Observation of an excited $B_{±c}$ meson state with the ATLAS detector


DOI
10.1103/PhysRevLett.113.212004

Publication date
2014

Document Version
Final published version

Published in
Physical Review Letters

Citation for published version (APA):
Observation of an Excited $B_c^{±}$ Meson State with the ATLAS Detector

G. Aad et al.*

(ATLAS Collaboration)

(Received 3 July 2014; published 21 November 2014)

A search for excited states of the $B_c^+$ meson is performed using 4.9 fb$^{-1}$ of 7 TeV and 19.2 fb$^{-1}$ of 8 TeV $pp$ collision data collected by the ATLAS experiment at the LHC. A new state is observed through its hadronic transition to the ground state, with the latter detected in the decay $B_c^+ \rightarrow J/\psi \pi^\pm$. The state appears in the $m(B_c^{\pm} \pi^\pm) - m(B_c^0) - 2m(\pi^\pm)$ mass difference distribution with a significance of 5.2 standard deviations. The mass of the observed state is 6842 ± 5 MeV, where the first error is statistical and the second is systematic. The mass and decay of this state are consistent with expectations for the second $S$-wave state of the $B_c^+$ meson, $B_c^+ (2S)$.

DOI: 10.1103/PhysRevLett.113.212004

PACS numbers: 14.40.Nd

* 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.
mass of the \( B_{c}^{\pm} \) candidate, \( m(B_{c}^{\pm}\pi) \) is the invariant mass of the \( B_{c}^{\pm} \) candidate combined with two charged pion candidates, and \( m(\pi^{\pm}) \) is the charged pion mass \([11]\). The \( B_{c}^{\pm} \) candidates are reconstructed through the decay \( B_{c}^{\pm} \rightarrow J/\psi(\mu^{+}\mu^{-})\pi^{\pm} \). Since hadronic decays of excited \( B \)-meson states have no observable displacement from the \( pp \) interaction point, these candidates are then combined with two charged pion candidates, both originating at the corresponding \( pp \) interaction point. The mass difference \((Q)\) distribution is formed and analyzed in the range 0–700 MeV.

The \( B_{c}^{\pm} \) selection criteria for the events are optimized separately for 7 and 8 TeV data using the corresponding Monte Carlo (MC) samples, produced in the ATLAS simulation framework \([12,13]\). Differences between the 7 and 8 TeV selection criteria are due to the higher \( \sqrt{s} \) and the number of simultaneous \( pp \) interactions per bunch crossing, hereafter called pileup. The increase in the \( B_{c}^{\pm} \) production cross section between the 7 and 8 TeV MC samples is approximately 3%.

The PYTHIA 6 and 8 MC generators \([14,15]\), tuned for the LHC conditions \([16]\), are used along with a dedicated PYTHIA extension for \( B_{c}^{\pm} \) meson production, based on calculations from Ref. \([17]\). The following MC samples are used to optimize the event selection criteria (charge conjugates implied): \( B_{c}^{\pm} \) decay modes \( J/\psi\pi^{\pm} \), \( J/\psi K^{+} \), \( J/\psi\rho^{+} \) (\( q^{+} \rightarrow \pi^{0}\pi^{+} \)), \( J/\psi\mu^{+}\nu \), \( J/\psi\pi^{0} \), \( J/\psi\pi^{+}\pi^{-} \), as well as \( J/\psi X \) produced inclusively or from \( bb \). The MC simulated events are treated in exactly the same way as the collision data, and the same analysis selections are always applied. The exclusive \( (B_{c}^{\pm}) \) channels are generated with PYTHIA 6, and inclusive \((J/\psi X)\) channels are generated with PYTHIA 8.

This analysis involves several steps. First the \( J/\psi \) candidates are formed as described below. Then a pion track candidate from the same vertex is added to form a \( B_{c}^{\pm} \) meson candidate. Finally, the \( B_{c}^{\pm}(28) \) candidates are formed by adding two pion candidates originating at the primary vertex (PV); the selection of the primary vertex is defined below.

