tight criteria is measured in  $Z \rightarrow \ell\ell$  events in data with a tag-and-probe method. The probability for a fake loose electron to satisfy the tight requirements ( $f_e$ ) is measured by requiring exactly one loose electron in an event with  $E_T^{\text{miss}} < 10$  GeV. The probability for a fake loose muon to satisfy the tight requirements ( $f_\mu$ ) is measured in a control region obtained by requiring exactly one loose muon with  $|\Delta\phi(\mu, E_T^{\text{miss}})| < 0.5$ . The baseline selection requirements from Section IV are not applied when checking these control regions.

## VI. MASS RECONSTRUCTION

After the baseline selection has been applied, mass reconstruction of heavy quark candidates is performed in order to discriminate the heavy-quark decays from the dominant  $t\bar{t}$  background. Direct reconstruction is not possible, as two neutrinos escape the detector. However, a unique feature of the heavy quark is the large momentum of the daughter  $W$  boson, which makes its decay products approximately collinear in the detector as seen in Figure 3.

Both neutrino momentum vectors are reconstructed by assuming that the neutrinos are the sole contributors to  $E_T^{\text{miss}}$  and that they are approximately collinear with the leptons. The optimal values of each  $|\Delta\eta(\nu, \ell)|$  and each  $|\Delta\phi(\nu, \ell)|$  are fit by minimizing the mass difference between the two reconstructed heavy quarks using MINUIT [38]. The fitted direction of each neutrino is constrained to be within  $\Delta R < 2.5$  of the direction taken by the neutrino's leptonic partner from the  $W$  boson decay, and all jet combinations are considered during each step of the mass difference minimization. A solution of the minimization procedure is penalized if the scalar sum of neutrino momenta exceeds the scalar sum of lepton momenta by at least 30%. The square of the difference between each reconstructed  $W$  boson mass and 80.4 GeV is



added to the square of the heavy-quark mass difference in the minimized function; the preferred solutions produce  $W$  bosons with reconstructed masses that are close to the  $W$  boson mass. The full minimization function is:  $f_{\min} = (m_{Q_1} - m_{Q_2})^2 + (m_{W_1} - (80.4 \text{ GeV}))^2 + (m_{W_2} - (80.4 \text{ GeV}))^2$ .

The two reconstructed mass values tend to be more correlated for signal than background, as shown in Figure 4. This is because the collinear approximation does not work well for single-top, diboson, Drell-Yan, and fake lepton events. An event is only kept if the two values of reconstructed mass are within 25 GeV of each other. The selection efficiency for this requirement is greater than 99% for each signal, 95% for  $t\bar{t}$ , and only 75% – 90% for other backgrounds.

The final reconstructed mass ( $m_{\text{Collinear}}$ ) is taken to be the average of the two reconstructed masses in the event. Distributions of  $m_{\text{Collinear}}$  for various simulated  $Q\bar{Q}$  samples and the  $t\bar{t}$  background are shown in Figure 5.

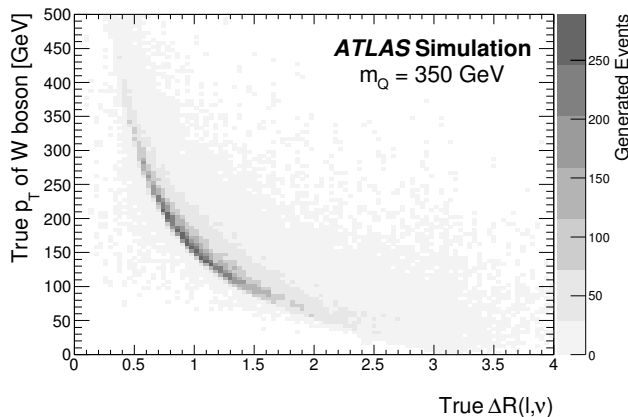


FIG. 3. True  $p_T$  of parent  $W$  boson versus true  $\Delta R$  between its daughter lepton and neutrino. The scale, shown on the right, indicates the number of generated MC events.

The expected background yields and number of observed events after the baseline selection are given in Table II. Distributions of  $H_T$  and  $m_{\text{Collinear}}$  are shown in Figure 6.

## VII. BACKGROUND VALIDATION

Event samples with the baseline selection and low  $H_T$ , low lepton  $p_T$ , low jet  $p_T$  or low  $E_T^{\text{miss}}$  are examined to validate the modeling of the background (Figure 7). These conditions cause the distributions to be depleted of signal. In each case, the data is described well by the background model, within uncertainties.

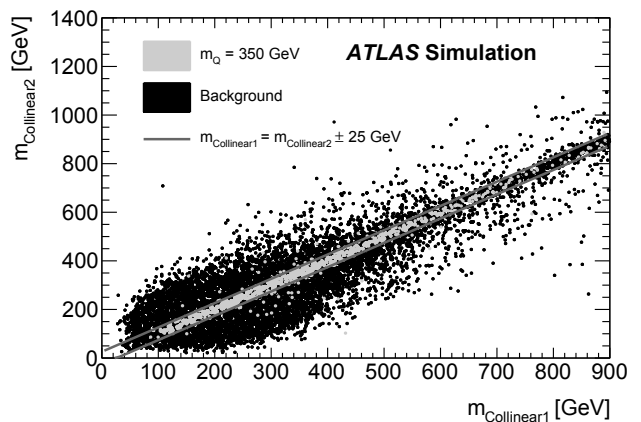


FIG. 4. Correlation between reconstructed masses for  $Q\bar{Q}$  pairs produced with  $m_Q = 350 \text{ GeV}$  and for background samples. The fitting method selects solutions with correlated mass values, however this correlation is smaller for background events. Events within  $|m_{\text{Collinear}_1} - m_{\text{Collinear}_2}| < 25 \text{ GeV}$  are kept; this region is found between the two lines in the figure.

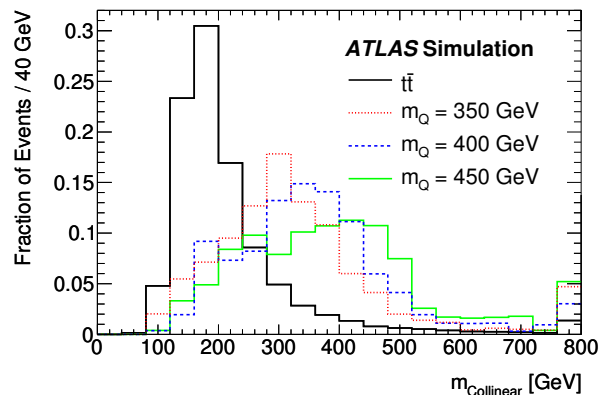
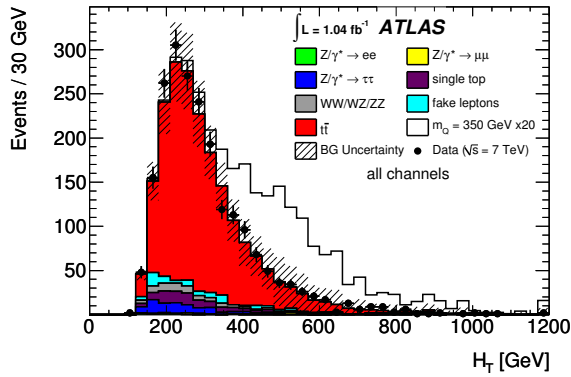


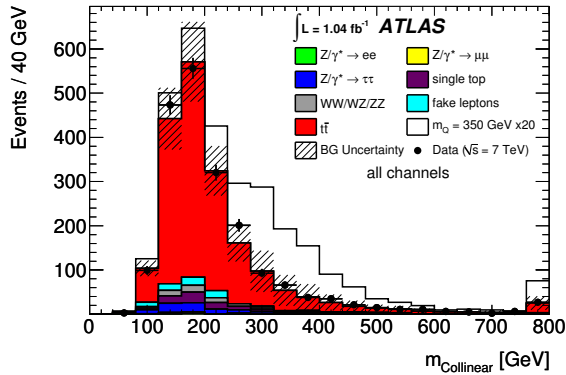
FIG. 5.  $m_{\text{Collinear}}$  for simulated heavy-quark pairs produced with masses of 350 GeV, 400 GeV and 450 GeV and for top quark pairs. Each histogram is normalized to unit area. The distributions have long tails that are produced by wrong jet assignment in events where at least one of the correct jets fails selection requirements.

