Author(s): ATLAS Collaboration

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Observation of a New χ_b State in Radiative Transitions to $\Upsilon(1S)$ and $\Upsilon(2S)$ at ATLAS

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

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The $\chi_b(nP)$ quarkonium states are produced in proton-proton collisions at the Large Hadron Collider at $\sqrt{s} = 7$ TeV and recorded by the ATLAS detector. Using a data sample corresponding to an integrated luminosity of 4.4 fb^{-1}, these states are reconstructed through their radiative decays to $\Upsilon(1S, 2S)$ with $\Upsilon \to \mu^+\mu^-$. In addition to the mass peaks corresponding to the decay modes $\chi_b(1P, 2P) \to \Upsilon(1S)\gamma$, a new structure centered at a mass of $10.530 \pm 0.005(\mathrm{stat}) \pm 0.009(\mathrm{syst})$ GeV is also observed, in both the $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$ decay modes. This structure is interpreted as the $\chi_b(3P)$ system.

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Measurements of the properties of heavy quark-antiquark bound states, or quarkonia, provide a unique insight into the nature of quantum chromodynamics close to the strong decay threshold. For the $b\bar{b}$ system, the quarkonium states with parallel quark spins ($s = 1$) include the S-wave Υ and the P-wave χ_b states, where the latter each comprise a closely spaced triplet of $J = 0, 1, 2$ spin states: χ_{b0}, χ_{b1}, and χ_{b2}. The $\chi_b(1P)$ and $\chi_b(2P)$, with spin-weighted mass barycenters of 9.90 and 10.26 GeV, respectively, can be readily produced in the radiative decays of $\Upsilon(2S)$ and $\Upsilon(3S)$ and have been studied experimentally [1].

In this Letter, χ_b quarkonium states are reconstructed with the ATLAS detector through the radiative decay modes $\chi_b(nP) \to \Upsilon(1S)\gamma$ and $\chi_b(nP) \to \Upsilon(2S)\gamma$, in which $\Upsilon(1S, 2S) \to \mu^+\mu^-$ and the photon is reconstructed either through conversion to e^+e^- or by direct calorimetric measurement. Previous experiments have measured the $\chi_b(1P)$ and $\chi_b(2P)$ through these decay modes [2]. The $\chi_b(3P)$ state has not previously been observed. It is predicted to have an average mass of approximately 10.52 GeV, with hyperfine mass splitting between the triplet states of 10–20 MeV [3,4].

The ATLAS detector [5] is a general-purpose particle physics detector with a forward-backward symmetric cylindrical geometry and near 4π coverage in solid angle. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field and by high-granularity liquid-argon sampling electromagnetic calorimeters. An iron-scintillator tile calorimeter provides hadronic coverage in the central rapidity range. The end cap and forward regions are instrumented with liquid-argon calorimeters for both electromagnetic and hadronic measurements. The muon spectrometer surrounds the calorimeters and consists of a system of precision tracking chambers and detectors for triggering, inside a toroidal magnetic field.

The data sample used for this measurement was recorded by the ATLAS experiment during the 2011 LHC proton-proton collision run at a center-of-mass energy $\sqrt{s} = 7$ TeV. The integrated luminosity of the data sample, which includes only data-taking periods where all relevant detector subsystems were operational, is 4.4 fb^{-1}. A set of muon triggers designed to select events containing muon pairs or single high transverse momentum muons was used to collect the data sample.