The \( J/\psi \) candidates are reconstructed from pairs of oppositely charged muons. These pairs are fitted to a common vertex with the procedure described in Ref. \([18]\). The following requirements are applied to each \( J/\psi \) candidate:

(i) The \( p_{T} \) of the higher-\( p_{T} \) muon candidate must be above 6 GeV, and the \( p_{T} \) of the lower-\( p_{T} \) muon candidate must be above 4 GeV; these are approximately the \( p_{T} \) values for which the trigger is fully efficient. (ii) The \( J/\psi \) vertex fit chi-square per degree of freedom \( \chi^{2}/\text{NDOF} < 15 \) (this selection keeps more than 99.9% of the candidates, and is included only to remove spurious dimuon combinations). (iii) The invariant mass resolution of the \( J/\psi \) depends on the direction of the muons, with more forward candidates showing poorer resolutions. The sample is split into three categories and selection requirements are optimized for each of them: (i) both muons have \( |\eta| < 1.05 \), (ii) one muon has \( |\eta| < 1.05 \) and the other one has \( 1.05 < |\eta| < 2.5 \), (iii) both muons have \( 1.05 < |\eta| < 2.5 \). The invariant mass \( m(\mu^{+}\mu^{-}) \) is calculated from the track parameters adjusted by the common-vertex fit to be in a three standard deviation \((\pm3\sigma)\) mass window around the world average mass \( m(J/\psi) \) \([11]\), where the \( J/\psi \) reconstructed width \( \sigma \) varies in the range 40–90 MeV depending on muon reconstruction precision in different regions of pseudorapidity and on the data-taking period.

Selection requirements for the \( B_{c}^{\pm} \) were chosen by maximizing \( S/\sqrt{S+B} \), using MC events. Here, \( S \) is the number of signal events and \( B \) refers to the number of background MC events scaled according to the production cross section. The production cross sections are taken from the MC generators’ predictions. The optimization has been carried out separately for the two different data sets.

The pion candidate from the \( B_{c}^{\pm} \) is required to have \( p_{T} > 4 \) GeV. Hit requirements in the pixel detector and SCT are imposed on all tracks to ensure a reliable impact parameter reconstruction.

\( B_{c}^{\pm} \) candidates are reconstructed by fitting two muon tracks from the \( J/\psi \) candidate together with a pion candidate track to a common vertex. The invariant mass of the two muons is constrained to the world average of \( m(J/\psi) \). The yields per unit of integrated luminosity, and the central values of the dimuon invariant mass distributions, are verified to be consistent within each data set.

A significant part of the combinatorial background consists of real \( J/\psi \) candidates combined with candidate pions that are not associated with a \( B_{c}^{\pm} \rightarrow J/\psi\pi^{\pm} \) decay. This background is reduced by imposing a lower cut on \( d_{0}/\sigma(d_{0}) \): \( d_{0} \) here represents the projection of the pion track impact parameter relative to the primary vertex onto the transverse plane, and \( \sigma(d_{0}) \) is the track-by-track uncertainty on \( d_{0} \). Pion candidates are required to have \( d_{0}/\sigma(d_{0}) > 5 \) for 7 TeV data and > 4.5 for 8 TeV data. In 7 TeV data the PV is defined as the collision vertex with the highest summed scalar \( p_{T}^{2} \) of its constituent tracks. In 8 TeV data—the data collected with higher pileup—the PV is identified as the vertex closest in three dimensions to the reconstructed decay vertex of the \( B_{c}^{\pm} \) candidate. All reconstructed \( B_{c}^{\pm} \) candidates are also required to satisfy the following selection criteria:

(i) The \( J/\psi \pi \) vertex fit \( \chi^{2}/\text{NDOF} < 2 \) for 7 TeV and < 1.5 for 8 TeV data. (ii) The \( p_{T} \) of the \( B_{c}^{\pm} \) candidate must be above 15 GeV for 7 TeV and above 18 GeV for 8 TeV data.

