Search for the Higgs boson in the $H \rightarrow WW(\ast) \rightarrow \ell^+ \nu \ell^- \bar{\nu}$ Decay Channel in pp Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector


DOI
10.1103/PhysRevLett.108.111802

Publication date
2012

Document Version
Final published version

Published in
Physical Review Letters

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).
Search for the Higgs Boson in the $H \to WW^{(*)} \rightarrow l^+\nu l^-\bar{\nu}$ Decay Channel in $pp$ Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector

G. Aad et al.*
(ATLAS Collaboration)

(Received 12 December 2011; published 13 March 2012)

A search for the Higgs boson has been performed in the $H \to WW^{(*)} \rightarrow \ell^+\nu l^-\bar{\nu}$ 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 < $m_H$ < 300 GeV. The observations exclude the presence of a standard model Higgs boson with a mass 145 < $m_H$ < 206 GeV at 95% confidence level.

DOI: 10.1103/PhysRevLett.108.111802

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, giving 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 ($gg \rightarrow H$) [2] due to the large gluon density, although vector boson fusion ($qq \rightarrow qH$) [3] is also important. Associated production of Higgs bosons ($WH, ZH$) also contributes more than 4% to the total rate for $m_H < 135$ 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 $m_H < 114.4$ GeV or $156$ GeV < $m_H$ < 177 GeV [5] at 95% confidence level (C.L.). The search for $H \rightarrow ZZ \rightarrow 4\ell$ at ATLAS excludes a standard model Higgs boson with a mass 340 < $m_H$ < 450 GeV, while the search for $H \rightarrow ZZ \rightarrow 4\ell$ 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 $H \rightarrow WW^{(*)} \rightarrow \ell^+\nu l^-\bar{\nu}$ [7] ($\ell = e/\mu$, but including contributions from $\tau \rightarrow e/\mu$ 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 $\textit{in situ}$ 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 $E_T > 20$ 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 $p_T > 20$ GeV and $|\eta| < 2.4$. Events are required to have a primary vertex with $z \geq 3$ tracks with $p_T > 0.4$ 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.

*Full author list given at the end of the article.

Published by the American Physical Society under the terms of the Creative Commons Attribution 3.0 License. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI.
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 $Z \rightarrow \ell \ell$, $J/\psi \rightarrow \ell \ell$, and $W \rightarrow \ell \nu$ 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 $\eta$ dependent correction factors based on MC simulation and validated by test beam and collision data studies [16]. They are required to have $E_T > 25$ 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 $E_T^{\text{miss}}$ [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 $E_T^{\text{miss}}$ distribution in the presence of pileup has been studied, and both $E_T^{\text{miss}}$ as a function of the number of reconstructed primary vertices and $E_T^{\text{miss}}$ 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 $\mu$) with $p_T > 15$ GeV for muons or $E_T > 20$ 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 ($tW/tb/tq\bar{b}$), $WW$, 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 $gg \rightarrow H$ and $qq \rightarrow qqH$ processes are modeled using POWHEG, with PYTHIA to handle the parton shower [19], and the $gg \rightarrow H$ 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 $qq/q\bar{q} \rightarrow WW/Z\gamma/Z\gamma$ processes are generated with MC@NLO, $t$-channel and $Wt$ single top with ACERMC (interfaced to the parton shower algorithm in PYTHIA), $gg \rightarrow WW$ with GG2WW interfaced to the parton shower algorithm in HERWIG [21], $W\gamma$ with MADGRAPH interfaced to PYTHIA, and $W +$ jets and $Z/\gamma^* +$ 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 $|m_{\ell\ell} - m_Z| < 15$ GeV to suppress backgrounds from $Y$ and $Z$ production, respectively.