In this analysis, each muon candidate must satisfy standard muon quality requirements [6]. It must have a track, reconstructed in the muon spectrometer, combined with a track reconstructed in the ID with transverse momentum $p_T > 4$ GeV and pseudorapidity $|\eta| < 2.3$. The dimuon selection requires a pair of oppositely charged muons, which are fitted to a common vertex. A very loose vertex quality requirement [χ^2 per degree of freedom (d.o.f.) <20] is used and no mass or momentum constraints are applied to the fit. The dimuon candidate is also required to have $p_T > 12$ GeV and rapidity $|y| < 2.0$. The invariant mass distribution, $m_{\mu\mu}$, of dimuon candidates is shown in Fig. 1. Those candidates with masses in the ranges $9.25 < m_{\mu\mu} < 9.65$ GeV and $9.80 < m_{\mu\mu} < 10.10$ GeV are selected as $\Upsilon(1S) \to \mu^+\mu^-$ and $\Upsilon(2S) \to \mu^+\mu^-$ candidates, respectively. The asymmetric mass window (evident from Fig. 1) for $\Upsilon(2S)$ candidates is chosen in order to reduce contamination from the $\Upsilon(3S)$ peak and continuum background contributions.

The reconstruction of photons in ATLAS is described in Ref. [7]. Further details related to this particular analysis are described below.

Converted photons are reconstructed from two oppositely charged ID tracks intersecting at a conversion vertex, with the opening angle between the two tracks at this vertex constrained to be zero. For tracks with signals in

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

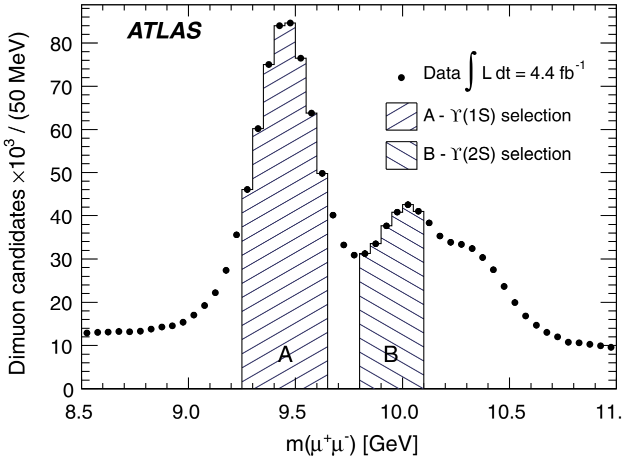

FIG. 1 (color online). The invariant mass of selected dimuon candidates. The shaded regions A and B show the selections for $\Upsilon(1S)$ and $\Upsilon(2S)$ candidates, respectively.

the transition radiation tracker, the transition radiation should be consistent with an electron hypothesis. In order to be reliably reconstructed, each conversion electron track must have a minimum transverse momentum of 500 MeV. It is also required to have at least four silicon detector hits and not to be associated to either of the two muon candidates. To reduce background contamination, the conversion candidate vertex is required to be at least 40 mm from the beam axis and have a vertex χ^2 probability of greater than 0.01. The converted photon impact parameter with respect to the dimuon vertex is required to be less than 2 mm.

Electromagnetic calorimeter energy deposits not matched to any track are classified as unconverted photons. This analysis uses the "loose" photon selection described in Ref. [7], with a minimum photon transverse energy of 2.5 GeV. The loose photon selection includes a limit on the fraction of the energy deposit in the hadronic calorimeter as well as a requirement that the transverse width of the shower be consistent with the narrow shape expected for an electromagnetic shower.

To check that an unconverted photon originates from the same vertex as the Υ, and to improve the mass resolution of the reconstructed χ_b, the polar angle of the photon is corrected using the procedure described in Ref. [8]. The corrected polar angle is determined using the measurement of the photon direction from the longitudinal segmentation of the calorimeter and the constraint from the dimuon vertex position. Photons incompatible with having originated from the dimuon vertex are rejected by means of a loose cut on the fit result (χ^2 per d.o.f. <200).

The converted (unconverted) photon candidates are required to be within $|\eta| < 2.30$ (2.37). Unconverted photons must also be outside the transition region between the barrel and the end cap calorimeters, $1.37 < |\eta| < 1.52$.

