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Aad, G.; Abbott, B.; Abdallah, J.; Abdelalim, A. A.; Abdesselam, A.; Abdinov, O.; Abi, B.; Abolins, M.; Abramowicz, H.; Abreu, H.; Acerbi, E.; Acharya, B. S.; Adamczyk, L.; Adams, D. L.; Addy, T. N.; Adelman, J.; Aderholz, M.; Adomeit, S.; Adragna, P.; Adye, T.; Aefsky, S.; Aguilar-Saavedra, J. A.; Aharrouche, M.; Ahlen, S. P.; Ahles, F.; Ahmad, A.; Ahsan, M.; Aielli, G.; Akdogan, T.; Åkesson, Torsten; Akimoto, G.; Akimov, A. V.; Akiyama, A.; Alam, M. S.; Alam, M. A.; Albert, J.; Albrand, S.; Aleksa, M.; Aleksandrov, I. N.; Alessandria, F.; Alexa, C.; Alexander, G.; Alexandre, G.; Alexopoulos, T.; Alhroob, M.; Aliev, M.; Alimonti, G.; Alison, J.; Aliyev, M.; Allport, P. P.

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Total number of authors:
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LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

Search for the Higgs Boson in the $H \to WW^{(*)} \to l^+\nu l^-\bar{\nu}$ Decay Channel in pp Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector

G. Aad *et al.**
(ATLAS Collaboration)

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A search for the Higgs boson has been performed in the $H \to WW^{(*)} \to \ell^+\nu\ell^-\bar{\nu}$ channel ($\ell = e/\mu$) with an integrated luminosity of 2.05 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV collected with the ATLAS detector at the Large Hadron Collider. No significant excess of events over the expected background is observed and limits on the Higgs boson production cross section are derived for a Higgs boson mass in the range 110 GeV $< m_{\mathrm{H}} <$ 300 GeV. The observations exclude the presence of a standard model Higgs boson with a mass $145 < m_{\mathrm{H}} < 206$ GeV at 95% confidence level.

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The standard model of particle physics postulates the existence of a complex scalar doublet with a vacuum expectation value, which spontaneously breaks the electroweak symmetry, gives masses to all the massive elementary particles in the theory, and gives rise to a physical scalar known as the Higgs boson [1]. At the LHC, the Higgs boson is expected to be produced mainly through gluon fusion ($gg \to H$) [2] due to the large gluon density, although vector boson fusion ($qq \to qqH$) [3] is also important. Associated production of Higgs bosons (WH, ZH) also contributes more than 4% to the total rate for $m_H \leq$ 135 GeV [4]. For $m_H > 135$ GeV, $H \to WW^{(*)}$ is the dominant decay mode of the Higgs boson. Direct searches at LEP and the Tevatron exclude a standard model Higgs boson with a mass $m_{\mathrm{H}} < 114.4$ GeV or 156 GeV $< m_{\mathrm{H}} <$ 177 GeV [5] at 95% confidence level (C.L.). The search for $H \to ZZ \to \ell\ell\nu\nu$ at ATLAS excludes a standard model Higgs boson with a mass $340 < m_H < 450$ GeV, while the search for $H \to ZZ \to 4\ell$ excludes $191 < m_H < 197$ GeV, $199 < m_H < 200$ GeV, and $214 < m_H < 224$ GeV [6].

This Letter reports the results of a search for the Higgs boson in the channel $H \to WW^{(*)} \to \ell^+\nu\ell^-\bar{\nu}$ [7] ($\ell = e/\mu$, but including contributions from $\tau \to e/\mu$ decays) in 2.05 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV recorded by the ATLAS detector during the LHC run of spring and summer 2011. As described in detail below, the search examines events containing two leptons and up to one jet. The main backgrounds are suppressed by cuts on angular distributions, invariant masses, and $b-$jet tagging information. The background normalization and composition is estimated *in situ* using several control samples defined by relaxing or reversing selection cuts. Similar searches were performed by CMS and ATLAS in 36 pb^{-1} [8] and 35 pb^{-1} [9], respectively. The ATLAS experiment [10] is a multipurpose particle physics detector with forward-backward symmetric cylindrical geometry allowing tracks within the pseudorapidity range $|\eta| < 2.5$ and energy deposits in calorimeters covering $|\eta| < 4.9$ to be reconstructed. It is modeled using GEANT4 [11] and simulated events are reconstructed using the same software that is used to perform the reconstruction on data. The effects of multiple pp interactions ("in-time" pileup) and residual energy deposits from neighboring bunch crossings ("out-of-time" pileup) are modeled in the Monte Carlo (MC) samples by superimposing a number of simulated minimum-bias events on the simulated signal and background events. MC samples with different numbers of pileup interactions are reweighted to match the conditions observed in the present data: about 6 interactions per bunch crossing, with a 50 ns bunch spacing. The data used in this analysis were recorded during periods when all ATLAS subdetectors were operating under nominal conditions. The events were triggered [12] by requiring the presence of a high-p_{T} electron or muon in the event.

Electron candidates are selected from clustered energy deposits in the electromagnetic (EM) calorimeter with an associated track reconstructed in the inner detector and are required to satisfy a stringent set of identification cuts [13] with an efficiency of 71% for electrons with transverse momentum $E_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.47$. Muons are reconstructed by combining tracks in the inner detector and muon spectrometer. The efficiency of this reconstruction is 92% for muons with $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.4$. Events are required to have a primary vertex with ≥ 3 tracks with $p_{\mathrm{T}} > 0.4$ GeV. For both electrons and muons, the track associated with the lepton candidate is required to be consistent with having been produced at the event's primary vertex. Leptons are required to be isolated, satisfying stringent cuts on tracks and calorimeter depositions inside a cone $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.2$ around the lepton

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candidate, where $\Delta\phi$ and $\Delta\eta$ are the transverse opening angle and pseudorapidity difference between the lepton and the track or energy deposit. The lepton reconstruction efficiencies are evaluated with tag-and-probe methods using $Z \to \ell\ell$, $J/\psi \to \ell\ell$, and $W \to \ell\nu$ events in data [14].

Jets are reconstructed from calibrated clusters using the anti-k_t algorithm [15] with radius parameter $R = 0.4$. Jet energies are calibrated using E_{T} and η dependent correction factors based on MC simulation and validated by test beam and collision data studies [16]. They are required to have $E_{\mathrm{T}} > 25$ GeV and $|\eta| < 4.5$. Jets are identified as having been produced by b quarks using an algorithm that combines information about the impact parameter significance of tracks in the jet and the topology of semileptonic b- and c-hadron decays [17]. The missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$ [18] is reconstructed from calibrated energy clusters in the calorimeters and the reconstructed momenta of the muons, which generally deposit only a small fraction of their energy in the calorimeters. The $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in the presence of pileup has been studied, and both $E_{\mathrm{T}}^{\mathrm{miss}}$ as a function of the number of reconstructed primary vertices and $E_{\mathrm{T}}^{\mathrm{miss}}$ as a function of the event's position in the bunch train are well-modeled by MC calculations.

