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

The ATLAS Collaboration
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The $\chi_b(nP)$ quarkonium states are produced in proton-proton collisions at the Large Hadron Collider (LHC) 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 $10.530\pm0.005$ (stat.$)\pm0.009$ (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.

Measurements of the properties of heavy quark-antiquark bound states, or quarkonia, provide a unique insight into the nature of Quantum Chromodynamics (QCD). The quarkonium states with parallel quark spins ($s = 1$) include the S-wave $\Upsilon$ and the P-wave $\chi_b$ states, which are reconstructed in the ID with transverse momentum $p_T > 500$ MeV. The $\chi_b$ is predicted to have an average mass of approximately 10.52 GeV, with hyperfine mass splitting between the triplet states of 9.90 and 10.26 GeV, respectively, and mass barycenters of 9.90 and 10.26 GeV, respectively, can be readily produced in proton-proton collisions at the LHC.

In this letter, $\chi_b$ 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. 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.

The ATLAS detector is a general-purpose particle physics detector with a forward-backward symmetric cylindrical geometry and near 4$\pi$ coverage in solid angle. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker (TRT). The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field and by high-granularity liquid-argon sampling electromagnetic (EM) calorimeters. An iron-scintillator tile calorimeter provides hadronic coverage in the central rapidity range. The endcap and forward regions are instrumented with liquid-argon calorimeters for both electromagnetic and hadronic measurements. The muon spectrometer (MS) 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 sub-systems were operational, is 4.4 fb$^{-1}$. A set of muon triggers designed to select events containing di-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. It must have a track, reconstructed in the MS, combined with a track reconstructed in the ID with transverse momentum $p_T > 4$ GeV and pseudorapidity $|\eta| < 2.3$. The di-muon selection requires a pair of oppositely charged muons, which are fitted to a common vertex. A very loose vertex quality requirement ($\chi^2$ per degree of freedom [d.o.f.] < 20) is used and no mass or momentum constraints are applied to the fit. The di-muon candidate is also required to have $p_T > 12$ GeV and $|\eta| < 2.0$. The invariant mass distribution, $m_{\mu\mu}$, of di-muon 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 $\Upsilon(1S)\gamma\mu^+\mu^-$ and $\Upsilon(2S)\gamma\mu^+\mu^-$ 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. 11. 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 the TRT, 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.
reduce background contamination, the conversion candidate vertex is required to be at least 40 mm from the beam axis and have a vertex $\chi^2$ probability of greater than 0.01. The converted photon impact parameter with respect to the di-muon 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. [1], 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 EM shower.

To check that an unconverted photon originates from the same vertex as the $\Upsilon$, and to improve the mass resolution of the reconstructed $\chi_b$, 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 di-muon vertex position. Photons incompatible with having originated from the di-muon vertex are rejected by means of a loose cut on the fit result ($\chi^2$ per d.o.f. $< 200$).

The converted (unconverted) photon candidates are required to be within $|\eta| < 2.3$ (2.37). Unconverted photons must also be outside the transition region between the barrel and the endcap calorimeters, $1.37 < |\eta| < 1.52$.

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

Figure 2(a) shows the $\hat{m}_1$ distribution for unconverted photons and Fig. 2(b) the $\hat{m}_1$ and $\hat{m}_2$ 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 $\hat{m}_k$ 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 $\hat{m}_1 = \Delta m + m_{\Upsilon(1S)}$ 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 independent normalization parameter, $N_n$, mean value, $\bar{m}_n$, and width parameter, $\sigma_n$. The background distribution is parameterized by the pdf $N_B \cdot \exp (A \cdot \Delta m + B \cdot \Delta m^2)$ 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 1. The mean value $\bar{m}_1$ is an estimate of the mass barycenter of the observed $\chi_b(3P)$ signal.

Likewise, the $\hat{m}_1 = \Delta m + m_{\Upsilon(1S)}$ and $\hat{m}_2 = \Delta m + m_{\Upsilon(2S)}$ 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 $\hat{m}_1$ and $\hat{m}_2$ 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 $\Delta m$ 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 [4] 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 parameterized by a dou-
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 $\chi_b$ states.