The χ_b candidates are formed by associating a reconstructed $\Upsilon \to \mu^+\mu^-$ candidate with a reconstructed photon. The invariant mass difference $\Delta m = m(\mu^+\mu^-\gamma) - m(\mu^+\mu^-)$ is calculated to minimize the effect of $\Upsilon \to \mu^+\mu^-$ mass resolution. In order to compare the Δm distributions of both $\chi_b(nP) \to \Upsilon(1S)\gamma$ and $\chi_b(nP) \to \Upsilon(2S)\gamma$ decays, the variable $\tilde{m}_k = \Delta m + m_{\Upsilon(kS)}$ is defined, where $m_{\Upsilon(kS)}$ are the world average masses [9] of the $\Upsilon(kS)$ states. Requirements of $p_T(\mu^+\mu^-) > 20$ GeV and $p_T(\mu^+\mu^-) > 12$ GeV are applied to Υ candidates with unconverted and converted photon candidates, respectively. These thresholds are

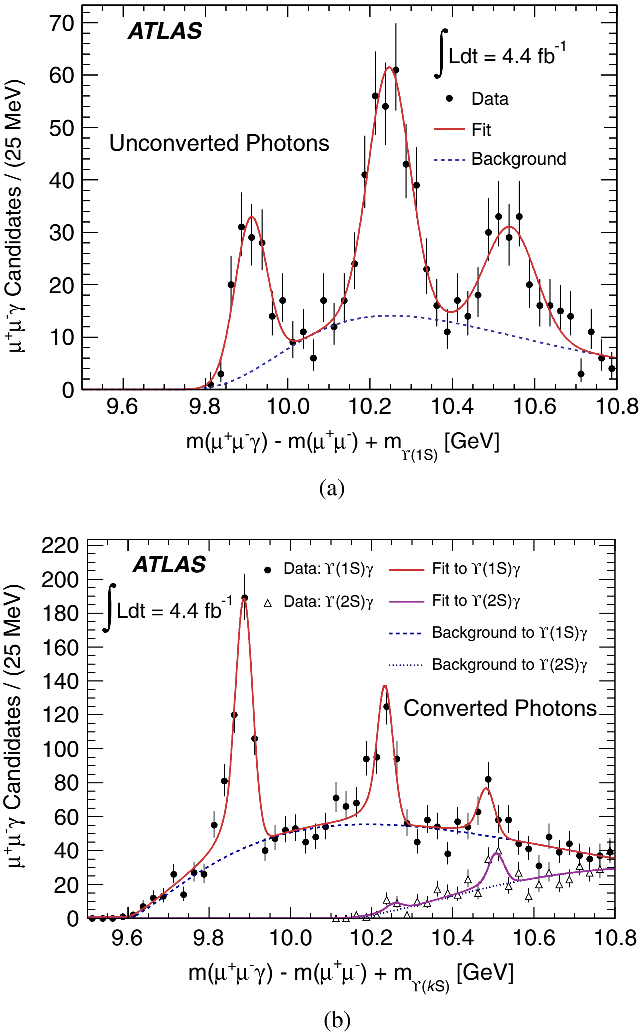

FIG. 2 (color online). (a) The mass distribution of $\chi_b \to \Upsilon(1S)\gamma$ candidates for unconverted photons reconstructed from energy deposits in the electromagnetic calorimeter ($\chi^2_{\mathrm{fit}}/\mathrm{d.o.f.} = 0.85$). (b) The mass distributions of $\chi_b \to \Upsilon(kS)\gamma$ ($k = 1, 2$) candidates formed using photons which have converted and been reconstructed in the ID ($\chi^2_{\mathrm{fit}}/\mathrm{d.o.f.} = 1.3$). Data are shown before the correction for the energy loss from the photon conversion electrons due to bremsstrahlung and other processes. The data for decays of $\chi_b \to \Upsilon(1S)\gamma$ and $\chi_b \to \Upsilon(2S)\gamma$ are plotted using circles and triangles, respectively. Solid lines represent the total fit result for each mass window. The dashed lines represent the background components only.

chosen in order to optimize signal significance in the $\chi_b(1P, 2P)$ peaks.