Exactly two opposite-sign lepton candidates (e or μ) with $p_{\mathrm{T}} > 15$ GeV for muons or $E_{\mathrm{T}} > 20$ GeV for electrons are required. The leading lepton must have transverse momentum >25 GeV so the selected events have a high efficiency for the trigger selection.

After the selection of events with two leptons, the significant backgrounds are the Drell-Yan process, $t\bar{t}$ and single top ($tW/tb/tqb$), WW, other diboson processes ($WZ/ZZ/W\gamma$), and W + jets where a jet is misidentified as a lepton. In addition to data-driven validations of the background estimates discussed later, MC simulations of the signal and backgrounds are studied in detail. The $gg \to H$ and $qq \to qqH$ processes are modeled using POWHEG, with PYTHIA to handle the parton shower [19], and the $gg \to H$ Higgs boson p_{T} spectrum is reweighted to agree with the prediction of Ref. [20]. PYTHIA is used to model WH/ZH production. Signal MC calculations are performed in steps of 5 GeV for m_{H} below 200 GeV and in steps of 20 GeV for larger masses. Signal expectations for intermediate mass values are obtained by linear interpolation of the signal efficiency. The $t\bar{t}$, s-channel single top (tb), and $qq/qg \to WW/WZ/ZZ$ processes are generated with MC@NLO, t-channel and Wt single top with ACERMC (interfaced to the parton shower algorithm in PYTHIA), $gg \to WW$ with GG2WW interfaced to the parton shower algorithm in HERWIG [21], $W\gamma$ with MADGRAPH interfaced to PYTHIA, and W + jets and Z/γ^* + jets with ALPGEN interfaced to PYTHIA [22].

If the two leptons have different flavors, their invariant mass ($m_{\ell\ell}$) is required to be above 10 GeV. Otherwise, they must satisfy $m_{\ell\ell} > 15$ GeV and they must lie outside the region with $|m_{\ell\ell} - m_{\mathrm{Z}}| < 15$ GeV to suppress backgrounds from Υ and Z production, respectively.

The quantity $E_{\mathrm{T,rel}}^{\mathrm{miss}}$ is defined as $E_{\mathrm{T}}^{\mathrm{miss}}$ if the angle $\Delta\phi$ between the missing transverse momentum and the transverse momentum of the nearest lepton or jet is greater than $\pi/2$, or $E_{\mathrm{T}}^{\mathrm{miss}} \sin(\Delta\phi)$ otherwise. $E_{\mathrm{T,rel}}^{\mathrm{miss}}$ is less sensitive to the mismeasurement of a single lepton or jet than $E_{\mathrm{T}}^{\mathrm{miss}}$. To suppress backgrounds from multijet events and Drell-Yan production, it is required that $E_{\mathrm{T,rel}}^{\mathrm{miss}} > 40$ GeV if the two leptons have the same flavor, or $E_{\mathrm{T,rel}}^{\mathrm{miss}} > 25$ GeV if they have different flavor.

After these requirements, the data are separated into $H + 0-$jet and $H + 1-$jet [23] samples based on whether they have zero or exactly one jet. In the $H + 0-$jet channel, the dilepton system is required to have a large transverse boost, $p_{\mathrm{T}}^{\ell\ell} > 30$ GeV, to suppress backgrounds from Z + jets and continuum WW production.

To suppress background from top-quark production, events in the $H + 1-$jet channel are rejected if the jet is identified as the decay of a b quark. These candidates are further required to have $|\mathbf{p}_{\mathrm{T}}^{\mathrm{tot}}| < 30$ GeV, where $\mathbf{p}_{\mathrm{T}}^{\mathrm{tot}}$ is the vector sum of the transverse momenta of the jet, the two leptons, and the $E_{\mathrm{T}}^{\mathrm{miss}}$ vector. This latter selection suppresses events with significant hadronic activity that recoils against the $\mathbf{p}_{\mathrm{T}}^{\mathrm{tot}}$ system but does not leave high p_{T} jets in the detector. In the $H + 1-$jet channel, the event is required to pass the $Z \to \tau\tau$ rejection cut used in the $H \to WW$ analysis of Ref. [24].

Top and WW backgrounds are suppressed by an upper bound on $m_{\ell\ell}$. Because the $m_{\ell\ell}$ distribution for the signal depends strongly on m_{H}, the chosen upper bound depends on the Higgs boson mass hypothesis. For $m_{\mathrm{H}} < 170$ GeV, $m_{\ell\ell} < 50$ GeV is required, while for $170 \le m_{\mathrm{H}} < 220$ GeV, the cut is $m_{\ell\ell} < 65$ GeV. For $m_{\mathrm{H}} \ge 220$ GeV, the requirement is $50 < m_{\ell\ell} < 180$ GeV.

For $m_{\mathrm{H}} < 220$ GeV, an upper bound is imposed on the azimuthal angle between the two leptons to exploit differences in spin correlations between signal and background: $\Delta\phi_{\ell\ell} < 1.3$ for $m_{\mathrm{H}} < 170$ GeV, or $\Delta\phi_{\ell\ell} < 1.8$ for $m_{\mathrm{H}} < 220$ GeV. The final requirement uses the transverse mass m_{T} [25] which is defined as $(m_{\mathrm{T}})^2 = m_v^2 + 2(e_v|\mathbf{p}_{\mathrm{T},i}| - \mathbf{p}_{\mathrm{T},v} \cdot \mathbf{p}_{\mathrm{T},i})$, where the subscripts v and i denote the visible and invisible decay products and $e_v = \sqrt{\mathbf{p}_{\mathrm{T},v} \cdot \mathbf{p}_{\mathrm{T},v} + m_v^2}$ denotes the transverse energy. The transverse mass m_{T} is required to lie within $0.75 m_{\mathrm{H}} < m_{\mathrm{T}} < m_{\mathrm{H}}$ if $m_{\mathrm{H}} < 220$ GeV or $0.6 m_{\mathrm{H}} < m_{\mathrm{T}} < m_{\mathrm{H}}$ otherwise. The upper bound on this window reduces the WW and top backgrounds and excludes regions of phase space where interference effects between the signal and the $gg \to WW$ background are large [26].

Table I shows the expected and observed event yields after these cuts. As described below, the W + jets background is entirely determined from data, whereas for the other processes the expectations are based on simulation,

TABLE I. The expected numbers of signal ($m_H = 150$ GeV) and background events after the requirements listed in the first column, as well as the observed numbers of events in data. All numbers are summed over lepton flavor.