The quantity $E_T^{\text{miss},\ell \ell}$ is defined as $E_T^{\text{miss}}$ if the angle $\Delta \phi$ between the missing transverse momentum and the transverse momentum of the nearest lepton or jet is greater than $\frac{\pi}{2}$, or $E_T^{\text{miss}} \sin(\Delta \phi)$ otherwise. $E_T^{\text{miss},\ell \ell}$ is less sensitive to the mismeasurement of a single lepton or jet than $E_T^{\text{miss}}$. To suppress backgrounds from multijet events and Drell-Yan production, it is required that $E_T^{\text{miss},\ell \ell} > 40$ GeV if the two leptons have the same flavor, or $E_T^{\text{miss},\ell \ell} > 25$ 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 $H + 1 -$ jet channel, the dilepton system is required to have a large transverse boost, $p_T^{\ell \ell} > 30$ 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 $|p_T^\text{jet}| < 30$ GeV, where $p_T^\text{jet}$ is the vector sum of the transverse momenta of the jet, the two leptons, and the $E_T^{\text{miss}}$ vector. This latter selection suppresses events with significant hadronic activity that recoils against the $p_T^\text{jet}$ system but does not leave high $p_T^\text{jet}$ jets in the detector. In the $H + 1 -$ jet channel, the event is required to pass the $Z \rightarrow \tau\tau$ rejection cut used in the $H \rightarrow WW$ 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 $m_t$, the chosen upper bound depends on the Higgs boson mass hypothesis. For $m_H < 170$ GeV, $m_{\ell\ell} < 50$ GeV is required, while for $170 \leq m_H < 220$ GeV, the cut is $m_{\ell\ell} < 65$ GeV. For $m_H \geq 220$ GeV, the requirement is $50 < m_{\ell\ell} < 180$ GeV.

For $m_H < 220$ 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 $m_H < 170$ GeV, or $\Delta \phi_{\ell\ell} < 1.8$ for $m_H < 220$ GeV. The final requirement uses the transverse mass $m_T$ [25] which is defined as $(m_T)^2 = m_{\ell\ell}^2 + 2(e_\nu p_{T\ell\nu} - p_{T\ell\nu} \cdot p_{T\ell\ell}),$ where the subscripts $\nu$ and $i$ denote the visible and invisible decay products and $e_\nu = \sqrt{p_{T\ell\nu} \cdot p_{T\ell\nu} + m_\nu^2}$ denotes the transverse energy. The transverse mass $m_T$ is required to lie within $0.75 m_H < m_T < m_H$ if $m_H < 220$ GeV or $0.6 m_H < m_T < m_H$ 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 $gg \rightarrow WW$ 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,
with $Z/\gamma^* + \text{jets}$, $t\bar{t}$, and $tW/tb/tq$ 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 $W + \text{jets}$ 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 $E_T^{\text{miss}}$ at high values based on the observed difference between the fraction of events passing the $E_T^{\text{miss}} > 40$ 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.
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 \( m_H < 220 \) GeV, the cut is changed to \( m_{\ell\ell} > 80 \) GeV, while for \( m_H > 220 \) 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 \( E_T^{\text{miss}} \). 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 \( E_T^{\text{miss}} \) 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.](image-url)
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 $134 < m_H < 200$ GeV at the 95% C.L. The Higgs boson mass interval excluded by the measurements presented in this Letter, $145 < m_H < 206$ 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].

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; AHAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; ARTEMIS, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMFB, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINEVRA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNISw, Poland; GRICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular, from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.