Figure 2(a) shows the $\tilde{m}_1$ distribution for unconverted photons and Fig. 2(b) shows the $\tilde{m}_1$ and $\tilde{m}_2$ distributions for converted photons. In addition to the expected peaks for $\chi_b(1P, 2P) \rightarrow \Upsilon(1S, 2S)\gamma$, structures are observed at an invariant mass of approximately 10.5 GeV. These additional structures are interpreted as the radiative decays of the previously unobserved $\chi_b(3P)$ states, $\chi_b(3P) \rightarrow \Upsilon(1S)\gamma$ and $\chi_b(3P) \rightarrow \Upsilon(2S)\gamma$.

Separate fits are performed to the $\tilde{m}_k$ distributions of the selected $\mu^+\mu^-\gamma$ candidates reconstructed from converted and unconverted photons to extract mass information from the observed $\chi_b(3P)$ signals. The higher threshold for unconverted photons (2.5 GeV, versus 1 GeV for converted photons) prevents the reconstruction of the soft photons from $\chi_b(2P, 3P)$ decays into $\Upsilon(2S)$.

An unbinned extended maximum likelihood fit is performed to the $\tilde{m}_1 = \Delta m + m_{\Upsilon(1S)}$ distribution of the selected unconverted $\mu^+\mu^-\gamma$ candidates. The three peaks in the distribution are each modeled by a Gaussian probability density function (PDF) with an independent normalization parameter N_n, mean value $\bar{m}_n$, and width parameter σ_n. The background distribution is parametrized by the PDF $N_B \exp(A\Delta m + B\Delta m^{-2})$ where N_B, A, and B are all free parameters. The three mean values $\bar{m}_{n=1,2,3}$ determined by the fit are shown in Table I. The mean value $\bar{m}_3$ is an estimate of the mass barycenter of the observed $\chi_b(3P)$ signal.

Likewise, the $\tilde{m}_1 = \Delta m + m_{\Upsilon(1S)}$ and $\tilde{m}_2 = \Delta m + m_{\Upsilon(2S)}$ distributions for the sample of $\mu^+\mu^-\gamma$ candidates reconstructed from converted photons are fitted using an unbinned extended maximum likelihood method. A simultaneous fit is performed on the $\tilde{m}_1$ and $\tilde{m}_2$ distributions for the $\chi_b(nP) \rightarrow \Upsilon(1S)\gamma$ (for $n = 1, 2, 3$) and $\chi_b(nP) \rightarrow \Upsilon(2S)\gamma$ (for $n = 2, 3$ only) signals, with the distributions modeled by three signal components [two of which are shared between the $\Upsilon(1S)$ and $\Upsilon(2S)$ distributions] and two background distributions.

In the Δm distribution for the converted photon candidates the typical mass resolution is found to be in the range 16–20 MeV, of similar magnitude to the hyperfine splittings, motivating the need for multiple signal components for each of the $\chi_b(nP)$ peaks. For $n = 1, 2$, the radiative branching fractions of the $J = 0$ states are suppressed with respect to the $J = 1, 2$ states [9] and therefore a $J = 0$ component is not included in the fit. Similar behavior is assumed for the $n = 3$ case. Each of the three peaks ($n = 1, 2, 3$) is therefore parametrized by a doublet of Crystal Ball (CB) [10] functions (corresponding to $J = 1, 2$ states) with resolution σ and radiative tail parameters common to all peaks. For $n = 1$ and $n = 2$, the peak mass values and hyperfine splittings are fixed to the world averages [9] for the respective χ_b states (see Table I). For $n = 3$, the hyperfine mass splitting is fixed to the theoretically predicted value of 12 MeV [4], while the average mass is left as a free parameter. The unknown relative normalization of the $J = 1$ and $J = 2$ CB peaks is taken to be equal and treated as a systematic uncertainty (for all doublets) for the baseline fit.