<table>
<thead>
<tr>
<th>State</th>
<th>Model predictions [3, 4] [MeV]</th>
<th>Unconverted Photons</th>
<th>Fitted masses [MeV]</th>
<th>Converted Photons</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi_b(1P)$</td>
<td>9900</td>
<td>$9910 \pm 6$ (stat.) $\pm 11$ (syst.)</td>
<td>Fixed to $\chi_{b1} = 9892.78$ &amp; $\chi_{b2} = 9912.00$ [9]</td>
<td></td>
</tr>
<tr>
<td>$\chi_b(2P)$</td>
<td>10260</td>
<td>$10246 \pm 5$ (stat.) $\pm 18$ (syst.)</td>
<td>Fixed to $\chi_{b1} = 10255.46$ &amp; $\chi_{b2} = 10268.65$ [9]</td>
<td></td>
</tr>
<tr>
<td>$\chi_b(3P)$</td>
<td>10525</td>
<td>$10541 \pm 11$ (stat.) $\pm 30$ (syst.)</td>
<td>$10530 \pm 5$ (stat.) $\pm 9$ (syst.)</td>
<td></td>
</tr>
</tbody>
</table>

bution is determined to be $\Delta m > q$ from modeling of the background distribution using di-muon pairs from the low-mass $N$, and zero otherwise, where $N_{B}^{k}$, $q_{0}^{k}$, $A_k$, 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. 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 $\Delta m$ 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 $\Delta m$ distributions for the $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$ final states are each modeled by the pdf $N_{B}^{k} \cdot (\Delta m - q_{0}^{k})^{A_k} \cdot \exp \left[ B_k \cdot (\Delta m - q_{0}^{k}) \right]$ for $\Delta m > q_{0}^{k}$, and zero otherwise, where $N_{B}^{k}$, $q_{0}^{k}$, $A_k$, 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 refit using an alternative (two Gaussians) model for each of the three $\chi_b$ states, resulting in a negligible change in the peak positions. Alternative fits to the background distributions are scaled by a common parameter $\lambda$ and treated as a systematic uncertainty (for all doublets) for the baseline fit.

For the fit using converted photons, alternative signal and background models are compared, as well as releasing various constraints in the fit model. 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 $\pm 0.25$, resulting in a maximum variation in $\bar{m}_3$ of $\pm 5$ 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 $\pm 5$ 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 [3], 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 negligible effect on the fitted $\chi_b$ 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 $\log(L_{\text{max}}/L_0)$, where $L_{\text{max}}$ 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 re-evaluated. The significance of the $\chi_b(3P)$ signal is found to be in excess of six 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 $\sqrt{s} = 7 \text{ TeV}$...
is observed through 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 $10.530 \pm 0.005$ (stat.) $\pm 0.009$ (syst.) GeV.

FIG. 2: (a) The mass distribution of $\chi_b \to \Upsilon(1S) \gamma$ candidates for unconverted photons reconstructed from energy deposits in the electromagnetic calorimeter ($\chi^2/d.o.f. = 0.85$). (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 ($\chi^2/d.o.f. = 1.3$). 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.

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Section de Physique, Université de Genève, Geneva, Switzerland

INFN Sezione di Genova; Dipartimento di Fisica, Università di Genova, Genova, Italy

E. Andronikashvili Institute of Physics, Tbilisi State University, Tbilisi; High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany

SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom

II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany

Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France

Department of Physics, Hampton University, Hampton VA, United States of America

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

Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany

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

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

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

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

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

Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia

KEK, High Energy Accelerator Research Organization, Tsukuba, Japan

Graduate School of Science, Kobe University, Kobe, Japan

Faculty of Science, Kyoto University, Kyoto, Japan

Kyoto University of Education, Kyoto, Japan

Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina

Physics Department, Lancaster University, Lancaster, United Kingdom

Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom

Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia

School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom

Department of Physics, Royal Holloway University of London, Surrey, United Kingdom

Department of Physics and Astronomy, University College London, London, United Kingdom

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

Fysiska institutionen, Lunds universitet, Lund, Sweden

Departamento de Física Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain

Institut für Physik, Universität Mainz, Mainz, Germany

School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom

CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

Department of Physics, University of Massachusetts, Amherst MA, United States of America