M. G. Vincter,28 E. Vinck,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. 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. Walders,42 J. Walder,70 R. Walker,97
W. Walkowiak,140 R. Wall,173 P. Waller,72 A. Walz,43 C. Wang,44 H. Wang,171 H. Wang,32b,ff J. Wang,150 J. Wang,54
T. Wengler,29 S. Wenig,29 N. Wermes,20 M. Werner,47 P. Werner,29 M. Werth,162 M. Wessels,75a C. Weydert,54
K. Whalen,28 J. W. Wheeler-Ellis,162 S. P. Whitaker,21 A. White,7 M. J. White,85 S. R. Whitehead,117 D. Whiteson,162
C. Wiglesworth,74 L. A. M. Wiik,127 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. Wingert-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. Wrait,52 C. Wright,52 M. Wright,52 B. Wrone,72 S. L. Wu,171 X. Wu,46 Y. Wu,32b,ff E. Wulf,34
R. Wunstorf,42 B. M. Wynne,45 S. Xella,35 M. Xiao,135 S. Xie,47 Y. Xie,32c, X. Xu,32,32h, D. Xue,138 G. Xu,12a
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
Z. Zajacova,29 Yo. K. Zalite,120 L. Zanello,131,a,131b P. Zarzhitsky,39 A. Zaytsev,106 C. Zeitnitz,137 M. Zeller,174
M. Zeman,124 A. Zemla,38 C. Zendler,20 O. Zenin,127 T. Zeni,143a Z. Zenonos,121a,121b S. Zenz,14 D. Zerwas,114
G. Zevi della Porta,56 Z. Zhao,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
S. Zimmermann,17 M. Ziolkowski,140 R. Zitoun,4 L. Živković,34 V. V. Zmouchko,127,a G. Zobernig,171
A. Zoccoli,19,a,19b Y. Zolnierowski,4 A. Zsenei,29 M. zur Nedden,15 V. Zutshi,105 and L. Zwalinski29

(ITALIS Collaboration)

1University at Albany, Albany, New York, USA
2Department of Physics, University of Alberta, Edmonton, Alberta, Canada
3Department of Physics, Ankara University, Ankara, Turkey
3aDepartment of Physics, Dumlupinar University, Kutahya, Turkey
3bDepartment of Physics, TOBB University of Economics and Technology, Ankara, Turkey
3cDivision of Physics, TOBB University of Economics and Technology, Ankara, Turkey
4LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
5High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
6Department of Physics, University of Arizona, Tucson, Arizona, USA
7Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA
8Physics Department, National Technical University of Athens, Zografou, Greece
9Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
10Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
11Instituto de Física de Partículas and Departamento de Física de la Universidad Autónoma de Barcelona, Spain
12Institute of Physics, University of Belgrade, Belgrade, Serbia
13Institut de Física de Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Spain
14Turkish Atomic Energy Authority, Ankara, Turkey
15Department for Physics and Technology, University of Bergen, Bergen, Norway
16Department of Physics, University of Bergen, Bergen, Norway
17Department of Physics, University of Belgrade, Belgrade, Serbia
18Vinca Institute of Nuclear Sciences, Belgrade, Serbia
19Department for Physics and Technology, University of Bergen, Bergen, Norway