## VIII. FINAL EVENT SELECTION

The baseline selection provides excellent discrimination against  $Z/\gamma^*$  production and other backgrounds, but additional selection requirements are necessary to suppress the dominant  $t\bar{t}$  background. A triangular selection in  $H_T + E_T^{\text{miss}}$  versus  $m_{\text{Collinear}}$ ,  $H_T + E_T^{\text{miss}} > X - 0.4 \times m_{\text{Collinear}}$  with  $X$  dependent on the assumed signal mass, is applied. Mass-dependent requirements on  $E_T^{\text{miss}}$  and leading jet  $p_T$  are imposed as well. These selection requirements are optimized in MC simulation by seeking a point of maximum significance,  $S/\sqrt{S+B}$ , while simultaneously varying all of



(a)

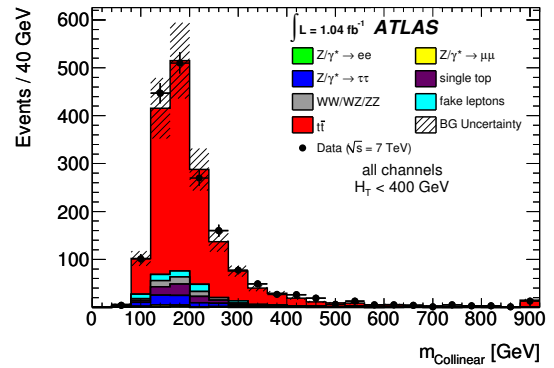


(b)

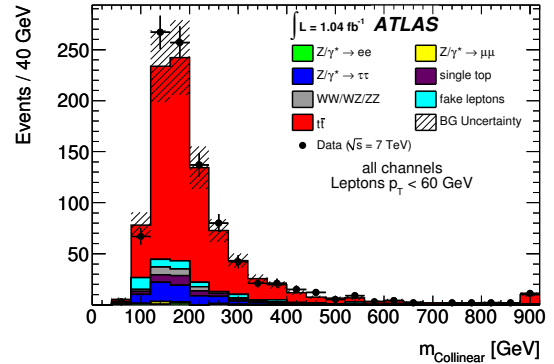
FIG. 6. Expected and observed distributions of (a)  $H_T$  and (b)  $m_{\text{Collinear}}$  for the sum of  $ee$ ,  $\mu\mu$  and  $e\mu$  channels after the baseline selection. The last bin contains overflow events. Samples are stacked in the same order as they are presented in the legend, from left to right; the first entry in the legend is at the bottom of the stack. The signal has been amplified to 20 times the expected rate.

TABLE II. Expected and observed number of events after baseline selection. Uncertainties shown are statistical and systematic, added in quadrature.

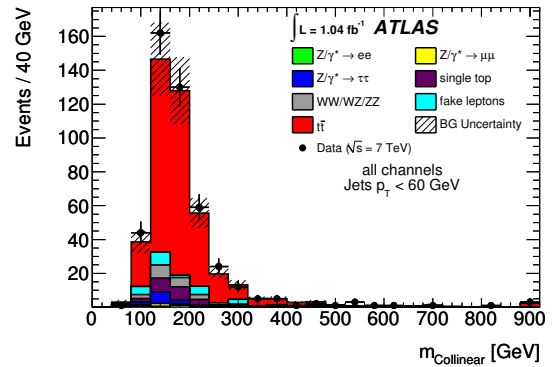
Process	$ee$	$e\mu$	$\mu\mu$
$t\bar{t}$	190 $^{+40}_{-30}$	1140 $^{+250}_{-200}$	370 $^{+80}_{-70}$
single-top	9.4 $^{+2.2}_{-1.9}$	60 $^{+14}_{-11}$	24 $^{+5}_{-5}$
$Z/\gamma^* \rightarrow ee$	6.3 $^{+2.0}_{-1.9}$	0.0 $^{+0.1}_{-0.0}$	0.0 $^{+0.1}_{-0.0}$
$Z/\gamma^* \rightarrow \mu\mu$	0.0 $^{+0.1}_{-0.0}$	2.2 $^{+1.1}_{-1.1}$	17 $^{+5}_{-4}$
$Z/\gamma^* \rightarrow \tau\tau$	7.3 $^{+2.4}_{-2.2}$	62 $^{+15}_{-12}$	16 $^{+4}_{-4}$
$WW, WZ, ZZ$	8.7 $^{+2.2}_{-1.9}$	49 $^{+11}_{-10}$	12.7 $^{+3.0}_{-2.6}$
fake leptons	3.7 $\pm 2.8$	70 $\pm 40$	0.5 $\pm 0.8$
Total Bg	230 $^{+50}_{-40}$	1380 $^{+310}_{-250}$	440 $^{+90}_{-80}$
Observed	243	1410	460



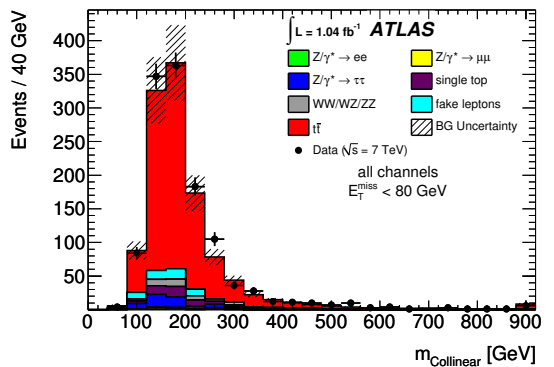
(a)



(b)



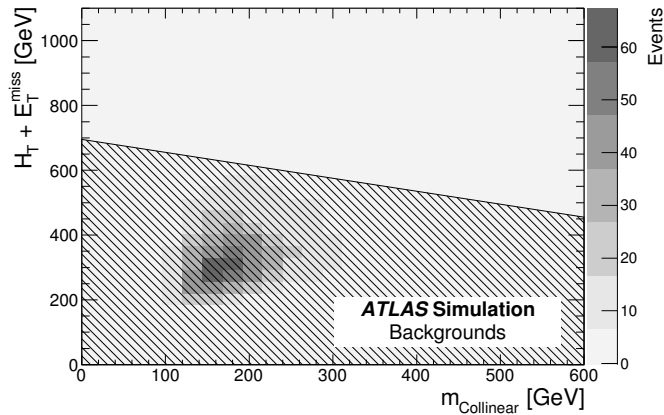
(c)



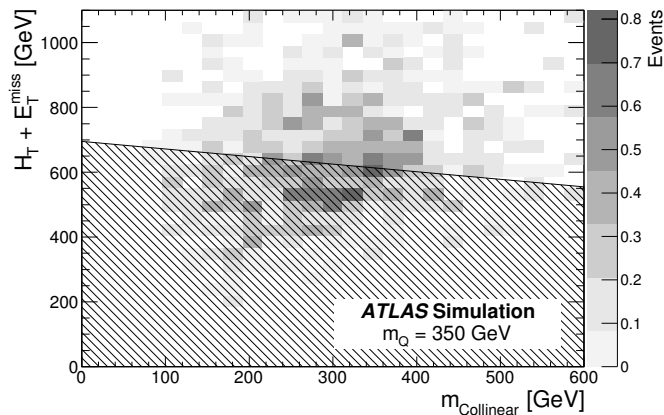
(d)

FIG. 7. Distributions of  $m_{\text{Collinear}}$  in events that have (a)  $H_T < 400$  GeV, (b) two leptons with  $p_T < 60$  GeV, (c) all jets with  $p_T < 60$  GeV or (d)  $E_T^{\text{miss}} < 80$  GeV. Each histogram contains the sum of the  $ee$ ,  $\mu\mu$  and  $e\mu$  channels. The last bin contains overflow events. Samples are stacked in the same order as they are presented in the legend, from left to right; the first entry in the legend is at the bottom of the stack.

the selection requirement parameters. Distributions of  $H_T + E_T^{\text{miss}}$  versus  $m_{\text{Collinear}}$  for background and signal are shown in Figure 8. Tables III and IV list the full set of optimized selection requirements at each mass point. Table V lists the expected backgrounds, expected signal and observed data for each mass point after this final selection. Figure 9 shows the distributions in  $m_{\text{Collinear}}$  for two signal samples after the final selection.



(a)



(b)

FIG. 8.  $H_T + E_T^{\text{miss}}$  versus  $m_{\text{Collinear}}$  for (a) background and (b)  $m_Q = 350$  GeV signal events for the sum of  $ee$ ,  $\mu\mu$ , and  $e\mu$  channels. The scale, shown on the right, indicates the number of reconstructed MC events per bin passing the baseline selection and weighted to  $\int \mathcal{L} dt = 1.04 \text{ fb}^{-1}$ . The shaded region is removed by the triangular selection requirement shown in Table III.

## IX. SYSTEMATIC UNCERTAINTIES

The major sources of systematic uncertainty are due to modeling of the signal and most sources of background.

The uncertainties due to simulation of the lepton trigger, reconstruction and selection efficiencies are assessed

TABLE III. List of  $H_T + E_T^{\text{miss}}$  versus  $m_{\text{Collinear}}$  requirements for each  $m_Q$ .

$m_Q$ (GeV)	Triangle Requirement (GeV)
300	$H_T + E_T^{\text{miss}} > 610 - 0.4 \times m_{\text{Collinear}}$
350	$H_T + E_T^{\text{miss}} > 700 - 0.4 \times m_{\text{Collinear}}$
400	$H_T + E_T^{\text{miss}} > 790 - 0.4 \times m_{\text{Collinear}}$
450	$H_T + E_T^{\text{miss}} > 880 - 0.4 \times m_{\text{Collinear}}$
500	$H_T + E_T^{\text{miss}} > 970 - 0.4 \times m_{\text{Collinear}}$

TABLE IV. List of jet  $p_T$  and  $E_T^{\text{miss}}$  requirements for each  $m_Q$ .