$H + 0 -$ jet Channel	Signal	WW	$W +$ jets	$Z/\gamma^* +$ jets	$t\bar{t}$	$tW/tb/tqb$	$WZ/ZZ/W\gamma$	Total Bkg.	Observed
Jet Veto	99 ± 21	524 ± 52	84 ± 41	174 ± 169	42 ± 14	32 ± 8	15 ± 4	872 ± 182	920
$p_T^{\ell\ell} > 30$ GeV	95 ± 20	467 ± 45	69 ± 34	30 ± 12	39 ± 14	29 ± 8	13 ± 4	648 ± 60	700
$m_{\ell\ell} < 50$ GeV	68 ± 15	118 ± 15	21 ± 8	13 ± 8	7 ± 4	5.8 ± 1.8	1.9 ± 0.6	166 ± 19	199
$\Delta\phi_{\ell\ell} < 1.3$	58 ± 13	91 ± 12	12 ± 5	9 ± 6	6 ± 3	5.8 ± 1.8	1.7 ± 0.6	125 ± 15	149
$0.75 m_H < m_T < m_H$	40 ± 9	52 ± 7	5 ± 2	2 ± 4	2.4 ± 1.6	1.5 ± 1.0	1.1 ± 0.5	63 ± 9	81
$H + 1 -$ jet Channel	Signal	WW	$W +$ jets	$Z/\gamma^* +$ jets	$t\bar{t}$	$tW/tb/tqb$	$WZ/ZZ/W\gamma$	Total Bkg.	Observed
1 jet	50 ± 9	193 ± 20	38 ± 21	74 ± 65	473 ± 124	174 ± 26	14 ± 2	967 ± 145	952
$b -$ jet veto	48 ± 9	188 ± 19	35 ± 19	73 ± 61	174 ± 49	66 ± 11	14 ± 2	549 ± 83	564
$\lvert\mathbf{p}_T^{\text{tot}}\rvert < 30$ GeV	39 ± 7	154 ± 16	18 ± 9	38 ± 32	106 ± 30	50 ± 9	9.7 ± 1.5	376 ± 48	405
$Z \to \tau\tau$ veto	39 ± 7	150 ± 17	18 ± 8	34 ± 23	102 ± 23	48 ± 8	9 ± 2	361 ± 38	388
$m_{\ell\ell} < 50$ GeV	26 ± 6	33 ± 5	3.3 ± 1.4	8 ± 7	20 ± 7	11 ± 3	1.8 ± 0.5	77 ± 12	90
$\Delta\phi_{\ell\ell} < 1.3$	23 ± 5	25 ± 4	2.1 ± 1.0	4 ± 6	17 ± 6	9 ± 3	1.5 ± 0.4	60 ± 10	72
$0.75 m_H < m_T < m_H$	14 ± 3	12 ± 3	0.9 ± 0.4	1.3 ± 1.9	8 ± 2	4.0 ± 1.6	0.7 ± 0.3	28 ± 4	29
Control Regions	Signal	WW	$W +$ jets	$Z/\gamma^* +$ jets	$t\bar{t}$	$tW/tb/tqb$	$WZ/ZZ/W\gamma$	Total Bkg.	Observed
$WW0 -$ jet ($m_H < 220$ GeV)	1.7 ± 0.4	223 ± 30	20 ± 15	6 ± 8	25 ± 10	15 ± 4	8 ± 3	296 ± 36	296
$WW0 -$ jet ($m_H \geq 220$ GeV)	10 ± 2	173 ± 23	24 ± 12	13 ± 19	15 ± 6	8 ± 3	3.3 ± 0.6	236 ± 33	258
$WW1 -$ jet ($m_H < 220$ GeV)	1.0 ± 0.3	76 ± 13	5 ± 3	5 ± 5	56 ± 14	23 ± 5	5.3 ± 1.4	171 ± 21	184
$WW1 -$ jet ($m_H \geq 220$ GeV)	5.8 ± 1.5	51 ± 9	3.9 ± 1.8	10 ± 10	35 ± 9	18 ± 4	2.8 ± 0.6	120 ± 17	129
$t\bar{t}1 -$ jet	0.9 ± 0.3	3.9 ± 1.0	$\cdots$	1 ± 17	184 ± 64	80 ± 19	0.2 ± 0.9	270 ± 69	249

with $Z/\gamma^* +$ jets, $t\bar{t}$, and $tW/tb/tqb$ corrected by scale factors derived from control samples. The uncertainties shown are the sum in quadrature of systematic uncertainties and statistical errors due to the finite number of MC events. Figure 1 shows the distributions of $m_{\ell\ell}$ and $\Delta\phi_{\ell\ell}$ before the final cut on $m_{\ell\ell}$, and the distribution of m_T after the cut on $\Delta\phi_{\ell\ell}$.

The background from $W +$ jets events where one jet is misidentified as a lepton is estimated from data using a control sample where one of the two leptons satisfies a loosened set of identification and isolation criteria but not the full set of criteria normally used. The extrapolation from this control sample to the signal region is extracted from dijet events [27].

The Drell-Yan background is corrected for mismodeling of the distribution of E_T^{miss} at high values based on the observed difference between the fraction of events passing the $E_{T,\text{rel}}^{\text{miss}} > 40$ GeV selection in data and MC simulation for events with $m_{\ell\ell}$ within 10 GeV of the Z boson mass. The correction factors are all found to be between 0.8 and 0.9, which indicates that the background in the signal region is about 15% less than the MC estimates.