PRL 108, 111802 (2012) PHYSICAL REVIEW LETTERS week ending 16 MARCH 2012

111802-14
14Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
15Department of Physics, Humboldt University, Berlin, Germany
16Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
17School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
18Department of Physics, Bogazici University, Istanbul, Turkey
19Division of Physics, Dogus University, Istanbul, Turkey
18cDepartment of Physics, Istanbul Technical University, Istanbul, Turkey
18dINFN Sezione di Bologna, Italy
19aINFN Sezione di Bologna, Bologna, Italy
20Physikalisches Institut, University of Bonn, Bonn, Germany
21Department of Physics, Boston University, Boston, Massachusetts, USA
22Department of Physics, Brandeis University, Waltham, Massachusetts, USA
23Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
23aFederal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
23bFederal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
23cInstituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
24Physics Department, Brookhaven National Laboratory, Upton, New York, USA
25aNational Institute of Physics and Nuclear Engineering, Bucharest, Romania
25bUniversity Politehnica Bucharest, Bucharest, Romania
25cWest University in Timisoara, Timisoara, Romania
26Departamento de Fisica, Universidad de Buenos Aires, Buenos Aires, Argentina
27Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
28Department of Physics, Carleton University, Ottawa, Ontario, Canada
29CERN, Geneva, Switzerland
30Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
31aDepartamento de Fisica, Pontificia Universidad Catolica de Chile, Santiago, Chile
31bDepartamento de Fisica, Universidad Tecnica Federico Santa Maria, Valparaiso, Chile
32aInstitute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
32bDepartment of Modern Physics, University of Science and Technology of China, Anhui, China
32cDepartment of Physics, Nanjing University, Nanjing, China
32dHigh Energy Physics Group, Shandong University, Shandong, China
33Laboratoire de Physique Corpusculaire, Clermont Universite and Universite Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France
34Nevis Laboratory, Columbia University, Irvington, New York, USA
35Niels Bohr Institute, University of Copenhagen, Kopenhagen, Denmark
36aINFN Gruppo Collegato di Cosenza, Italy
36bDipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
37Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland
38The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
39Physics Department, Southern Methodist University, Dallas, Texas, USA
40Physics Department, University of Texas at Dallas, Richardson, Texas, USA
41DESY, Hamburg and Zeuthen, Germany
42Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
43Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
44Department of Physics, Duke University, Durham, North Carolina, USA
45SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
46INFN Laboratori Nazionali di Frascati, Frascati, Italy
47Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg im Breisgau, Germany
48Section de Physique, Université de Genève, Geneva, Switzerland
49aINFN Sezione di Genova, Italy
49bDipartimento di Fisica, Università di Genova, Genova, Italy
50aE.Andronikashvili Institute of Physics, Georgian Academy of Sciences, Tbilisi, Georgia
50bHigh Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
51II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
52SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
53II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
54Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
55Department of Physics, Hampton University, Hampton, Virginia, USA
56Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France
Graduate School of Science, Osaka University, Osaka, Japan
Department of Physics, University of Oslo, Oslo, Norway
Department of Physics, Oxford University, Oxford, United Kingdom
INFN Sezione di Pavia, Italy
Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
Petersburg Nuclear Physics Institute, Gatchina, Russia
INFN Sezione di Pisa, Italy
Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
Laboratorio de Instrumentación y Física Experimental de Partículas - LIP, Lisboa, Portugal
Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
Faculty of Mathematics and Physics, Charles University in Prague, Prague, Czech Republic
Czech Technical University in Prague, Prague, Czech Republic
State Research Center Institute for High Energy Physics, Protvino, Russia
Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
Physics Department, University of Regina, Regina, Saskatchewan, Canada
Ritsumeikan University, Kusatsu, Shiga, Japan
INFN Sezione di Roma I, Italy
Dipartimento di Fisica, Università La Sapienza, Roma, Italy
INFN Sezione di Roma Tor Vergata, Italy
Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
INFN Sezione di Roma Tre, Italy
Dipartimento di Fisica, Università Roma Tre, Roma, Italy
Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco
Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco
Université Cadi Ayyad, Faculté des sciences Semlalia Département de Physique, B.P. 2390 Marrakech 40000, Morocco
Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
Faculté des Sciences, Université Mohammed V, Rabat, Morocco
DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France
Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
Department of Physics, University of Washington, Seattle, Washington, USA
Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
Department of Physics, Shinshu University, Nagano, Japan
Fachbereich Physik, Universität Siegen, Siegen, Germany
Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada
SLAC National Accelerator Laboratory, Stanford, California, USA
Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic
Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
Department of Physics, University of Johannesburg, Johannesburg, South Africa
School of Physics, University of the Witwatersrand, Johannesburg, South Africa
Department of Physics, Stockholm University, Sweden
The Oskar Klein Centre, Stockholm, Sweden
Physics Department, Royal Institute of Technology, Stockholm, Sweden
Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA
Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
School of Physics, University of Sydney, Sydney, Australia
Institute of Physics, Academia Sinica, Taipei, Taiwan
Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
Department of Physics, University of Toronto, Toronto, Ontario, Canada
TRIUMF, Vancouver, British Colombia, Canada
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.

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