$m_Q$ (GeV)	Jet $p_T$ (GeV)	$E_T^{\text{miss}}$ (GeV)
300	Leading jet $p_T > 80$	—
350	Leading jet $p_T > 120$	—
400	Leading jet $p_T > 130$	$E_T^{\text{miss}} > 70$
450	Leading jet $p_T > 130$	$E_T^{\text{miss}} > 70$
500	Leading jet $p_T > 130$	$E_T^{\text{miss}} > 70$

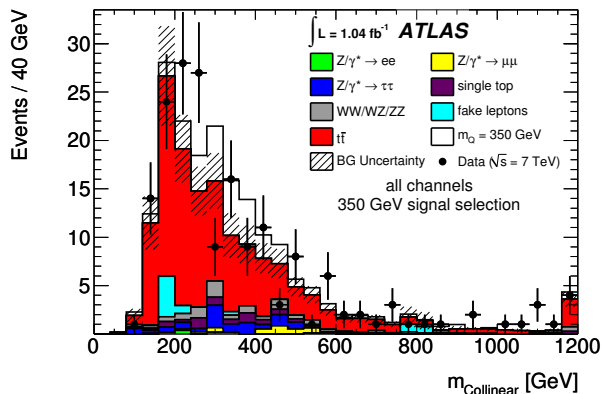
TABLE V. Expected background, expected signal and observed data in  $ee$ ,  $\mu\mu$ , and  $e\mu$  channels for  $m_Q = 300 - 500$  GeV after final selection. The uncertainties shown include both statistical and systematic contributions.

$m_Q$ (GeV)	Expected Background	Expected Signal	Observed Data
300	300 $^{+40}_{-40}$	95 $^{+14}_{-12}$	315
350	148 $^{+22}_{-18}$	35 $^{+5}_{-4}$	180
400	75 $^{+11}_{-10}$	17.1 $^{+2.5}_{-2.1}$	89
450	49 $^{+8}_{-6}$	8.4 $^{+1.2}_{-1.0}$	57
500	30 $^{+5}_{-4}$	4.4 $^{+0.6}_{-0.5}$	36

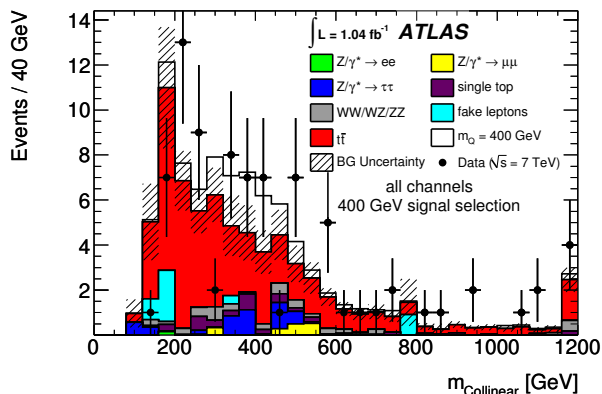
using leptons from  $Z \rightarrow ee$  and  $Z \rightarrow \mu\mu$  in data [36]. MC events are corrected for differences in data and simulation. The statistical and systematic uncertainties in these corrections are included in the uncertainties on the acceptance values. Uncertainties in the modeling of the lepton energy scale and resolution are studied using reconstructed  $Z$  boson mass distributions. The jet energy scale (JES) and its uncertainty are derived by combining information from test-beam data, LHC collision data and simulation [33]. The JES uncertainty varies as a function of jet  $p_T$  and  $\eta$  and also accounts for the presence of nearby jets and event pileup. There is additional uncertainty associated with jets originating from  $b$  quarks in simulation. Smaller uncertainties are associated with the jet energy resolution and jet finding efficiency.

Uncertainties related to the  $E_T^{\text{miss}}$  arise due to uncertainties associated with low momenta jets, event pileup, and calorimeter energy not associated with reconstructed leptons or jets [34]. There is also some uncertainty in esti-





(a)



(b)

FIG. 9. Distributions of  $m_{\text{Collinear}}$  for the sum of  $ee$ ,  $\mu\mu$ , and  $e\mu$  channels after applying the final selection for (a)  $m_Q = 350$  GeV and (b)  $m_Q = 400$  GeV. The last bin contains overflow events. The uncertainty bands include all statistical and systematic background uncertainties. The signal samples are normalized using the cross-sections in Table I. Samples are stacked in the same order as they are presented in the legend, from left to right; the first entry in the legend is at the bottom of the stack.

mating the effect of a readout problem affecting a subset of the LAr calorimeter channels in a part of the data set.

The use of simulated samples to calculate the signal and background acceptances gives rise to systematic uncertainties from the generator choice, the amount of initial and final state radiation (ISR/FSR), and from the PDF choice. The uncertainty due to the choice of generator for  $t\bar{t}$  events is evaluated by comparing the predictions of MC@NLO with those of POWHEG [39] interfaced to either HERWIG or PYTHIA. The uncertainty due to ISR/FSR is evaluated by studies using the ACERMC [40] generator interfaced to PYTHIA, varying the parameters controlling ISR and FSR in a range consistent with experimental data [41]. For  $Z/\gamma^*$ +jets events, the generator uncertainty is evaluated by comparing the predictions of ALPGEN with the PDF set CTEQ6.1 and SHERPA [42] with the PDF set CTEQ6.6. Finally, the uncertainty in

TABLE VI. Overall normalization uncertainties for each background, which are either due to cross-section uncertainties or uncertainties related to data-driven methods.

Background	+1 $\sigma$ Unc.	-1 $\sigma$ Unc.
$t\bar{t}$	7 %	10 %
single-top	7 %	7 %
$Z/\gamma^* \rightarrow ee$	60 %	30 %
$Z/\gamma^* \rightarrow \mu\mu$	40 %	30 %
$Z/\gamma^* \rightarrow \tau\tau$	40 %	40 %
$WW, WZ, ZZ$	5 %	5 %
fake leptons	50 %	50 %

the PDFs used to generate signal,  $t\bar{t}$  and single-top events is evaluated using the procedure adopted in a measurement of the  $t\bar{t}$  cross-section [36].

The integrated luminosity measurement carries a 3.7% uncertainty [16, 17]. Each sample also has an uncertainty associated with its theoretical cross-section or with its data-driven rate. For  $t\bar{t}$  [20], single-top [28, 29] and  $Z/\gamma^* \rightarrow \tau\tau$  [43] the rate uncertainty is estimated from theoretical calculations.  $Z/\gamma^* \rightarrow ee$ ,  $Z/\gamma^* \rightarrow \mu\mu$  and fake lepton event rate uncertainties are evaluated with the data-driven fitting described in Section V. The cross-section uncertainty for each signal point comes from HATHOR NNLO calculations and can be found in Table I. The background normalization uncertainties are listed in Table VI.

The effects of the systematic uncertainties on the overall background yield are summarized in Table VII for the cuts used for  $m_Q = 350$  GeV.

## X. RESULTS AND DISCUSSION

A binned maximum-likelihood ratio technique is used to fit distributions of  $m_{\text{Collinear}}$  to the observed data in order to measure the most likely  $Q\bar{Q}$  production cross-section,  $\sigma(pp \rightarrow Q\bar{Q})$ . In the fitting technique, all events with  $m_{\text{Collinear}} > 760$  GeV are considered to belong in the same bin. A shape fit is performed on background and signal simultaneously; this allows the background normalization to float, but maintains the bin-to-bin relationships which defines the background and signal shapes in  $m_{\text{Collinear}}$ . This fitting procedure allows for the possibility of an underestimated or overestimated background in the signal region. To take into account systematic uncertainties, the signal and background shapes are smoothly deformed in generated samples of pseudo-data by random variations consistent with these uncertainties as shown in Table VI and Table VII; these fluctuations are not constrained by the data. Most of the systematic uncertainties are assumed to be correlated between signal and background; the uncertainties due to cross-section or data-driven estimates, Drell-Yan modeling,  $t\bar{t}$  modeling,

TABLE VII. The effects of the  $\pm 1\sigma$  systematic uncertainties on the overall background yield.

Source	+1 $\sigma$ Unc.	-1 $\sigma$ Unc.
Lepton trigger	1 %	1 %
Lepton ID and reconstruction	2 %	< 1 %
Jet reconstruction	3 %	3 %
Jet energy resolution	2 %	2 %
Jet energy scale	13 %	11 %
$\mu$ momentum resolution	2 %	2 %
$\mu$ momentum scale	1 %	2 %
$e$ energy resolution	1 %	1 %
$e$ energy scale	< 1 %	< 1 %
$e$ isolation pileup term	1 %	1 %
$e$ isolation $p_T$ term	< 1 %	< 1 %
$E_T^{\text{miss}}$ uncertainties	1 %	< 1 %
LAr readout problem	2 %	2 %
ISR/FSR: $t\bar{t}$	8 %	5 %
MC generator: $t\bar{t}$	1 %	< 1 %
MC fragmentation/model: $t\bar{t}$	1 %	1 %
Drell-Yan model	7 %	7 %

and  $t\bar{t}$  generation are uncorrelated between signal and background.

A small excess is observed over the background expectation for each hypothetical  $Q$  mass.

Since the statistical interpretation uses the full shape of the signal and background distributions, the results the results in Table V do not entirely determine the results; only a signal-like excess would weaken the observed limits. The excess shape in the  $m_{\text{Collinear}}$  distribution is not particularly signal-like and the data are found to be in better agreement with the background-only than the signal+background hypothesis.