Figure 1 shows the invariant mass distributions for the \( B_{c}^{\pm} \) candidates for 7 TeV data and 8 TeV data in the mass range 5620–6820 MeV. Both distributions are fitted separately using an extended unbinned maximum likelihood fit, with a Gaussian function modeling the signal and an exponential modeling the background shape. The various
additional selection requirement is applied to the results of the fits are summarized in Table I. The fitted mass value of the corresponding data set. These candidates are combined as described below with two pion candidate decays that were reconstructed with similar structure is small relative to the detector resolution. The found to be negligible, implying that the natural width of the only free parameter. Alternative models for the signal data are represented by the points with error bars (statistical only). The solid line is the projection of the results of the unbinned maximum likelihood fit to all candidates in the mass range 5620–6820 MeV. The dashed line is the projection of the background component of the same fit.

deck topology: the refitted triplet of the $B^\pm_c$ tracks and the pair of PV pion tracks must intersect in two separate $B^\pm_c$ and $B^{\pm}_c$ ($2S$) vertices. The invariant mass of the refitted muon tracks is constrained to the $J/\psi$ world average mass, and the combined momentum of the refitted $B^\pm_c$ tracks must point to the $B^{\pm}_c$ ($2S$) vertex. When multiple $B^{\pm}_c$ ($2S$) candidates are found in the same event, the one with the best $\chi^2$ value returned by the fitter is kept as an excited state candidate. Wrong-charge combinations ($B^{\pm}_c\pi^+\pi^-$ and $B^{\pm}_c\pi^-\pi^-$) are kept separately for comparison with the combinatorial background shape in the right-charge combinations (oppositely charged pion pairs).

Figure 2 shows the mass difference distribution $m(B^{\pm}_c\pi\pi) - m(B^{\pm}_c) - 2m(\pi)$ for the right-charge combinations $B^{\pm}_c\pi^+\pi^-$ as well as the wrong-charge combinations.

A structure is observed in the mass difference distribution. In order to characterize it, an unbinned maximum likelihood fit to the right-charge combinations is performed. The fit includes a third-order polynomial to model the background and a Gaussian function for the structure. The background shape resulting from the fit is verified to be consistent with the wrong-charge combinations (which are not used to constrain the model in the right-charge fit) by fitting the same shape to them, with the normalization as the only free parameter. Alternative models for the signal and the background parametrizations are studied as sources of systematic uncertainty. A Breit-Wigner contribution was tested in convolution with the Gaussian function and was found to be negligible, implying that the natural width of the structure is small relative to the detector resolution. The resulting fit parameters (with statistical uncertainties only), as well as the distributions of the wrong-charge ($B^{\pm}_c\pi^+\pi^-$, $B^{\pm}_c\pi^-\pi^-$) combinations are shown in Fig. 2. The wrong-charge combinations, are normalized to the same yield as the right-charge background.

The relative $B^{\pm}_c$ ($2S$)/$B^{\pm}_c$ yield ratio is verified to be statistically consistent between the 7 and 8 TeV data. The fit finds the peak at a mass difference $(Q)$ value of 288.2 ± 5.1 MeV in the 7 TeV data and 288.4 ± 4.8 MeV in the 8 TeV data. The fit yields 22 ± 6 signal events in the 7 TeV data and 35 ± 13 events in the 8 TeV data. The Gaussian width of the structure is found to be 18.2 ± 3.8 MeV in the 7 TeV data and 17.6 ± 4.0 MeV in the 8 TeV data. All uncertainties mentioned in this paragraph do not include systematic uncertainties.

There are two dominant sources of systematic uncertainty on the position of the peak. One comes from the

### Table I. The results of the unbinned maximum likelihood fits of the invariant mass distribution of the $B^\pm_c$ candidates. Systematic uncertainties are not included.

<table>
<thead>
<tr>
<th>Data</th>
<th>Signal events</th>
<th>Peak mean [MeV]</th>
<th>Peak width [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>100 ± 23</td>
<td>6282 ± 8</td>
<td>49 ± 12</td>
</tr>
<tr>
<td>8 TeV</td>
<td>227 ± 25</td>
<td>6277 ± 6</td>
<td>50 ± 8</td>
</tr>
</tbody>
</table>

FIG. 1 (color online). Invariant mass distributions of the reconstructed $B^{\pm}_c \rightarrow J/\psi\pi^\pm$ candidates in 7 TeV data (top) and in 8 TeV data (bottom). The data are represented by the points with error bars (statistical only). The solid line is the projection of the results of the unbinned maximum likelihood fit to all candidates in the mass range 5620–6820 MeV. The dashed line is the projection of the background component of the same fit.