In order to take into account energy loss from the photon conversion electrons due to bremsstrahlung and other processes, the measured values of Δm in the $\tilde{m}_1$ and $\tilde{m}_2$ distributions are scaled by a common parameter $\lambda = 0.961 \pm 0.003$, which determines the energy scale and is derived from the fit to the $\chi_b(1P, 2P)$ signals. The background components of the Δm distributions for the $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$ final states are each modeled by the PDF $N_B^k(\Delta m - q_k^0)^{A_k} \exp[B_k(\Delta m - q_k^0)]$ for $\Delta m > q_k^0$, and zero otherwise, where N_B^k, q_k^0, A_k, and B_k ($k = 1, 2$) are all free parameters. The mean value $\bar{m}_3$ determined by the fit is shown in Table I.

In the fit using unconverted photons, the signal is refitted using an alternative (two Gaussians) model for each of the three χ_b states, resulting in a negligible change in the peak positions. Alternative fits to the background are also used, either including constraints on the Δm distribution using dimuon pairs from the low-mass ($8.0\ \text{GeV} < m_{\mu\mu} < 8.8\ \text{GeV}$) sideband or different background PDFs. The systematic uncertainty on the $\chi_b(3P)$ mass barycenter from the modeling of the background distribution is determined to be ±21 MeV. The systematic uncertainty associated with the unconverted photon energy scale is estimated to be ±2% on the Δm position, corresponding to a systematic uncertainty on $\bar{m}_3$ of ±22 MeV. The uncertainties due to background modeling and photon energy scale comprise the dominant sources of systematic uncertainty.

For the fit using converted photons, alternative signal and background models are compared, and various

TABLE I. The fitted mass of the $\chi_b(nP)$ signals for both converted and unconverted photons. The systematic uncertainty on the mass of candidates reconstructed with unconverted photons is determined in the same way for all three states. Also included are theoretical predictions [3,4] for the spin-averaged masses of the χ_b states.

		Fitted masses [MeV]	
State	Model predictions [3,4] [MeV]	Unconverted photons	Converted photons
$\chi_b(1P)$	9900	$9910 \pm 6(\text{stat}) \pm 11(\text{syst})$	Fixed to $\chi_{b1} = 9892.78$ and $\chi_{b2} = 9912.21$ [9]
$\chi_b(2P)$	10 260	$10\,246 \pm 5(\text{stat}) \pm 18(\text{syst})$	Fixed to $\chi_{b1} = 10\,255.46$ and $\chi_{b2} = 10\,268.65$ [9]
$\chi_b(3P)$	10 525	$10\,541 \pm 11(\text{stat}) \pm 30(\text{syst})$	$10\,530 \pm 5(\text{stat}) \pm 9(\text{syst})$

constraints in the fit model are also released. The unknown relative normalizations of the $J = 1$ and $J = 2$ CB peaks are varied both coherently and incoherently between the $1P$, $2P$, and $3P$ doublets by ± 0.25, resulting in a maximum variation in $\bar{m}_3$ of ± 5 MeV. Smaller variations are obtained if the common value of the relative normalization is allowed to be determined freely by the fit to the three doublets. Background modeling variations, decoupled fits to the $\tilde{m}_1$ and $\tilde{m}_2$ distributions, and individually released constraints on the mass position of the $n = 1, 2$ doublets each result in deviations of the order of ± 5 MeV or smaller. Furthermore, if the constraints on the masses of the $n = 1, 2$ peaks are released, the values obtained from the fit are consistent with expectations [9], within statistical errors and uncertainty in the relative contributions from $J = 1$ and $J = 2$ states. The effect of symmetrizing the $\Upsilon(2S)$ mass window is studied and found to have a negligible effect on the fitted χ_b masses while increasing background contamination. The resulting shifts in $\bar{m}_3$ for these independent variations are added in quadrature to provide an estimate of the systematic uncertainty.