Statistical interpretation of the fitted cross-section  $\sigma$  is made using the CLs technique [44, 45]. This technique performs fits in pseudo-data generated from the background model and varying levels of injected signal to measure the ability of the fit to distinguish between the background-only and background-plus-signal hypotheses. In the case that the data are in better agreement with the background-only hypothesis, 95% CL upper limits on the signal cross-section  $\sigma^{95}$  are derived. The limit  $\sigma^{95}$  is chosen so that

$$\frac{p_s}{1 - p_0} < 0.05$$

where  $p_s$  is the fraction of fits in pseudo-data with injected signal  $\sigma^{95}$  which give a result as seen in the data, and  $p_0$  is the corresponding fraction from pseudo-data drawn from the background hypothesis. Thus the performance of the fitting technique in ensembles of pseudo-data is naturally accounted for. Figure 10 shows the

observed and expected limits on the production cross-section  $\sigma(pp \rightarrow Q\bar{Q})$ .

The upper limit on the production cross-section is converted into a lower limit on  $m_Q$  by finding the point of intersection with the theoretical prediction as a function of  $m_Q$ . This analysis finds a lower limit of  $m_Q > 350$  GeV at 95% confidence level (C.L.) whereas a limit of  $m_Q > 335$  GeV was expected. This limit assumes that the branching ratio (BR) of  $Q \rightarrow Wq$  is 100%. Limits were calculated for simulated samples of  $Q \rightarrow Wb$ ,  $Q \rightarrow Ws$ , and  $Q \rightarrow Wd$ , but the results were approximately the same for all samples. The results from  $Q \rightarrow Wu$  and  $Q \rightarrow Wc$  were assumed to be analogous for  $Q \rightarrow Ws$  and  $Q \rightarrow Wd$ , respectively.

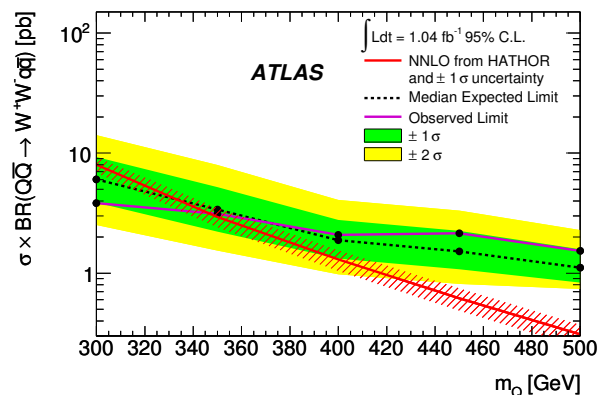


FIG. 10. Observed and median expected 95% C.L. cross-section upper limits on  $Q\bar{Q}$  production, compared to the theoretical prediction. The limit was calculated for five signal masses, and a linear interpolation has been made between mass points. Limits were calculated for simulated samples of  $Q \rightarrow Wb$ ,  $Q \rightarrow Ws$ , and  $Q \rightarrow Wd$ , but the results were approximately the same for all samples. The results from  $Q \rightarrow Wu$  and  $Q \rightarrow Wc$  were assumed to be analogous for  $Q \rightarrow Ws$  and  $Q \rightarrow Wd$ , respectively.

## XI. CONCLUSIONS

This Article presents a search for pair production of heavy quarks decaying to  $Wq$  in the dilepton channel at the CERN LHC. This search allows  $q = d, s, b$  for up-type  $Q$  final states or  $q = u, c$  for down-type  $Q$  final states. The analyzed data correspond to an integrated luminosity of  $1.04 \text{ fb}^{-1}$  collected by the ATLAS detector in  $pp$  collisions at  $\sqrt{s} = 7$  TeV. To enhance the sensitivity to a new quark, mass reconstruction is performed by exploiting the boost received by the heavy-quark decay products. The reconstructed mass is used for binned maximum-likelihood ratio fitting.

The data are found to be in agreement with the expectation from the Standard Model. A lower limit is set on the mass  $m_Q > 350$  GeV at 95% confidence level. This limit assumes  $\text{BR}(Q \rightarrow Wq) = 100\%$  and is appli-

cable to many exotic models [46, 47], including up-type fourth-generation quarks  $t'$ , down-type fourth generation quarks  $b'$ , and quarks with exotic charges (such as  $-4/3$ ) decaying to light quarks.