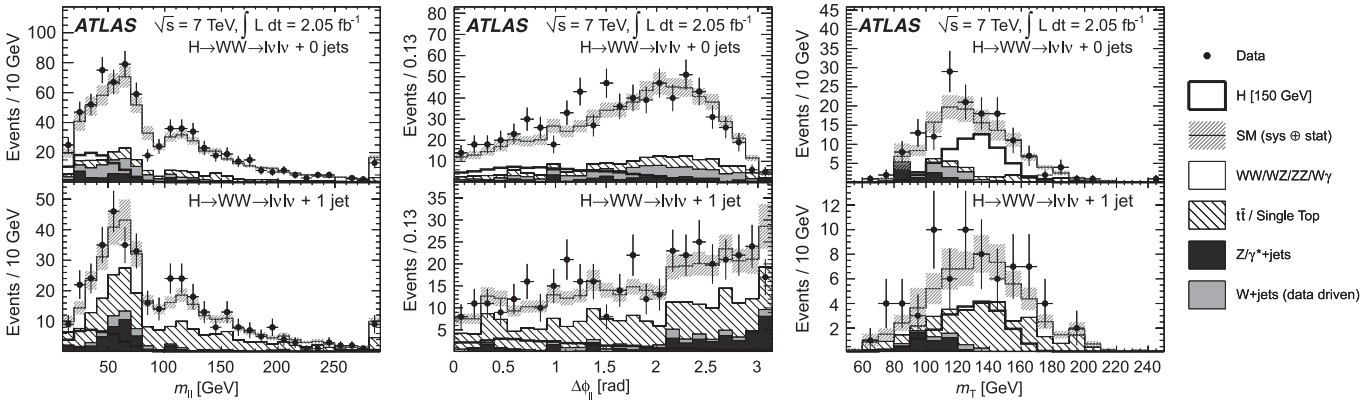

FIG. 1. Distributions of $m_{\ell\ell}$ (left), $\Delta\phi_{\ell\ell}$ (center), and m_T (right). The top row shows the selection for the $H + 0 -$ jet channel and the bottom row for the $H + 1 -$ jet channel. The left and central plots are shown after the $p_T^{\ell\ell}$ selection for the $H + 0 -$ jet channel and after the $|\mathbf{p}_T^{\text{tot}}|$ cut for the $H + 1 -$ jet channel. For the rightmost plots, the distributions are shown after all the cuts for $m_H = 150$ GeV except the cut on m_T itself. The background distributions are stacked, so that the top of the diboson background coincides with the standard model line which includes the statistical and systematic uncertainties on the expectation in the absence of a signal. The expected signal for $m_H = 150$ GeV is shown as a separate thicker line, and the final bin includes the overflow.

The WW and top backgrounds are normalized by a simultaneous fit to the numbers of observed events in the signal region and several control samples. A sample enriched in WW background is defined by removing the selections on m_{T} and $\Delta\phi_{\ell\ell}$ and changing the selection on $m_{\ell\ell}$. For $m_{\mathrm{H}} < 220$ GeV, the cut is changed to $m_{\ell\ell} > 80$ GeV, while for $m_{\mathrm{H}} > 220$ GeV, the control region is the union of the regions with $15 < m_{\ell\ell} < 50$ GeV and $m_{\ell\ell} > 180$ GeV. This control sample is studied separately for the $H + 0 -$ jet channel and the $H + 1 -$ jet channel, and the observed yields are consistent with expectations in both cases. The yields in these control regions, shown in Table I, are propagated to the signal region using scale factors computed with MC.

In the $H + 0 -$ jet channel, the top-enriched control sample consists of the same preselected sample used in the rest of this analysis: events with two leptons and $E_{\mathrm{T,rel}}^{\mathrm{miss}}$. The scale factor used to propagate the $t\bar{t}$ yield from this sample to the signal region is estimated as the square of the efficiency for one top decay to survive the jet veto (estimated using another control sample, defined by the presence of an additional $b -$ jet), with a correction computed using MC to account for the presence of single top [28]. A sample enriched in top background is defined for the $H + 1 -$ jet channel by reversing the $b -$ jet veto and removing the cuts on $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, and m_{T}. The extrapolation to the signal region is done using a scale factor computed using MC. The control samples for top in the $H + 0 -$ jet and $H + 1 -$ jet channels also normalize the top contamination in the corresponding WW control regions. In both cases, the estimated top backgrounds are consistent with the expected yields in Table I.

The signal significance and limits on Higgs boson production are derived from a likelihood function that is the product of the Poisson probabilities of each of the lepton flavor and jet multiplicity yields for the signal selections, the $WW + 0 -$ jet and $WW + 1 -$ jet control regions, and top control region for the $H + 1 -$ jet channel. The normalization of the signal, the WW cross sections for the $H + 0 -$ jet and $H + 1 -$ jet channels, and the top cross section for the $H + 1 -$ jet channel are allowed to vary independently; the control regions included in the fit constrain all of these except the signal yield. All other components are normalized to their expectations scaled by nuisance parameters constrained by Gaussian terms that include the systematic uncertainties described below. The results from the control sample measurements for the top background in the $H + 0 -$ jet channel and for the $W +$ jets and Drell-Yan backgrounds everywhere are used as the expected values for the corresponding backgrounds in the fit. Since these contributions are small, the control samples themselves are not explicitly modeled in the fit as they are for top in the $H + 1 -$ jet channel and for WW everywhere.

The systematic uncertainties include contributions from the 3.7% uncertainty in the luminosity [29], and from theoretical uncertainties, which are $-8/+12\%$ and $\pm 8\%$ from the QCD scale and 1% and 4% from the parton density functions, for $gg \to H$ and $qq \to qqH$ respectively. Additional theoretical uncertainties on the acceptance are assessed as described in Ref. [30]. In particular, the uncertainty in the assignment of events to jet multiplicity bins is included separately as an uncertainty on the cross section of each bin, calculated from the approximate 10% and 20% uncertainties of the inclusive $0 -$ jet and $1 -$ jet cross sections, respectively.

Several sources of measurement uncertainty are taken into account. The uncertainty on the jet energy scale is less than 10% on the global scale including flavor composition effects, with an additional uncertainty of up to 7% due to pileup [16]. The electron and muon efficiencies are determined from samples of W and Z boson data with uncertainties of 2%–5% and 0.3%–1%, respectively, depending on $|\eta|$ and p_{T}. Uncertainties are $<1\%$ and $<0.1\%$, respectively, on the lepton energy scale and $<0.6\%$ and $<5\%$ on the resolution [14]. The uncertainties on the b-tagging efficiency and mistag rate are 6%–15% and up to 21%, respectively [17]. A 13% uncertainty is applied to the energy scale for low-p_{T} depositions in the $E_{\mathrm{T}}^{\mathrm{miss}}$ measurement. All these sources of detector uncertainty are propagated to the result by varying reconstructed quantities and observing the effect on the expected yields. For the WW background, the total (theoretical and experimental) uncertainty on the ratio of cross sections in the signal and control regions is 7.6% in the $H + 0 -$ jet channel and 21% in the $H + 1 -$ jet channel; for the top background in $H + 1 -$ jet the total for the extrapolation to the signal region is 38%, and 29% to the WW control region.