The $\chi_b(3P)$ signal significance is assessed from $\log(L_{\max}/L_0)$, where $L_{\max}$ and L_0 are the likelihood values from the nominal fit and from a fit with no $\chi_b(3P)$ signal included, respectively. The fit is repeated with each of the systematic variations in the model, as discussed above, and the likelihood ratio reevaluated. The significance of the $\chi_b(3P)$ signal is found to be in excess of 6 standard deviations in each of the unconverted and converted photon selections independently.

The mass barycenter for the $\chi_b(3P)$ signal, determined from the fit using unconverted photon candidates is

$$\bar{m}_3 = 10.541 \pm 0.011(\text{stat}) \pm 0.030(\text{syst})\ \text{GeV}.$$

The mass barycenter for the $\chi_b(3P)$ signal, determined from the fit using converted photon candidates is

$$\bar{m}_3 = 10.530 \pm 0.005(\text{stat}) \pm 0.009(\text{syst})\ \text{GeV}.$$

The measured mass barycenters of the $\chi_b(1P)$, $\chi_b(2P)$, and $\chi_b(3P)$ systems are summarized in Table I. The results of the converted and unconverted photon analyses for the $\chi_b(3P)$ are found to be compatible. Given the substantially smaller systematic uncertainties in the conversion measurement, the final mass determination for $\bar{m}_3$ is quoted solely on the basis of this analysis.

In conclusion, the production of the heavy quarkonium states $\chi_b(nP)$ in proton-proton collisions at $\sqrt{s} = 7$ TeV is observed through the reconstruction of the radiative decay modes of $\chi_b(nP) \to \Upsilon(1S, 2S)\gamma$. Mass peaks corresponding to $\chi_b(1P, 2P)$ decays are observed, together with additional structures at higher mass, which are consistent with theoretical predictions for $\chi_b(3P) \to \Upsilon(1S)\gamma$ and $\chi_b(3P) \to \Upsilon(2S)\gamma$. These observations are interpreted as the $\chi_b(3P)$ multiplet, the mass barycenter of which is measured to be $10.530 \pm 0.005(\text{stat}) \pm 0.009(\text{syst})$ GeV.

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L. Yuan,[32a,ii] A. Yurkewicz,[105] B. Zabinski,[38] V. G. Zaets,[127] R. Zaidan,[62] A. M. Zaitsev,[127] Z. Zajacova,[29]
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. Zinonos,[121a,121b] S. Zenz,[14] D. Zerwas,[114] G. Zevi della Porta,[56]
Z. Zhan,[32d] D. Zhang,[32b,gg] 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 AB, 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 ON, 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]*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, 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 i.Br., 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 QC, 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 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
[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, Portugal*
[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*
[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]*Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, 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 BC, 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]*Departments of Physics & Astronomy and Chemistry, 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 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*
[158a]*TRIUMF, Vancouver BC, Canada*
[158b]*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, 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 Ingeniería 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 BC, Canada*
[168]*Department of Physics and Astronomy, University of Victoria, Victoria BC, 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 TRIUMF, Vancouver BC, Canada.

[f] Also at Department of Physics, California State University, Fresno CA, USA.

[g] Also at Novosibirsk State University, Novosibirsk, Russia.

[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 Department of Physics, University of Cape Town, Cape Town, South Africa.

[q] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

[r] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

[s] Also at Manhattan College, New York NY, USA.

[t] Also at School of Physics, Shandong University, Shandong, China.

[u] Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

[v] Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.

[w] Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

[x] 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.

[y] Also at Section de Physique, Université de Genève, Geneva, Switzerland.

[z] Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.

[aa] Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, USA.

[bb] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

[cc] Also at California Institute of Technology, Pasadena CA, USA.

[dd] Also at LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France.

[ee] Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.

[ff] Also at Department of Physics, Oxford University, Oxford, United Kingdom.

[gg] Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

[hh] Also at Department of Physics, The University of Michigan, Ann Arbor MI, USA.

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