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## The ATLAS Collaboration

G. Aad<sup>48</sup>, B. Abbott<sup>110</sup>, J. Abdallah<sup>11</sup>, A.A. Abdelalim<sup>49</sup>, A. Abdesselam<sup>117</sup>, O. Abidinov<sup>10</sup>, B. Abi<sup>111</sup>, M. Abolins<sup>87</sup>, O.S. AbouZeid<sup>157</sup>, H. Abramowicz<sup>152</sup>, H. Abreu<sup>114</sup>, E. Acerbi<sup>88a,88b</sup>, B.S. Acharya<sup>163a,163b</sup>, L. Adamczyk<sup>37</sup>, D.L. Adams<sup>24</sup>, T.N. Addy<sup>56</sup>, J. Adelman<sup>174</sup>, M. Aderholz<sup>98</sup>, S. Adomeit<sup>97</sup>, P. Adragna<sup>74</sup>, T. Adye<sup>128</sup>, S. Aefsky<sup>22</sup>, J.A. Aguilar-Saavedra<sup>123b,a</sup>, M. Aharrouche<sup>80</sup>, S.P. Ahlen<sup>21</sup>, F. Ahles<sup>48</sup>, A. Ahmad<sup>147</sup>, M. Ahsan<sup>40</sup>, G. Aielli<sup>132a,132b</sup>, T. Akdogan<sup>18a</sup>, T.P.A. Åkesson<sup>78</sup>, G. Akimoto<sup>154</sup>, A.V. Akimov<sup>93</sup>, A. Akiyama<sup>66</sup>, M.S. Alam<sup>1</sup>, M.A. Alam<sup>75</sup>, J. Albert<sup>168</sup>, S. Albrand<sup>55</sup>, M. Aleksa<sup>29</sup>, I.N. Aleksandrov<sup>64</sup>, F. Alessandria<sup>88a</sup>, C. Alexa<sup>25a</sup>, G. Alexander<sup>152</sup>, G. Alexandre<sup>49</sup>, T. Alexopoulos<sup>9</sup>, M. Alhroob<sup>20</sup>, M. Aliev<sup>15</sup>, G. Alimonti<sup>88a</sup>, J. Alison<sup>119</sup>, M. Aliyev<sup>10</sup>, B.M.M. Allbrooke<sup>17</sup>, P.P. Allport<sup>72</sup>, S.E. Allwood-Spiers<sup>53</sup>, J. Almond<sup>81</sup>, A. Aloisio<sup>101a,101b</sup>, R. Alon<sup>170</sup>, A. Alonso<sup>78</sup>, B. Alvarez Gonzalez<sup>87</sup>, M.G. Alviggi<sup>101a,101b</sup>, K. Amako<sup>65</sup>, P. Amaral<sup>29</sup>, C. Amelung<sup>22</sup>, V.V. Ammosov<sup>127</sup>, A. Amorim<sup>123a,b</sup>, G. Amorós<sup>166</sup>, N. Amram<sup>152</sup>, C. Anastopoulos<sup>29</sup>, L.S. Ancu<sup>16</sup>, N. Andari<sup>114</sup>, T. Andeen<sup>34</sup>, C.F. Anders<sup>20</sup>, G. Anders<sup>58a</sup>, K.J. Anderson<sup>30</sup>, A. Andreazza<sup>88a,88b</sup>, V. Andrei<sup>58a</sup>, M-L. Andrieux<sup>55</sup>, X.S. Anduaga<sup>69</sup>, A. Angerami<sup>34</sup>, F. Anghinolfi<sup>29</sup>, A. Anisenkov<sup>106</sup>, N. Anjos<sup>123a</sup>, A. Annovi<sup>47</sup>, A. Antonaki<sup>8</sup>, M. Antonelli<sup>47</sup>, A. Antonov<sup>95</sup>, J. Antos<sup>143b</sup>, F. Anulli<sup>131a</sup>, S. Aoun<sup>82</sup>, L. Aperio Bella<sup>4</sup>, R. Apolle<sup>117,c</sup>, G. Arabidze<sup>87</sup>, I. Aracena<sup>142</sup>, Y. Arai<sup>65</sup>, A.T.H. Arce<sup>44</sup>, S. Arfaoui<sup>147</sup>, J-F. Arguin<sup>14</sup>, E. Arik<sup>18a,\*</sup>, M. Arik<sup>18a</sup>, A.J. Armbruster<sup>86</sup>, O. Arnaez<sup>80</sup>, C. Arnault<sup>114</sup>, A. Artamonov<sup>94</sup>, G. Artoni<sup>131a,131b</sup>, D. Arutinov<sup>20</sup>, S. Asai<sup>154</sup>, R. Asfandiyarov<sup>171</sup>, S. Ask<sup>27</sup>, B. Åsman<sup>145a,145b</sup>, L. Asquith<sup>5</sup>, K. Assamagan<sup>24</sup>, A. Astbury<sup>168</sup>, A. Astvatsatourov<sup>52</sup>, B. Aubert<sup>4</sup>, E. Auge<sup>114</sup>, K. Augsten<sup>126</sup>, M. Aurousseau<sup>144a</sup>, G. Avolio<sup>162</sup>, R. Avramidou<sup>9</sup>, D. Axen<sup>167</sup>, C. Ay<sup>54</sup>, G. Azuelos<sup>92,d</sup>, Y. Azuma<sup>154</sup>, M.A. Baak<sup>29</sup>, G. Baccaglioni<sup>88a</sup>, C. Bacci<sup>133a,133b</sup>, A.M. Bach<sup>14</sup>, H. Bachacou<sup>135</sup>, K. Bachas<sup>29</sup>, M. Backes<sup>49</sup>, M. Backhaus<sup>20</sup>, E. Badescu<sup>25a</sup>, P. Bagnaia<sup>131a,131b</sup>, S. Bahinipati<sup>2</sup>, Y. Bai<sup>32a</sup>, D.C. Bailey<sup>157</sup>, T. Bain<sup>157</sup>, J.T. Baines<sup>128</sup>, O.K. Baker<sup>174</sup>, M.D. Baker<sup>24</sup>, S. Baker<sup>76</sup>, E. Banas<sup>38</sup>, P. Banerjee<sup>92</sup>, Sw. Banerjee<sup>171</sup>, D. Banfi<sup>29</sup>, A. Bangert<sup>149</sup>, V. Bansal<sup>168</sup>, H.S. Bansil<sup>17</sup>, L. Barak<sup>170</sup>, S.P. Baranov<sup>93</sup>, A. Barashkou<sup>64</sup>, A. Barbaro Galtieri<sup>14</sup>, T. Barber<sup>48</sup>, E.L. Barberio<sup>85</sup>, D. Barberis<sup>50a,50b</sup>, M. Barbero<sup>20</sup>, D.Y. Bardin<sup>64</sup>, T. Barillari<sup>98</sup>, M. Barisonzi<sup>173</sup>, T. Barklow<sup>142</sup>, N. Barlow<sup>27</sup>, B.M. Barnett<sup>128</sup>, R.M. Barnett<sup>14</sup>, A. Baroncelli<sup>133a</sup>, G. Barone<sup>49</sup>, A.J. Barr<sup>117</sup>, F. Barreiro<sup>79</sup>, J. Barreiro Guimarães da Costa<sup>57</sup>, P. Barrillon<sup>114</sup>, R. Bartoldus<sup>142</sup>, A.E. Barton<sup>70</sup>, V. Bartsch<sup>148</sup>, R.L. Bates<sup>53</sup>, L. Batkova<sup>143a</sup>, J.R. Batley<sup>27</sup>, A. Battaglia<sup>16</sup>, M. Battistin<sup>29</sup>, F. Bauer<sup>135</sup>, H.S. Bawa<sup>142,e</sup>, S. Beale<sup>97</sup>, T. Beau<sup>77</sup>, P.H. Beauchemin<sup>160</sup>, R. Beccherle<sup>50a</sup>, P. Bechtel<sup>20</sup>, H.P. Beck<sup>16</sup>, S. Becker<sup>97</sup>, M. Beckingham<sup>137</sup>, K.H. Becks<sup>173</sup>, A.J. Beddall<sup>18c</sup>, A. Beddall<sup>18c</sup>, S. Bedikian<sup>174</sup>, V.A. Bednyakov<sup>64</sup>, C.P. Bee<sup>82</sup>, M. Begel<sup>24</sup>, S. Behar Harpaz<sup>151</sup>, P.K. Behera<sup>62</sup>, M. Beimforde<sup>98</sup>, C. Belanger-Champagne<sup>84</sup>, P.J. Bell<sup>49</sup>, W.H. Bell<sup>49</sup>, G. Bella<sup>152</sup>, L. Bellagamba<sup>19a</sup>, F. Bellina<sup>29</sup>, M. Bellomo<sup>29</sup>, A. Belloni<sup>57</sup>, O. Beloborodova<sup>106,f</sup>, K. Belotskiy<sup>95</sup>, O. Beltramello<sup>29</sup>, S. Ben Ami<sup>151</sup>, O. Benary<sup>152</sup>, D. Benchekroun<sup>134a</sup>, C. Benchouk<sup>82</sup>, M. Bendel<sup>80</sup>, N. Benekos<sup>164</sup>, Y. Benhammou<sup>152</sup>, E. Benhar Noccioli<sup>49</sup>, J.A. Benitez Garcia<sup>158b</sup>, D.P. Benjamin<sup>44</sup>, M. Benoit<sup>114</sup>, J.R. Bensinger<sup>22</sup>, K. Benslama<sup>152</sup>, S. Bentvelsen<sup>104</sup>, D. Berge<sup>29</sup>, E. Bergeas Kuitmann<sup>41</sup>, N. Berger<sup>4</sup>, F. Berghaus<sup>168</sup>, E. Berglund<sup>104</sup>, J. Beringer<sup>14</sup>, P. Bernat<sup>76</sup>, R. Bernhard<sup>48</sup>, C. Bernius<sup>24</sup>, T. Berry<sup>75</sup>, C. Bertella<sup>82</sup>, A. Bertin<sup>19a,19b</sup>, F. Bertinelli<sup>29</sup>, F. Bertolucci<sup>121a,121b</sup>, M.I. Besana<sup>88a,88b</sup>, N. Besson<sup>135</sup>, S. Bethke<sup>98</sup>, W. Bhimji<sup>45</sup>, R.M. Bianchi<sup>29</sup>, M. Bianco<sup>71a,71b</sup>, O. Biebel<sup>97</sup>, S.P. Bieniek<sup>76</sup>, K. Bierwagen<sup>54</sup>, J. Biesiada<sup>14</sup>, M. Biglietti<sup>133a</sup>, H. Bilokon<sup>47</sup>, M. Bindi<sup>19a,19b</sup>, S. Binet<sup>114</sup>, A. Bingul<sup>18c</sup>, C. Bini<sup>131a,131b</sup>, C. Biscarat<sup>176</sup>, U. Bitenc<sup>48</sup>, K.M. Black<sup>21</sup>, R.E. Blair<sup>5</sup>, J.-B. Blanchard<sup>135</sup>, G. Blanchot<sup>29</sup>, T. Blazek<sup>143a</sup>, C. Blocker<sup>22</sup>, J. Blocki<sup>38</sup>, A. Blondel<sup>49</sup>, W. Blum<sup>80</sup>, U. Blumenschein<sup>54</sup>, G.J. Bobbink<sup>104</sup>, V.B. Bobrovnikov<sup>106</sup>, S.S. Bocchetta<sup>78</sup>, A. Bocci<sup>44</sup>, C.R. Boddy<sup>117</sup>, M. Boehler<sup>41</sup>, J. Boek<sup>173</sup>, N. Boelaert<sup>35</sup>, J.A. Bogaerts<sup>29</sup>, A. Bogdanchikov<sup>106</sup>, A. Bogouch<sup>89,\*</sup>, C. Bohm<sup>145a</sup>, V. Boisvert<sup>75</sup>, T. Bold<sup>37</sup>, V. Boldea<sup>25a</sup>, N.M. Bolnet<sup>135</sup>, M. Bona<sup>74</sup>, V.G. Bondarenko<sup>95</sup>, M. Bondioli<sup>162</sup>, M. Boonekamp<sup>135</sup>, C.N. Booth<sup>138</sup>, S. Bordon<sup>77</sup>, C. Borer<sup>16</sup>, A. Borisov<sup>127</sup>, G. Borissov<sup>70</sup>, I. Borjanovic<sup>12a</sup>, M. Borri<sup>81</sup>, S. Borroni<sup>86</sup>, V. Bortolotto<sup>133a,133b</sup>, K. Bos<sup>104</sup>, D. Boscherini<sup>19a</sup>, M. Bosman<sup>11</sup>, H. Boterenbrood<sup>104</sup>, D. Botterill<sup>128</sup>, J. Bouchami<sup>92</sup>, J. Boudreau<sup>122</sup>, E.V. Bouhova-Thacker<sup>70</sup>, D. Boumediene<sup>33</sup>, C. Bourdarios<sup>114</sup>, N. Bousson<sup>82</sup>, A. Boveia<sup>30</sup>, J. Boyd<sup>29</sup>, I.R. Boyko<sup>64</sup>, N.I. Bozhko<sup>127</sup>, I. Bozovic-Jelisavcic<sup>12b</sup>, J. Bracinik<sup>17</sup>, A. Braem<sup>29</sup>, P. Branchini<sup>133a</sup>, G.W. Brandenburg<sup>57</sup>, A. Brandt<sup>7</sup>, G. Brandt<sup>117</sup>, O. Brandt<sup>54</sup>, U. Bratzler<sup>155</sup>, B. Brau<sup>83</sup>, J.E. Brau<sup>113</sup>, H.M. Braun<sup>173</sup>, B. Brelier<sup>157</sup>, J. Bremer<sup>29</sup>, R. Brenner<sup>165</sup>, S. Bressler<sup>170</sup>, D. Britton<sup>53</sup>, F.M. Brochu<sup>27</sup>, I. Brock<sup>20</sup>, R. Brock<sup>87</sup>, T.J. Brodbeck<sup>70</sup>, E. Brodet<sup>152</sup>, F. Broggi<sup>88a</sup>, C. Bromberg<sup>87</sup>, J. Bronner<sup>98</sup>, G. Brooijmans<sup>34</sup>, W.K. Brooks<sup>31b</sup>, G. Brown<sup>81</sup>, H. Brown<sup>7</sup>, P.A. Bruckman de Renstrom<sup>38</sup>, D. Bruncko<sup>143b</sup>, R. Bruneliere<sup>48</sup>, S. Brunet<sup>60</sup>, A. Bruni<sup>19a</sup>, G. Bruni<sup>19a</sup>, M. Bruschi<sup>19a</sup>, T. Buanes<sup>13</sup>, Q. Buat<sup>55</sup>, F. Bucci<sup>49</sup>, J. Buchanan<sup>117</sup>, N.J. Buchanan<sup>2</sup>, P. Buchholz<sup>140</sup>, R.M. Buckingham<sup>117</sup>, A.G. Buckley<sup>45</sup>, S.I. Buda<sup>25a</sup>, I.A. Budagov<sup>64</sup>, B. Budick<sup>107</sup>, V. Büscher<sup>80</sup>, L. Bugge<sup>116</sup>, O. Bulekov<sup>95</sup>, M. Bunse<sup>42</sup>, T. Buran<sup>116</sup>, H. Burchart<sup>29</sup>, S. Burdin<sup>72</sup>, T. Burgess<sup>13</sup>, S. Burke<sup>128</sup>, E. Busato<sup>33</sup>, P. Bussey<sup>53</sup>, C.P. Buszello<sup>165</sup>, F. Butin<sup>29</sup>, B. Butler<sup>142</sup>, J.M. Butler<sup>21</sup>, C.M. Buttar<sup>53</sup>, J.M. Butterworth<sup>76</sup>, W. Buttinger<sup>27</sup>, S. Cabrera Urbán<sup>166</sup>, D. Caforio<sup>19a,19b</sup>, O. Cakir<sup>3a</sup>, P. 