Department of Physics, McGill University, Montreal QC, Canada

School of Physics, University of Melbourne, Victoria, Australia

Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America

INFN Sezione di Milano; Dipartimento di Fisica, Università di Milano, Milano, Italy

B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus

National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus

Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America

Group of Particle Physics, University of Montreal, Montreal QC, Canada

P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia

Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia

Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany

Nagasaki Institute of Applied Science, Nagasaki, Japan
Graduate School of Science, Nagoya University, Nagoya, Japan

INFN Sezione di Napoli; Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy

Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America

Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands

Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands

Department of Physics, Northern Illinois University, DeKalb IL, United States of America

Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia

Department of Physics, New York University, New York NY, United States of America

Ohio State University, Columbus OH, United States of America

Faculty of Science, Okayama University, Okayama, Japan

Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America

Department of Physics, Oklahoma State University, Stillwater OK, United States of America

Palacký University, RCPTM, Olomouc, Czech Republic

Center for High Energy Physics, University of Oregon, Eugene OR, United States of America

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; Dipartimento di Fisica, Università di Pavia, Pavia, Italy

Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America

Petersburg Nuclear Physics Institute, Gatchina, Russia

INFN Sezione di Pisa; Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy

Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America

Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal; Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain

Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic

Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic

Czech Technical University in Prague, Praha, 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 SK, Canada

Ritsumeikan University, Kusatsu, Shiga, Japan

INFN Sezione di Roma I; Dipartimento di Fisica, Università La Sapienza, Roma, Italy

INFN Sezione di Roma Tor Vergata; Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy

INFN Sezione di Roma Tre; Dipartimento di Fisica, Università Roma Tre, Roma, Italy

Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Énergies - Université Hassan II, Casablanca; Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat; Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; Faculté des Sciences, Université Mohammed V- Agdal, 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 CA, United States of America

Department of Physics, University of Washington, Seattle WA, United States of America

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 BC, Canada

SLAC National Accelerator Laboratory, Stanford CA, United States of America

Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic

Department of Physics, University of Johannesburg, Johannesburg; School of Physics, University of the Witwatersrand, Johannesburg, South Africa

Department of Physics, Stockholm University; The Oskar Klein Centre, Stockholm, Sweden
Physics Department, Royal Institute of Technology, Stockholm, Sweden
Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
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 Inst. 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 ON, Canada
(a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada
Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki 305-8571, Japan
Science and Technology Center, Tufts University, Medford MA, United States of America
Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
(a) INFN Gruppo Collegato di Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
Department of Physics, University of Illinois, Urbana IL, United States of America
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
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
Department of Physics, University of British Columbia, Vancouver BC, Canada
Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
Waseda University, Tokyo, Japan
Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
Department of Physics, University of Wisconsin, Madison WI, United States of America
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Department of Physics, Yale University, New Haven CT, United States of America
Yerevan Physics Institute, Yerevan, Armenia
Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France
(a) Also at Laboratorio de Instrumentacae e Fisica Experimental de Particulas - LIP, Lisboa, Portugal
(b) Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal
c Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
d Also at TRIUMF, Vancouver BC, Canada
e Also at Department of Physics, California State University, Fresno CA, United States of America
f Also at Novosibirsk State University, Novosibirsk, Russia
g Also at Fermilab, Batavia IL, United States of America
h Also at Department of Physics, University of Coimbra, Coimbra, Portugal
i Also at Università di Napoli Parthenope, Napoli, Italy
j Also at Institute of Particle Physics (IPP), Canada
k Also at Department of Physics, Middle East Technical University, Ankara, Turkey
l Also at Louisiana Tech University, Ruston LA, United States of America
m Also at Department of Physics and Astronomy, University College London, London, United Kingdom
n Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada
(o) Also at Department of Physics, University of Cape Town, Cape Town, South Africa
p Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
q Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
r Also at Manhattan College, New York NY, United States of America
s Also at School of Physics, Shandong University, Shandong, China
t Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China

Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan

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 Section de Physique, Université de Genève, Geneva, Switzerland

Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal

Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America

Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary

Also at California Institute of Technology, Pasadena CA, United States of America

Also at Institute of Physics, Jagiellonian University, Krakow, Poland

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

Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom

Also at Department of Physics, Oxford University, Oxford, United Kingdom

Also at Institute of Physics, Academia Sinica, Taipei, Taiwan

Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

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

* Deceased