The reconstruction of the excited state candidates uses the $B^{\pm}_c$ ground state candidates within ±3σ of the fitted mass value of the corresponding data set. These candidates are combined as described below with two pion candidate tracks associated with the corresponding primary vertex. The $p_T$ threshold of the pion candidates is 400 MeV. No additional selection requirement is applied to the $B^{\pm}_c$ ($2S$) pion candidates. The three tracks from the secondary vertex and the two tracks from the primary vertex are refitted simultaneously with the following constraints given by the

The fit yields 22 ± 6 signal events in the 7 TeV data and 35 ± 13 events in the 8 TeV data. The Gaussian width of the structure is found to be 18.2 ± 3.8 MeV in the 7 TeV data and 17.6 ± 4.0 MeV in the 8 TeV data. All uncertainties mentioned in this paragraph do not include systematic uncertainties.
The contribution from the uncertainty on the pion momentum procedure and estimated below to be about 3.6 MeV. The mass of the mass difference distribution itself. The uncertainty on the other involves systematic uncertainties in the fit of the fit mass value of the new structure. This results in a negligible systematic uncertainty, compared to the above two.

In each case the largest difference between any of the variations mentioned and the default fit model is used as the systematic uncertainty. The values are calculated as the weighted mean of the 7 and 8 TeV mass values.

An additional systematic uncertainty of 2 MeV is obtained from the study of the mass bias in the selection of the candidate with the best $\chi^2$ of the vertex fit.

The various sources of systematic uncertainty are treated as uncorrelated. The total averaged systematic uncertainty propagated to the mass value of the new structure is approximately 4.1 MeV.

The significance of the new structure is evaluated with pseudoexperiments. A large number of background-only mass difference distributions are generated. Parameters of the generation are taken from the fit with their uncertainties to account for systematic effects. The background shape is scaled to the observed number of events. The mean mass value of the signal contribution is left free to vary within the theoretically motivated range (6835–6917 MeV) to evaluate the "look-elsewhere effect" [19]. The significance is calculated as the fraction of the pseudoexperiments in which the difference of the logarithms of fit likelihoods $\Delta \ln L$ with and without signal is larger than in the data. In terms of standard deviations the significance of the observation is 3.7$\sigma$ in the 7 TeV data and 4.5$\sigma$ in the 8 TeV data. For the combined 7 and 8 TeV data set the total significance of the observation is found to be 5.2$\sigma$. The local significance of the observation, obtained by fixing the mean value of the signal component, is 5.4$\sigma$.

The residual uncertainty on the mass of the $B_{s}^{0}$ ground state candidate and is largely canceled in the mass difference distribution. The uncertainty on the mass of the $B_{s}^{0}$ (2S) candidate is dominated by the fitting procedure and estimated below to be about 3.6 MeV. The contribution from the uncertainty on the pion momentum scale to the $B_{s}^{0}$ mass is 1.2 MeV. The residual uncertainty from the $B_{s}^{0}$ candidate mass in the mass difference distribution, $\delta m_{B_s^{0}(2S)} = \delta m_{B_s^{0}} \times (m_{B_s^{0}}/m_{B_s^{0}(2S)})$, where the $\delta m_{B_s^{0}}$ is the world average uncertainty on the $B_{s}^{0}$ mass [11], is about 1.7 MeV. The systematic uncertainty on the mass difference introduced by the fitting procedure is estimated by (i) varying the background model. An exponential threshold function ($f(Q) \sim Q^a e^{-bQ}$, where $a$ and $b$ are free parameters) and second- and fourth-order polynomials were considered as alternatives, resulting in a 3.4 MeV systematic uncertainty; (ii) varying the fit mass range from 0–700 to 0–1500 MeV, results in a 1.2 MeV contribution to the systematic uncertainty; (iii) using different models for the signal. A single Breit-Wigner function, a Breit-Wigner function convolved with a Gaussian function, and a double Gaussian function were considered. This results in a negligible systematic uncertainty, compared to the above two.

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; REC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CF, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DLR, Germany; INFN, Italy; INFN-TRIUMF, Canada; NDGF (Denmark, Norway, Sweden), in particular, from CERN and the ATLAS Tier-1 facilities at DOE and NSF, USA. 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.