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M. Campanelli<sup>76</sup>, V. Canale<sup>101a,101b</sup>, F. Canelli<sup>30,g</sup>, A. Canepa<sup>158a</sup>, J. Cantero<sup>79</sup>, L. Capasso<sup>101a,101b</sup>, M.D.M. Capeans Garrido<sup>29</sup>, I. Caprini<sup>25a</sup>, M. Caprini<sup>25a</sup>, D. Capriotti<sup>98</sup>, M. Capua<sup>36a,36b</sup>, R. Caputo<sup>80</sup>, C. Caramarcu<sup>24</sup>, R. Cardarelli<sup>132a</sup>, T. Carli<sup>29</sup>, G. Carlino<sup>101a</sup>, L. Carminati<sup>88a,88b</sup>, B. Caron<sup>84</sup>, S. Caron<sup>103</sup>, G.D. Carrillo Montoya<sup>171</sup>, A.A. Carter<sup>74</sup>, J.R. Carter<sup>27</sup>, J. Carvalho<sup>123a,h</sup>, D. Casadei<sup>107</sup>, M.P. Casado<sup>11</sup>, M. Cascella<sup>121a,121b</sup>, C. Caso<sup>50a,50b,\*</sup>, A.M. Castaneda Hernandez<sup>171</sup>, E. Castaneda-Miranda<sup>171</sup>, V. Castillo Gimenez<sup>166</sup>, N.F. Castro<sup>123a</sup>, G. Cataldi<sup>71a</sup>, F. Cataneo<sup>29</sup>, A. Catinaccio<sup>29</sup>, J.R. Catmore<sup>29</sup>, A. Cattai<sup>29</sup>, G. Cattani<sup>132a,132b</sup>, S. Caughron<sup>87</sup>, D. Cauz<sup>163a,163c</sup>, P. Cavalleri<sup>77</sup>, D. Cavalli<sup>88a</sup>, M. Cavalli-Sforza<sup>11</sup>, V. Cavasinini<sup>121a,121b</sup>, F. Ceradini<sup>133a,133b</sup>, A.S. Cerqueira<sup>23b</sup>, A. Cerri<sup>29</sup>, L. Cerrito<sup>74</sup>, F. Cerutti<sup>47</sup>, S.A. Cetin<sup>18b</sup>, F. Cevenini<sup>101a,101b</sup>, A. Chafaq<sup>134a</sup>, D. Chakraborty<sup>105</sup>, K. Chan<sup>2</sup>, B. Chapleau<sup>84</sup>, J.D. Chapman<sup>27</sup>, J.W. Chapman<sup>86</sup>, E. Chareyre<sup>77</sup>, D.G. Charlton<sup>17</sup>, V. Chavda<sup>81</sup>, C.A. Chavez Barajas<sup>29</sup>, S. Cheatham<sup>84</sup>, S. Chekanov<sup>5</sup>, S.V. Chekulaev<sup>158a</sup>, G.A. Chelkov<sup>64</sup>, M.A. Chelstowska<sup>103</sup>, C. Chen<sup>63</sup>, H. Chen<sup>24</sup>, S. Chen<sup>32c</sup>, T. Chen<sup>32c</sup>, X. Chen<sup>171</sup>, S. Cheng<sup>32a</sup>, A. 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Clemens<sup>82</sup>, B. Clement<sup>55</sup>, C. Clement<sup>145a,145b</sup>, R.W. Clift<sup>128</sup>, Y. Coadou<sup>82</sup>, M. Cobal<sup>163a,163c</sup>, A. Cocco<sup>171</sup>, J. Cochran<sup>63</sup>, P. Coe<sup>117</sup>, J.G. Cogan<sup>142</sup>, J. Coggeshall<sup>164</sup>, E. Cogneras<sup>176</sup>, J. Colas<sup>4</sup>, A.P. Colijn<sup>104</sup>, N.J. Collins<sup>17</sup>, C. Collins-Tooth<sup>53</sup>, J. Collot<sup>55</sup>, G. Colon<sup>83</sup>, P. Conde Muino<sup>123a</sup>, E. Coniavitis<sup>117</sup>, M.C. Conidi<sup>11</sup>, M. Consonni<sup>103</sup>, V. Consorti<sup>48</sup>, S. Constantinescu<sup>25a</sup>, C. Conta<sup>118a,118b</sup>, F. Conventi<sup>101a,i</sup>, J. Cook<sup>29</sup>, M. Cooke<sup>14</sup>, B.D. Cooper<sup>76</sup>, A.M. Cooper-Sarkar<sup>117</sup>, K. Copic<sup>14</sup>, T. Cornelissen<sup>173</sup>, M. Corradi<sup>19a</sup>, F. Corriveau<sup>84,j</sup>, A. Cortes-Gonzalez<sup>164</sup>, G. Cortiana<sup>98</sup>, G. Costa<sup>88a</sup>, M.J. Costa<sup>166</sup>, D. Costanzo<sup>138</sup>, T. Costin<sup>30</sup>, D. Côté<sup>29</sup>, R. Coura Torres<sup>23a</sup>, L. Courneyea<sup>168</sup>, G. Cowan<sup>75</sup>, C. Cowden<sup>27</sup>, B.E. Cox<sup>81</sup>, K. Cranmer<sup>107</sup>, F. Crescioli<sup>121a,121b</sup>, M. Cristinziani<sup>20</sup>, G. Crosetti<sup>36a,36b</sup>, R. Crupi<sup>71a,71b</sup>, S. Crépé-Renaudin<sup>55</sup>, C.-M. Cuciuc<sup>25a</sup>, C. Cuenca Almenar<sup>174</sup>, T. Cuhadar Donszelmann<sup>138</sup>, M. Curatolo<sup>47</sup>, C.J. Curtis<sup>17</sup>, C. Cuthbert<sup>149</sup>, P. Cwetanski<sup>60</sup>, H. Czirr<sup>140</sup>, P. Czodrowski<sup>43</sup>, Z. Czyczula<sup>174</sup>, S. D'Auria<sup>53</sup>, M. D'Onofrio<sup>72</sup>, A. D'Orazio<sup>131a,131b</sup>, P.V.M. Da Silva<sup>23a</sup>, C. Da Via<sup>81</sup>, W. Dabrowski<sup>37</sup>, T. Dai<sup>86</sup>, C. Dallapiccola<sup>83</sup>, M. Dam<sup>35</sup>, M. Dameri<sup>50a,50b</sup>, D.S. Damiani<sup>136</sup>, H.O. 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V.B. Vinogradov<sup>64</sup>, M. Virchaux<sup>135,\*</sup>, J. Virzi<sup>14</sup>, O. Vitells<sup>170</sup>, M. Viti<sup>41</sup>, I. Vivarelli<sup>48</sup>, F. Vives Vaque<sup>2</sup>, S. Vlachos<sup>9</sup>, D. Vladoiu<sup>97</sup>, M. Vlasak<sup>126</sup>, N. Vlasov<sup>20</sup>, A. Vogel<sup>20</sup>, P. Vokac<sup>126</sup>, G. Volpi<sup>47</sup>, M. Volpi<sup>85</sup>, G. Volpini<sup>88a</sup>, H. von der Schmitt<sup>98</sup>, J. von Loeben<sup>98</sup>, H. von Radziewski<sup>48</sup>, E. von Toerne<sup>20</sup>, V. Vorobel<sup>125</sup>, A.P. Vorobiev<sup>127</sup>, V. Vorwerk<sup>11</sup>, M. Vos<sup>166</sup>, R. Voss<sup>29</sup>, T.T. Voss<sup>173</sup>, J.H. Vosseveld<sup>72</sup>, N. Vranjes<sup>135</sup>, M. Vranjes Milosavljevic<sup>104</sup>, V. Vrba<sup>124</sup>, M. Vreeswijk<sup>104</sup>, T. Vu Anh<sup>48</sup>, R. Vuillermet<sup>29</sup>, I. Vukotic<sup>114</sup>, W. Wagner<sup>173</sup>, P. Wagner<sup>119</sup>, H. Wahlen<sup>173</sup>, J. 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Weng<sup>150,u</sup>, T. Wengler<sup>29</sup>, S. Wenig<sup>29</sup>, N. Wermes<sup>20</sup>, M. Werner<sup>48</sup>, P. Werner<sup>29</sup>, M. Werth<sup>162</sup>, M. Wessels<sup>58a</sup>, C. Weydert<sup>55</sup>, K. Whalen<sup>28</sup>, S.J. Wheeler-Ellis<sup>162</sup>, S.P. Whitaker<sup>21</sup>, A. White<sup>7</sup>, M.J. White<sup>85</sup>, S.R. Whitehead<sup>117</sup>, D. Whiteson<sup>162</sup>, D. Whittington<sup>60</sup>, F. Wicek<sup>114</sup>, D. Wicke<sup>173</sup>, F.J. Wickens<sup>128</sup>, W. Wiedenmann<sup>171</sup>, M. Wielers<sup>128</sup>, P. Wienemann<sup>20</sup>, C. Wiglesworth<sup>74</sup>, L.A.M. Wiik-Fuchs<sup>48</sup>, P.A. Wijeratne<sup>76</sup>, A. Wildauer<sup>166</sup>, M.A. Wildt<sup>41,q</sup>, I. Wilhelm<sup>125</sup>, H.G. Wilkens<sup>29</sup>, J.Z. Will<sup>97</sup>, E. Williams<sup>34</sup>, H.H. Williams<sup>119</sup>, W. Willis<sup>34</sup>, S. Willocq<sup>83</sup>, J.A. Wilson<sup>17</sup>, M.G. Wilson<sup>142</sup>, A. Wilson<sup>86</sup>, I. Wingerter-Seez<sup>4</sup>, S. Winkelmann<sup>48</sup>, F. Winklmeier<sup>29</sup>, M. Wittgen<sup>142</sup>, M.W. Wolter<sup>38</sup>, H. Wolters<sup>123a,h</sup>, W.C. Wong<sup>40</sup>, G. Wooden<sup>86</sup>, B.K. Wosiek<sup>38</sup>, J. Wotschack<sup>29</sup>, M.J. Woudstra<sup>83</sup>, K.W. Wozniak<sup>38</sup>, K. Wraight<sup>53</sup>, C. Wright<sup>53</sup>, M. Wright<sup>53</sup>, B. Wrona<sup>72</sup>, S.L. Wu<sup>171</sup>, X. Wu<sup>49</sup>, Y. Wu<sup>32b,ah</sup>, E. Wulf<sup>34</sup>, R. Wunstorf<sup>42</sup>, B.M. Wynne<sup>45</sup>, S. Xella<sup>35</sup>, M. Xiao<sup>135</sup>, S. Xie<sup>48</sup>, Y. Xie<sup>32a</sup>, C. Xu<sup>32b,w</sup>, D. Xu<sup>138</sup>, G. Xu<sup>32a</sup>, B. Yabsley<sup>149</sup>, S. Yacoub<sup>144b</sup>, M. Yamada<sup>65</sup>, H. Yamaguchi<sup>154</sup>, A. Yamamoto<sup>65</sup>, K. Yamamoto<sup>63</sup>, S. Yamamoto<sup>154</sup>, T. Yamamura<sup>154</sup>, T. Yamanaka<sup>154</sup>, J. Yamaoka<sup>44</sup>, T. Yamazaki<sup>154</sup>, Y. Yamazaki<sup>66</sup>, Z. Yan<sup>21</sup>, H. Yang<sup>86</sup>, U.K. Yang<sup>81</sup>, Y. Yang<sup>60</sup>, Y. Yang<sup>32a</sup>, Z. Yang<sup>145a,145b</sup>, S. Yanush<sup>90</sup>, Y. Yao<sup>14</sup>, Y. Yasu<sup>65</sup>, G.V. Ybeles Smit<sup>129</sup>, J. Ye<sup>39</sup>, S. Ye<sup>24</sup>, M. Yilmaz<sup>3c</sup>, R. Yoosoofmiya<sup>122</sup>, K. Yorita<sup>169</sup>, R. Yoshida<sup>5</sup>, C. Young<sup>142</sup>, S. Youssef<sup>21</sup>, D. Yu<sup>24</sup>, J. Yu<sup>7</sup>, J. Yu<sup>111</sup>, L. Yuan<sup>32a,ai</sup>, A. Yurkewicz<sup>105</sup>, B. Zabinski<sup>38</sup>, V.G. Zaets<sup>127</sup>, R. Zaidan<sup>62</sup>, A.M. Zaitsev<sup>127</sup>, Z. Zajacova<sup>29</sup>, L. Zanello<sup>131a,131b</sup>, A. Zaytsev<sup>106</sup>, C. Zeitnitz<sup>173</sup>, M. Zeller<sup>174</sup>, M. Zeman<sup>124</sup>, A. Zemla<sup>38</sup>, C. Zendler<sup>20</sup>, O. Zenin<sup>127</sup>, T. Ženiš<sup>143a</sup>, Z. Zinonos<sup>121a,121b</sup>, S. Zenz<sup>14</sup>, D. Zerwas<sup>114</sup>, G. Zevi della Porta<sup>57</sup>, Z. Zhan<sup>32d</sup>, D. Zhang<sup>32b,ag</sup>, H. Zhang<sup>87</sup>, J. Zhang<sup>5</sup>, X. Zhang<sup>32d</sup>, Z. Zhang<sup>114</sup>, L. Zhao<sup>107</sup>, T. Zhao<sup>137</sup>, Z. Zhao<sup>32b</sup>, A. Zhemchugov<sup>64</sup>, S. Zheng<sup>32a</sup>, J. Zhong<sup>117</sup>, B. Zhou<sup>86</sup>, N. Zhou<sup>162</sup>, Y. Zhou<sup>150</sup>, C.G. Zhu<sup>32d</sup>, H. Zhu<sup>41</sup>, J. Zhu<sup>86</sup>, Y. Zhu<sup>32b</sup>, X. Zhuang<sup>97</sup>, V. Zhuravlov<sup>98</sup>, D. Ziemska<sup>60</sup>, R. Zimmermann<sup>20</sup>, S. Zimmermann<sup>20</sup>, S. Zimmermann<sup>48</sup>, M. Ziolkowski<sup>140</sup>, R. Zitoun<sup>4</sup>, L. Živković<sup>34</sup>, V.V. Zmouchko<sup>127,\*</sup>, G. Zoernig<sup>171</sup>, A. Zoccoli<sup>19a,19b</sup>, Y. Zolnierowski<sup>4</sup>, A. Zsenei<sup>29</sup>, M. zur Nedden<sup>15</sup>, V. Zutshi<sup>105</sup>, L. Zwalinski<sup>29</sup>.