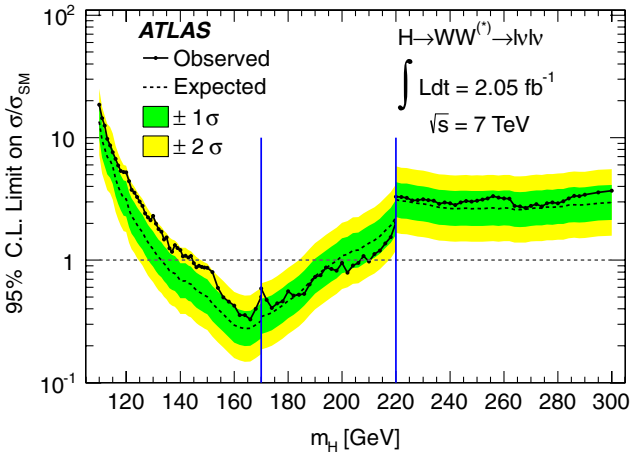

FIG. 2 (color online). The expected (dashed) and observed (solid) 95% C.L. upper limits on the cross section, normalized to the standard model cross section, as a function of the Higgs boson mass. Expected limits are given for the scenario where there is no signal. The vertical lines in the curves indicate the points where the selection cuts change, and the bands around the dashed line indicate the expected statistical fluctuations of the limit.

No significant excess of events is observed. The largest observed deviation from the expected background is 1.9σ. A 95% C.L. upper bound is set on the Higgs boson cross section as a function of m_{H} using the CL_s formalism [31]. Figure 2 shows the expected and observed limits. Discontinuities occur where the selection changes, since the signal regions there are less statistically correlated between adjacent masses. In the absence of a signal, one would expect to exclude a standard model Higgs boson in the range $134 < m_{\mathrm{H}} < 200$ GeV at the 95% C.L. The Higgs boson mass interval excluded by the measurements presented in this Letter, $145 < m_{\mathrm{H}} < 206$ GeV, is consistent with that expectation. This measurement excludes, at 95% C.L., a larger part of the mass range favored by the electroweak fits than previous limits [32].

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M. J. Shochet,[30] D. Short,[117] S. Shrestha,[63] M. A. Shupe,[6] P. Sicho,[124] A. Sidoti,[131a,131b] A. Siebel,[173] F. Siegert,[47] Dj. Sijacki,[12a] O. Silbert,[170] J. Silva,[123a,c] Y. Silver,[152] D. Silverstein,[142] S. B. Silverstein,[145a] V. Simak,[126] O. Simard,[135] Lj. Simic,[12a] S. Simion,[114] B. Simmons,[76] M. Simonyan,[35] P. Sinervo,[157] N. B. Sinev,[113] V. Sipica,[140] G. Siragusa,[172] A. Sircar,[24] A. N. Sisakyan,[64] S. Yu. Sivoklokov,[96] J. Sjölin,[145a,145b] T. B. Sjursen,[13] L. A. Skinnari,[14] H. P. Skottowe,[56] K. Skovpen,[106] P. Skubic,[110] N. Skvorodnev,[22] M. Slater,[17] T. Slavicek,[126] K. Sliwa,[160] J. Sloper,[29] V. Smakhtin,[170] S. Yu. Smirnov,[95] L. N. Smirnova,[96] O. Smirnova,[78] B. C. Smith,[56] D. Smith,[142] K. M. Smith,[52] M. Smizanska,[70] K. Smolek,[126] A. A. Snesarev,[93] S. W. Snow,[81] J. Snow,[110] J. Snuverink,[104] S. Snyder,[24] M. Soares,[123a] R. Sobie,[168,k] J. Sodomka,[126] A. Soffer,[152] C. A. Solans,[166] M. Solar,[126] J. Solc,[126] E. Soldatov,[95] U. Soldevila,[166] E. Solfaroli Camillocci,[131a,131b] A. A. Solodkov,[127] O. V. Solovyanov,[127] J. Sondericker,[24] N. Soni,[2] V. Sopko,[126] B. Sopko,[126] M. Sosebee,[7] R. Soualah,[163a,163c] A. Soukharev,[106] S. Spagnolo,[71a,71b] F. Spanò,[75] R. Spighi,[19a] G. Spigo,[29] F. Spila,[131a,131b] R. Spiwoks,[29] M. Spousta,[125] T. Spreitzer,[157] B. Spurlock,[7] R. D. St. Denis,[52] T. Stahl,[140] J. Stahlman,[119] R. Stamen,[57a] E. Stanecka,[38] R. W. Stanek,[5] C. Stanescu,[133a] S. Stapnes,[116] E. A. Starchenko,[127] J. Stark,[54] P. Staroba,[124] P. Starovoitov,[90] A. Staude,[97] P. Stavina,[143a] G. Stavropoulos,[14] G. Steele,[52] P. Steinbach,[43] P. Steinberg,[24] I. Stekl,[126] B. Stelzer,[141] H. J. Stelzer,[87] O. Stelzer-Chilton,[158a] H. Stenzel,[51] S. Stern,[98] K. Stevenson,[74] G. A. Stewart,[29] J. A. Stillings,[20] M. C. Stockton,[29] K. Stoerig,[47] G. Stoicea,[25a] S. Stonjek,[98] P. Strachota,[125] A. R. Stradling,[7] A. Straessner,[43] J. Strandberg,[146] S. Strandberg,[145a,145b] A. Strandlie,[116] M. Strang,[108] E. Strauss,[142] M. Strauss,[110] P. Strizenec,[143b] R. Ströhmer,[172] D. M. Strom,[113] J. A. Strong,[75,a] R. Stroynowski,[39] J. Strube,[128] B. Stugu,[13] I. Stumer,[24,a] J. Stupak,[147] P. Sturm,[173] N. A. Styles,[41] D. A. Soh,[150,t] D. Su,[142] HS. Subramania,[2] A. Succurro,[11] Y. Sugaya,[115] T. Sugimoto,[100] C. Suhr,[105] K. Suita,[66] M. Suk,[125] V. V. Sulin,[93] S. Sultansoy,[3d] T. Sumida,[67] X. Sun,[54] J. E. Sundermann,[47] K. Suruliz,[138] S. Sushkov,[11] G. Susinno,[36a,36b] M. R. Sutton,[148] Y. Suzuki,[65] Y. Suzuki,[66] M. Svatos,[124] Yu. M. Sviridov,[127] S. Swedish,[167] I. Sykora,[143a] T. Sykora,[125] B. Szeless,[29] J. Sánchez,[166] D. Ta,[104] K. Tackmann,[41] A. Taffard,[162] R. Tafirout,[158a] N. Taiblum,[152] Y. Takahashi,[100] H. Takai,[24] R. Takashima,[68] H. Takeda,[66] T. Takeshita,[139] M. Talby,[82] A. Talyshev,[106,e] M. C. Tamsett,[24] J. Tanaka,[154] R. Tanaka,[114] S. Tanaka,[130] S. Tanaka,[65] Y. Tanaka,[99] K. Tani,[66] N. Tannoury,[82] G. P. Tappern,[29] S. Tapprogge,[80] D. Tardif,[157] S. Tarem,[151] F. Tarrade,[28] G. F. Tartarelli,[88a] P. Tas,[125] M. Tasevsky,[124] E. Tassi,[36a,36b] M. Tatarkhanov,[14] Y. Tayalati,[134d] C. Taylor,[76] F. E. Taylor,[91] G. N. Taylor,[85] W. Taylor,[158b] M. Teinturier,[114] M. Teixeira Dias Castanheira,[74] P. Teixeira-Dias,[75] K. K. Temming,[47] H. Ten Kate,[29] P. K. Teng,[150] S. Terada,[65] K. Terashi,[154] J. Terron,[79] M. Testa,[46] R. J. Teuscher,[157,k] J. Thadome,[173] J. Therhaag,[20] T. Theveneaux-Pelzer,[77] M. Thioye,[174] S. Thoma,[47] J. P. Thomas,[17] E. N. Thompson,[34] P. D. Thompson,[17] P. D. Thompson,[157] A. S. Thompson,[52] E. Thomson,[119] M. Thomson,[27] R. P. Thun,[86] F. Tian,[34] M. J. Tibbetts,[14] T. Tic,[124] V. O. Tikhomirov,[93] Y. A. Tikhonov,[106] S. Timoshenko,[95] P. Tipton,[174] F. J. Tique Aires Viegas,[29] S. Tisserant,[82] J. Tobias,[47] B. Toczek,[37] T. Todorov,[4] S. Todorova-Nova,[160] B. Toggerson,[162] J. Tojo,[65] S. Tokár,[143a] K. Tokunaga,[66] K. Tokushuku,[65] K. Tollefson,[87] M. Tomoto,[100] L. Tompkins,[30] K. Toms,[102] G. Tong,[32a] A. Tonoyan,[13] C. Topfel,[16] N. D. Topilin,[64] I. Torchiani,[29] E. Torrence,[113] H. Torres,[77] E. Torró Pastor,[166] J. Toth,[82,z] F. Touchard,[82] D. R. Tovey,[138] T. Trefzger,[172] L. Tremblet,[29] A. Tricoli,[29] I. M. Trigger,[158a] S. Trincaz-Duvoid,[77] T. N. Trinh,[77] M. F. Tripiana,[69] W. Trischuk,[157] A. Trivedi,[24,y] B. Trocmé,[54] C. Troncon,[88a] M. Trottier-McDonald,[141] M. Trzebinski,[38] A. Trzupek,[38] C. Tsarouchas,[29] J. C-L. Tseng,[117] M. Tsiakiris,[104] P. V. Tsiareshka,[89] D. Tsionou,[4,dd] G. Tsipolitis,[9] V. Tsiskaridze,[47] E. G. Tskhadadze,[50a] I. I. Tsukerman,[94] V. Tsulaia,[14] J.-W. Tsung,[20] S. Tsuno,[65] D. Tsybychev,[147] A. Tua,[138] A. Tudorache,[25a] V. Tudorache,[25a] J. M. Tuggle,[30] M. Turala,[38] D. Turecek,[126] I. Turk Cakir,[3e] E. Turlay,[104] R. Turra,[88a,88b] P. M. Tuts,[34] A. Tykhonov,[73] M. Tylmad,[145a,145b] M. Tyndel,[128] H. Tyrvainen,[29] G. Tzanakos,[8] K. Uchida,[20] I. Ueda,[154] R. Ueno,[28] M. Ugland,[13] M. Uhlenbrock,[20] M. Uhrmacher,[53] F. Ukegawa,[159] G. Unal,[29] D. G. Underwood,[5] A. Undrus,[24] G. Unel,[162] Y. Unno,[65] D. Urbaniec,[34] G. Usai,[7] M. Uslenghi,[118a] L. Vacavant,[82] V. Vacek,[126] B. Vachon,[84] S. Vahsen,[14] J. Valenta,[124] P. Valente,[131a] S. Valentinetti,[19a,19b] S. Valkar,[125] E. Valladolid Gallego,[166] S. Vallecorsa,[151] J. A. Valls Ferrer,[166] H. van der Graaf,[104] E. van der Kraaij,[104] R. Van Der Leeuw,[104] E. van der Poel,[104] D. van der Ster,[29] N. van Eldik,[83] P. van Gemmeren,[5] Z. van Kesteren,[104] I. van Vulpen,[104] M. Vanadia,[98] W. Vandelli,[29] G. Vandoni,[29] A. Vaniachine,[5] P. Vankov,[41] F. Vannucci,[77] F. Varela Rodriguez,[29] R. Vari,[131a] E. W. Varnes,[6] D. Varouchas,[14] A. Vartapetian,[7] K. E. Varvell,[149] V. I. Vassilakopoulos,[55] F. Vazeille,[33] G. Vegni,[88a,88b] J. J. Veillet,[114] C. Vellidis,[8] F. Veloso,[123a] R. Veness,[29] S. Veneziano,[131a] A. Ventura,[71a,71b] D. Ventura,[137] M. Venturi,[47] N. Venturi,[157] V. Vercesi,[118a] M. Verducci,[137] W. Verkerke,[104] J. C. Vermeulen,[104] A. Vest,[43] M. C. Vetterli,[141,f] I. Vichou,[164] T. Vickey,[144b,ee] O. E. Vickey Boeriu,[144b] G. H. A. Viehhauser,[117] S. Viel,[167] M. Villa,[19a,19b] M. Villaplana Perez,[166] E. Vilucchi,[46]