[7] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam line. The x axis points from the IP to the center of the LHC ring, and the y axis points upward. Polar coordinates (r, θ) are used in the transverse (x, y) plane, φ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as η = − ln tan(θ/2).
Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

Turkish Atomic Energy Authority, Ankara, Turkey

LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France

High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA

Department of Physics, University of Arizona, Tucson, Arizona, USA

Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA

Physics Department, University of Athens, Athens, Greece

Physics Department, National Technical University of Athens, Zografou, Greece

Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain

Institute of Physics, University of Belgrade, Belgrade, Serbia

Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

Department for Physics and Technology, University of Bergen, Bergen, Norway

Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA

Department of Physics, Humboldt University, Berlin, Germany

Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

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

Department of Physics, Bogazici University, Istanbul, Turkey

Department of Physics, Dogus University, Istanbul, Turkey

Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey

INFN Sezione di Bologna, Italy

Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy

Physikalisches Institut, University of Bonn, Bonn, Germany

Department of Physics, Boston University, Boston, Massachusetts, USA

Department of Physics, Brandeis University, Waltham, Massachusetts, USA

Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil

Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil

Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil

Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil

Physics Department, Brookhaven National Laboratory, Upton, New York, USA

National Institute of Physics and Nuclear Engineering, Bucharest, Romania

Physics Department, National Institute for Research and Development of Isotopic and Molecular Technologies, Cluj Napoca, Romania

University Politehnica Bucharest, Bucharest, Romania

West University in Timisoara, Timisoara, Romania

Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

Department of Physics, Carleton University, Ottawa, Ontario, Canada

CERN, Geneva, Switzerland

Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA

Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile

Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China

Department of Modern Physics, University of Science and Technology of China, Anhui, China

Department of Physics, Nanjing University, Jiangsu, China

School of Physics, Shandong University, Shandong, China

Physics Department, Shanghai Jiao Tong University, Shanghai, China

Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France

Nevis Laboratory, Columbia University, Irvington, New York, USA

Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy

Dipartimento di Fisica, Università della Calabria, Rende, Italy

Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, Krakow, Poland

Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland

The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland

Physics Department, Southern Methodist University, Dallas, Texas, USA

Physics Department, University of Texas at Dallas, Richardson, Texas, USA

DESY, Hamburg and Zeuthen, Germany

Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
D.V. Skobeltsyn Institute of Nuclear Physics, M.V. 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 and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
INFN Sezione di Napoli, Italy
Dipartimento di Fisica, Università di Napoli, Napoli, Italy
Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
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, Illinois, USA
Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
Department of Physics, New York University, New York, New York, USA
Ohio State University, Columbus, Ohio, USA
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
Palacký University, RCPTM, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
LAL, Université 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, Università di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
Petersburg Nuclear Physics Institute, Gatchina, Russia
INFN Sezione di Roma, Italy
Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
Laboratorio de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal
Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
Department of Physics, University of Coimbra, Coimbra, Portugal
Departamento de Física, Universidade do Minho, Braga, Portugal
Département de Physique Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
Dep Física and CEFITEC de Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
Czech Technical University in Prague, Praha, Czech Republic
Faculty of Mathematics and Physics, Charles 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, Saskatchewan, Canada
Ritsumeikan University, Kusatsu, Shiga, Japan
INFN Sezione di Roma Tor Vergata, Italy
Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
INFN Sezione di Roma Tre, Italy
Dipartimento di Matematica e 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 Nucléaires, Rabat, Morocco
Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), 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
Also at Chinese University of Hong Kong, China.
Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
Also at Louisiana Tech University, Ruston, LA, USA.
Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
Also at Department of Physics, The University of Texas at Austin, Austin, TX, USA.
Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
Also at CERN, Geneva, Switzerland.
Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
Also at Manhattan College, New York, NY, USA.
Also at Novosibirsk State University, Novosibirsk, Russia.
Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.
Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India.
Also at Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy.
Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
Also at Section de Physique, Université de Genève, Geneva, Switzerland.
Also at International School for Advanced Studies (SISSA), Trieste, Italy.
Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.
Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
Also at Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia.
Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
Also at Department of Physics, Oxford University, Oxford, United Kingdom.
Also at Department of Physics, Nanjing University, Jiangsu, China.
Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.
Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.
Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.