<sup>1</sup> University at Albany, Albany NY, United States of America

<sup>2</sup> Department of Physics, University of Alberta, Edmonton AB, Canada

<sup>3</sup> <sup>(a)</sup>Department of Physics, Ankara University, Ankara; <sup>(b)</sup>Department of Physics, Dumlupinar University, Kutahya; <sup>(c)</sup>Department of Physics, Gazi University, Ankara; <sup>(d)</sup>Division of Physics, TOBB University of Economics and Technology, Ankara; <sup>(e)</sup>Turkish Atomic Energy Authority, Ankara, Turkey

<sup>4</sup> LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France

<sup>5</sup> High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America

<sup>6</sup> Department of Physics, University of Arizona, Tucson AZ, United States of America

<sup>7</sup> Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America

<sup>8</sup> Physics Department, University of Athens, Athens, Greece

<sup>9</sup> Physics Department, National Technical University of Athens, Zografou, Greece

<sup>10</sup> Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

<sup>11</sup> Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain

<sup>12</sup> <sup>(a)</sup>Institute of Physics, University of Belgrade, Belgrade; <sup>(b)</sup>Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

<sup>13</sup> Department for Physics and Technology, University of Bergen, Bergen, Norway

<sup>14</sup> Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America

<sup>15</sup> Department of Physics, Humboldt University, Berlin, Germany

<sup>16</sup> Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

<sup>17</sup> School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

<sup>18</sup> <sup>(a)</sup>Department of Physics, Bogazici University, Istanbul; <sup>(b)</sup>Division of Physics, Dogus University, Istanbul;

<sup>(c)</sup>Department of Physics Engineering, Gaziantep University, Gaziantep; <sup>(d)</sup>Department of Physics, Istanbul

Technical University, Istanbul, Turkey

19 <sup>(a)</sup>INFN Sezione di Bologna; <sup>(b)</sup>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 of America

22 Department of Physics, Brandeis University, Waltham MA, United States of America

23 <sup>(a)</sup>Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; <sup>(b)</sup>Federal University of Juiz de Fora (UFJF), Juiz de Fora; <sup>(c)</sup>Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; <sup>(d)</sup>Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil

24 Physics Department, Brookhaven National Laboratory, Upton NY, United States of America

25 <sup>(a)</sup>National Institute of Physics and Nuclear Engineering, Bucharest; <sup>(b)</sup>University Politehnica Bucharest, Bucharest; <sup>(c)</sup>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 of America

31 <sup>(a)</sup>Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; <sup>(b)</sup>Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

32 <sup>(a)</sup>Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; <sup>(b)</sup>Department of Modern Physics, University of Science and Technology of China, Anhui; <sup>(c)</sup>Department of Physics, Nanjing University, Jiangsu;