M. G. Vincter,[28] E. Vinek,[29] V. B. Vinogradov,[64] M. Virchaux,[135,a] J. Virzi,[14] O. Vitells,[170] M. Viti,[41] I. Vivarelli,[47] F. Vives Vaque,[2] S. Vlachos,[9] D. Vladoiu,[97] M. Vlasak,[126] N. Vlasov,[20] A. Vogel,[20] P. Vokac,[126] G. Volpi,[46] M. Volpi,[85] G. Volpini,[88a] H. von der Schmitt,[98] J. von Loeben,[98] H. von Radziewski,[47] E. von Toerne,[20] V. Vorobel,[125] A. P. Vorobiev,[127] V. Vorwerk,[11] M. Vos,[166] R. Voss,[29] T. T. Voss,[173] J. H. Vossebeld,[72] N. Vranjes,[12a] M. Vranjes Milosavljevic,[104] V. Vrba,[124] M. Vreeswijk,[104] T. Vu Anh,[80] R. Vuillermet,[29] I. Vukotic,[114] W. Wagner,[173] P. Wagner,[119] H. Wahlen,[173] J. Wakabayashi,[100] J. Walbersloh,[42] S. Walch,[86] J. Walder,[70] R. Walker,[97] W. Walkowiak,[140] R. Wall,[174] P. Waller,[72] A. Walz,[47] C. Wang,[44] H. Wang,[171] H. Wang,[32b,ff] J. Wang,[150] J. Wang,[54] J. C. Wang,[137] R. Wang,[102] S. M. Wang,[150] A. Warburton,[84] C. P. Ward,[27] M. Warsinsky,[47] R. Wastie,[117] P. M. Watkins,[17] A. T. Watson,[17] I. J. Watson,[149] M. F. Watson,[17] G. Watts,[137] S. Watts,[81] A. T. Waugh,[149] B. M. Waugh,[76] J. Weber,[42] M. Weber,[128] M. S. Weber,[16] P. Weber,[53] A. R. Weidberg,[117] P. Weigell,[98] J. Weingarten,[53] C. Weiser,[47] H. Wellenstein,[22] P. S. Wells,[29] M. Wen,[46] T. Wenaus,[24] S. Wendler,[122] Z. Weng,[150,t] T. Wengler,[29] S. Wenig,[29] N. Wermes,[20] M. Werner,[47] P. Werner,[29] M. Werth,[162] M. Wessels,[57a] C. Weydert,[54] K. Whalen,[28] S. J. Wheeler-Ellis,[162] S. P. Whitaker,[21] A. White,[7] M. J. White,[85] S. R. Whitehead,[117] D. Whiteson,[162] D. Whittington,[60] F. Wicek,[114] D. Wicke,[173] F. J. Wickens,[128] W. Wiedenmann,[171] M. Wielers,[128] P. Wienemann,[20] C. Wiglesworth,[74] L. A. M. Wiik,[47] L. A. M. Wiik-Fuchs,[47] P. A. Wijeratne,[76] A. Wildauer,[166] M. A. Wildt,[41,q] I. Wilhelm,[125] H. G. Wilkens,[29] J. Z. Will,[97] E. Williams,[34] H. H. Williams,[119] W. Willis,[34] S. Willocq,[83] J. A. Wilson,[17] M. G. Wilson,[142] A. Wilson,[86] I. Wingerter-Seez,[4] S. Winkelmann,[47] F. Winklmeier,[29] M. Wittgen,[142] M. W. Wolter,[38] H. Wolters,[123a,i] W. C. Wong,[40] G. Wooden,[86] B. K. Wosiek,[38] J. Wotschack,[29] M. J. Woudstra,[83] K. W. Wozniak,[38] K. Wraight,[52] C. Wright,[52] M. Wright,[52] B. Wrona,[72] S. L. Wu,[171] X. Wu,[48] Y. Wu,[32b,gg] E. Wulf,[34] R. Wunstorf,[42] B. M. Wynne,[45] S. Xella,[35] M. Xiao,[135] S. Xie,[47] Y. Xie,[32a] C. Xu,[32b,hh] D. Xu,[138] G. Xu,[32a] B. Yabsley,[149] S. Yacoob,[144b] M. Yamada,[65] H. Yamaguchi,[154] A. Yamamoto,[65] K. Yamamoto,[63] S. Yamamoto,[154] T. Yamamura,[154] T. Yamanaka,[154] J. Yamaoka,[44] T. Yamazaki,[154] Y. Yamazaki,[66] Z. Yan,[21] H. Yang,[86] U. K. Yang,[81] Y. Yang,[60] Y. Yang,[32a] Z. Yang,[145a,145b] S. Yanush,[90] Y. Yao,[14] Y. Yasu,[65] G. V. Ybeles Smit,[129] J. Ye,[39] S. Ye,[24] M. Yilmaz,[3c] R. Yoosoofmiya,[122] K. Yorita,[169] R. Yoshida,[5] K. Yoshihara,[154] C. Young,[142] S. Youssef,[21] D. Yu,[24] J. Yu,[7] J. Yu,[111] L. Yuan,[32a,ii] A. Yurkewicz,[105] B. Zabinski,[38] V. G. Zaets,[127] R. Zaidan,[62] A. M. Zaitsev,[127] Z. Zajacova,[29] Yo. K. Zalite,[120] L. Zanello,[131a,131b] P. Zarzhitsky,[39] A. Zaytsev,[106] C. Zeitnitz,[173] M. Zeller,[174] M. Zeman,[124] A. Zemla,[38] C. Zendler,[20] O. Zenin,[127] T. Ženiš,[143a] Z. Zenonos,[121a,121b] S. Zenz,[14] D. Zerwas,[114] G. Zevi della Porta,[56] Z. Zhan,[32d] D. Zhang,[32b,ff] H. Zhang,[87] J. Zhang,[5] X. Zhang,[32d] Z. Zhang,[114] L. Zhao,[107] T. Zhao,[137] Z. Zhao,[32b] A. Zhemchugov,[64] S. Zheng,[32a] J. Zhong,[117] B. Zhou,[86] N. Zhou,[162] Y. Zhou,[150] C. G. Zhu,[32d] H. Zhu,[41] J. Zhu,[86] Y. Zhu,[32b] X. Zhuang,[97] V. Zhuravlov,[98] D. Zieminska,[60] R. Zimmermann,[20] S. Zimmermann,[20] S. Zimmermann,[47] M. Ziolkowski,[140] R. Zitoun,[4] L. Živković,[34] V. V. Zmouchko,[127,a] G. Zobernig,[171] A. Zoccoli,[19a,19b] Y. Zolnierowski,[4] A. Zsenei,[29] M. zur Nedden,[15] V. Zutshi,[105] and L. Zwalinski[29]