<sup>(d)</sup>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 of America

35 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark

36 <sup>(a)</sup>INFN Gruppo Collegato di Cosenza; <sup>(b)</sup>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 of America

40 Physics Department, University of Texas at Dallas, Richardson TX, United States of America

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 of America

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 <sup>(a)</sup>INFN Sezione di Genova; <sup>(b)</sup>Dipartimento di Fisica, Università di Genova, Genova, Italy

51 <sup>(a)</sup>E.Andronikashvili Institute of Physics, Tbilisi State University, Tbilisi; <sup>(b)</sup>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 of America

57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America

58 <sup>(a)</sup>Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(b)</sup>Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(c)</sup>ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany

59 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan

60 Department of Physics, Indiana University, Bloomington IN, United States of America

61 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria

62 University of Iowa, Iowa City IA, United States of America

63 Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America

- 64 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- 65 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- 66 Graduate School of Science, Kobe University, Kobe, Japan
- 67 Faculty of Science, Kyoto University, Kyoto, Japan
- 68 Kyoto University of Education, Kyoto, Japan
- 69 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- 70 Physics Department, Lancaster University, Lancaster, United Kingdom
- 71 <sup>(a)</sup>INFN Sezione di Lecce; <sup>(b)</sup>Dipartimento di Fisica, Università del Salento, Lecce, Italy
- 72 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- 73 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- 74 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- 75 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- 76 Department of Physics and Astronomy, University College London, London, United Kingdom
- 77 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- 78 Fysiska institutionen, Lunds universitet, Lund, Sweden
- 79 Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- 80 Institut für Physik, Universität Mainz, Mainz, Germany
- 81 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- 82 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- 83 Department of Physics, University of Massachusetts, Amherst MA, United States of America
- 84 Department of Physics, McGill University, Montreal QC, Canada
- 85 School of Physics, University of Melbourne, Victoria, Australia
- 86 Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- 87 Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
- 88 <sup>(a)</sup>INFN Sezione di Milano; <sup>(b)</sup>Dipartimento di Fisica, Università di Milano, Milano, Italy
- 89 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
- 90 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
- 91 Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
- 92 Group of Particle Physics, University of Montreal, Montreal QC, Canada
- 93 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- 94 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- 95 Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
- 96 Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 97 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- 98 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- 99 Nagasaki Institute of Applied Science, Nagasaki, Japan
- 100 Graduate School of Science, Nagoya University, Nagoya, Japan
- 101 <sup>(a)</sup>INFN Sezione di Napoli; <sup>(b)</sup>Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
- 102 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
- 103 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- 104 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- 105 Department of Physics, Northern Illinois University, DeKalb IL, United States of America
- 106 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- 107 Department of Physics, New York University, New York NY, United States of America
- 108 Ohio State University, Columbus OH, United States of America
- 109 Faculty of Science, Okayama University, Okayama, Japan
- 110 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
- 111 Department of Physics, Oklahoma State University, Stillwater OK, United States of America
- 112 Palacký University, RCPTM, Olomouc, Czech Republic
- 113 Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
- 114 LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France
- 115 Graduate School of Science, Osaka University, Osaka, Japan
- 116 Department of Physics, University of Oslo, Oslo, Norway
- 117 Department of Physics, Oxford University, Oxford, United Kingdom
- 118 <sup>(a)</sup>INFN Sezione di Pavia; <sup>(b)</sup>Dipartimento di Fisica, Università di Pavia, Pavia, Italy

- 119 Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
- 120 Petersburg Nuclear Physics Institute, Gatchina, Russia
- 121 <sup>(a)</sup>INFN Sezione di Pisa; <sup>(b)</sup>Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- 122 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
- 123 <sup>(a)</sup>Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal; <sup>(b)</sup>Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
- 124 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- 125 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- 126 Czech Technical University in Prague, Praha, Czech Republic
- 127 State Research Center Institute for High Energy Physics, Protvino, Russia
- 128 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- 129 Physics Department, University of Regina, Regina SK, Canada
- 130 Ritsumeikan University, Kusatsu, Shiga, Japan
- 131 <sup>(a)</sup>INFN Sezione di Roma I; <sup>(b)</sup>Dipartimento di Fisica, Università La Sapienza, Roma, Italy
- 132 <sup>(a)</sup>INFN Sezione di Roma Tor Vergata; <sup>(b)</sup>Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- 133 <sup>(a)</sup>INFN Sezione di Roma Tre; <sup>(b)</sup>Dipartimento di Fisica, Università Roma Tre, Roma, Italy
- 134 <sup>(a)</sup>Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; <sup>(b)</sup>Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; <sup>(c)</sup>Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; <sup>(d)</sup>Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; <sup>(e)</sup>Faculté des Sciences, Université Mohammed V- Agdal, Rabat, Morocco
- 135 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France
- 136 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
- 137 Department of Physics, University of Washington, Seattle WA, United States of America
- 138 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- 139 Department of Physics, Shinshu University, Nagano, Japan
- 140 Fachbereich Physik, Universität Siegen, Siegen, Germany
- 141 Department of Physics, Simon Fraser University, Burnaby BC, Canada
- 142 SLAC National Accelerator Laboratory, Stanford CA, United States of America
- 143 <sup>(a)</sup>Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; <sup>(b)</sup>Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- 144 <sup>(a)</sup>Department of Physics, University of Johannesburg, Johannesburg; <sup>(b)</sup>School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- 145 <sup>(a)</sup>Department of Physics, Stockholm University; <sup>(b)</sup>The Oskar Klein Centre, Stockholm, Sweden
- 146 Physics Department, Royal Institute of Technology, Stockholm, Sweden
- 147 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
- 148 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- 149 School of Physics, University of Sydney, Sydney, Australia
- 150 Institute of Physics, Academia Sinica, Taipei, Taiwan
- 151 Department of Physics, Technion: Israel Inst. of Technology, Haifa, Israel
- 152 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- 153 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- 154 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- 155 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- 156 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- 157 Department of Physics, University of Toronto, Toronto ON, Canada
- 158 <sup>(a)</sup>TRIUMF, Vancouver BC; <sup>(b)</sup>Department of Physics and Astronomy, York University, Toronto ON, Canada
- 159 Institute of Pure and Applied Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8571, Japan
- 160 Science and Technology Center, Tufts University, Medford MA, United States of America
- 161 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- 162 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
- 163 <sup>(a)</sup>INFN Gruppo Collegato di Udine; <sup>(b)</sup>ICTP, Trieste; <sup>(c)</sup>Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- 164 Department of Physics, University of Illinois, Urbana IL, United States of America
- 165 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden



- <sup>166</sup> 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
- <sup>167</sup> Department of Physics, University of British Columbia, Vancouver BC, Canada
- <sup>168</sup> Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
- <sup>169</sup> Waseda University, Tokyo, Japan
- <sup>170</sup> Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
- <sup>171</sup> Department of Physics, University of Wisconsin, Madison WI, United States of America
- <sup>172</sup> Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
- <sup>173</sup> Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
- <sup>174</sup> Department of Physics, Yale University, New Haven CT, United States of America
- <sup>175</sup> Yerevan Physics Institute, Yerevan, Armenia
- <sup>176</sup> Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France
- <sup>177</sup> Faculty of Science, Hiroshima University, Hiroshima, Japan
- <sup>a</sup> Also at Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal
- <sup>b</sup> Also at Faculdade de Ciências and CFNUL, Universidade de Lisboa, Lisboa, Portugal
- <sup>c</sup> Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- <sup>d</sup> Also at TRIUMF, Vancouver BC, Canada
- <sup>e</sup> Also at Department of Physics, California State University, Fresno CA, United States of America
- <sup>f</sup> Also at Novosibirsk State University, Novosibirsk, Russia
- <sup>g</sup> Also at Fermilab, Batavia IL, United States of America
- <sup>h</sup> Also at Department of Physics, University of Coimbra, Coimbra, Portugal
- <sup>i</sup> Also at Università di Napoli Parthenope, Napoli, Italy
- <sup>j</sup> Also at Institute of Particle Physics (IPP), Canada
- <sup>k</sup> Also at Department of Physics, Middle East Technical University, Ankara, Turkey
- <sup>l</sup> Also at Louisiana Tech University, Ruston LA, United States of America
- <sup>m</sup> Also at Department of Physics and Astronomy, University College London, London, United Kingdom
- <sup>n</sup> Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada
- <sup>o</sup> Also at Department of Physics, University of Cape Town, Cape Town, South Africa
- <sup>p</sup> Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- <sup>q</sup> Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
- <sup>r</sup> Also at Manhattan College, New York NY, United States of America
- <sup>s</sup> Also at School of Physics, Shandong University, Shandong, China
- <sup>t</sup> Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- <sup>u</sup> Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China
- <sup>v</sup> Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
- <sup>w</sup> Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique), Gif-sur-Yvette, France
- <sup>x</sup> Also at Section de Physique, Université de Genève, Geneva, Switzerland
- <sup>y</sup> Also at Departamento de Física, Universidade de Minho, Braga, Portugal
- <sup>z</sup> Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
- <sup>aa</sup> Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
- <sup>ab</sup> Also at California Institute of Technology, Pasadena CA, United States of America
- <sup>ac</sup> Also at Institute of Physics, Jagiellonian University, Krakow, Poland
- <sup>ad</sup> Also at LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France
- <sup>ae</sup> Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- <sup>af</sup> Also at Department of Physics, Oxford University, Oxford, United Kingdom
- <sup>ag</sup> Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
- <sup>ah</sup> Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- <sup>ai</sup> Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- \* Deceased