(ATLAS Collaboration)

[1]*University at Albany, Albany, New York, USA*
[2]*Department of Physics, University of Alberta, Edmonton, Alberta, Canada*
[3a]*Department of Physics, Ankara University, Ankara, Turkey*
[3b]*Department of Physics, Dumlupinar University, Kutahya, Turkey*
[3c]*Department of Physics, Gazi University, Ankara, Turkey*
[3d]*Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey*
[3e]*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, Illinois, USA*
[6]*Department of Physics, University of Arizona, Tucson, Arizona, USA*
[7]*Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA*
[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*
[12a]*Institute of Physics, University of Belgrade, Belgrade, Serbia*
[12b]*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, California, USA
[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
[18a]Department of Physics, Bogazici University, Istanbul, Turkey
[18b]Division of Physics, Dogus University, Istanbul, Turkey
[18c]Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
[18d]Department of Physics, Istanbul Technical University, Istanbul, Turkey
[19a]INFN Sezione di Bologna, Italy
[19b]Dipartimento di Fisica, Università di Bologna, Bologna, Italy
[20]Physikalisches Institut, University of Bonn, Bonn, Germany
[21]Department of Physics, Boston University, Boston, Massachusetts, USA
[22]Department of Physics, Brandeis University, Waltham, Massachusetts, USA
[23a]Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
[23b]Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
[23c]Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
[23d]Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
[24]Physics Department, Brookhaven National Laboratory, Upton, New York, USA
[25a]National Institute of Physics and Nuclear Engineering, Bucharest, Romania
[25b]University Politehnica Bucharest, Bucharest, Romania
[25c]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, Ontario, Canada
[29]CERN, Geneva, Switzerland
[30]Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
[31a]Departamento de Fisica, Pontificia Universidad Católica de Chile, Santiago, Chile
[31b]Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
[32a]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
[32b]Department of Modern Physics, University of Science and Technology of China, Anhui, China
[32c]Department of Physics, Nanjing University, Jiangsu, China
[32d]High Energy Physics Group, 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, New York, USA
[35]Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
[36a]INFN Gruppo Collegato di Cosenza, Italy
[36b]Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
[37]Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland
[38]The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
[39]Physics Department, Southern Methodist University, Dallas, Texas, USA
[40]Physics Department, University of Texas at Dallas, Richardson, Texas, USA
[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, North Carolina, USA
[45]SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[46]INFN Laboratori Nazionali di Frascati, Frascati, Italy
[47]Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg im Breisgau, Germany
[48]Section de Physique, Université de Genève, Geneva, Switzerland
[49a]INFN Sezione di Genova, Italy
[49b]Dipartimento di Fisica, Università di Genova, Genova, Italy
[50a]E.Andronikashvili Institute of Physics, Georgian Academy of Sciences, Tbilisi, Georgia
[50b]High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
[51]II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
[52]SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[53]II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
[54]Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
[55]Department of Physics, Hampton University, Hampton, Virginia, USA
[56]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA

[57a]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[57b]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[57c]ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
[58]Faculty of Science, Hiroshima University, Hiroshima, Japan
[59]Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
[60]Department of Physics, Indiana University, Bloomington, Indiana, USA
[61]Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
[62]University of Iowa, Iowa City, Iowa, USA
[63]Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
[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
[71a]INFN Sezione di Lecce, Italy
[71b]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 Fisica Teorica C-15, Universidad Autonoma 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, Massachusetts, USA
[84]Department of Physics, McGill University, Montreal, Quebec, Canada
[85]School of Physics, University of Melbourne, Victoria, Australia
[86]Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA
[87]Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
[88a]INFN Sezione di Milano, Italy
[88b]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, Massachusetts, USA
[92]Group of Particle Physics, University of Montreal, Montreal, Quebec, 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
[101a]INFN Sezione di Napoli, Italy
[101b]Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
[102]Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
[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, Illinois, USA
[106]Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia
[107]Department of Physics, New York University, New York, New York, USA
[108]Ohio State University, Columbus, Ohio, USA
[109]Faculty of Science, Okayama University, Okayama, Japan
[110]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
[111]Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
[112]Palacký University, RCPTM, Olomouc, Czech Republic

[113]Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
[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
[118a]INFN Sezione di Pavia, Italy
[118b]Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy
[119]Department of Physics, University of Pennsylvania, Philadelphia,, Pennsylvania, USA
[120]Petersburg Nuclear Physics Institute, Gatchina, Russia
[121a]INFN Sezione di Pisa, Italy
[121b]Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
[122]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
[123a]Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal
[123b]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, Saskatchewan, Canada
[130]Ritsumeikan University, Kusatsu, Shiga, Japan
[131a]INFN Sezione di Roma I, Italy
[131b]Dipartimento di Fisica, Università La Sapienza, Roma, Italy
[132a]INFN Sezione di Roma Tor Vergata, Italy
[132b]Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
[133a]INFN Sezione di Roma Tre, Italy
[133b]Dipartimento di Fisica, Università Roma Tre, Roma, Italy
[134a]Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco
[134b]Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat, Morocco
[134c]Université Cadi Ayyad, Faculté des sciences Semlalia Département de Physique, B.P. 2390 Marrakech 40000, Morocco
[134d]Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
[134e]Faculté des Sciences, Université Mohammed V, 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, California, USA
[137]Department of Physics, University of Washington, Seattle, Washington, USA
[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, British Columbia, Canada
[142]SLAC National Accelerator Laboratory, Stanford, California, USA
[143a]Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic
[143b]Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
[144a]Department of Physics, University of Johannesburg, Johannesburg, South Africa
[144b]School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[145a]Department of Physics, Stockholm University, Sweden
[145b]The Oskar Klein Centre, Stockholm, Sweden
[146]Physics Department, Royal Institute of Technology, Stockholm, Sweden
[147]Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA
[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 Institute 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, Ontario, Canada
[158a]TRIUMF, Vancouver, British Colombia, Canada

[158b]*Department of Physics and Astronomy, York University, Toronto, Ontario, 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, Massachusetts, USA*
[161]*Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia*
[162]*Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*
[163a]*INFN Gruppo Collegato di Udine, Italy*
[163b]*ICTP, Trieste, Italy*
[163c]*Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy*
[164]*Department of Physics, University of Illinois, Urbana, Illinois, USA*
[165]*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
[166]*Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingenierá Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain*
[167]*Department of Physics, University of British Columbia, Vancouver, British Colombia, Canada*
[168]*Department of Physics and Astronomy, University of Victoria, Victoria, British Colombia, Canada*
[169]*Waseda University, Tokyo, Japan*
[170]*Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel*
[171]*Department of Physics, University of Wisconsin, Madison, Wisconsin, USA*
[172]*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany*
[173]*Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
[174]*Department of Physics, Yale University, New Haven, Connecticut, USA*
[175]*Yerevan Physics Institute, Yerevan, Armenia*
[176]*Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France*

[a]Deceased.
[b]Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas—LIP, Lisboa, Portugal.
[c]Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
[d]Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
[e]Also at Novosibirsk State University, Novosibirsk, Russia.
[f]Also at TRIUMF, Vancouver, BC, Canada.
[g]Also at Department of Physics, California State University, Fresno, CA, United States of America., USA
[h]Also at Fermilab, Batavia, IL, USA.
[i]Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
[j]Also at Università di Napoli Parthenope, Napoli, Italy.
[k]Also at Institute of Particle Physics (IPP), Canada.
[l]Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
[m]Also at Louisiana Tech University, Ruston, LA, USA.
[n]Also at Department of Physics and Astronomy, University College London, London, United Kingdom.
[o]Also at Group of Particle Physics, University of Montreal, Montreal, QC, Canada.
[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, USA.
[s]Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
[t]Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
[u]Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
[v]Also at High Energy Physics Group, Shandong University, Shandong, China.
[w]Also at Section de Physique, Université de Genève, Geneva, Switzerland.
[x]Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.
[y]Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.
[z]Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
[aa]Also at California Institute of Technology, Pasadena, CA, USA.
[bb]Also at Institute of Physics, Jagiellonian University, Krakow, Poland.
[cc]Also at Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China.
[dd]Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
[ee]Also at Department of Physics, Oxford University, Oxford, United Kingdom.
[ff]Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
[gg]Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.

[hh]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.
[ii]Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.