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):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).
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 $B_c^± → J/ψπ^±$. The state appears in the $m(B_c^±π^±π^-) - m(B_c^±) - 2m(π^±)$ mass difference distribution with a significance of 5.2 standard deviations. The mass of the observed state is 6842 ± 4 ± 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, $B_c^±(2S)$.

The $B_c^±$ meson was first observed by the CDF experiment in the semileptonic decay mode [1], and its hadronic decay mode was observed later by both the CDF [2] and the D0 [3] experiments. The $B_c^±$ meson has also been observed by the LHCb experiment in various decay modes [4]. Excited states of the $B_c^±$ meson have not previously been observed. The spectrum and properties of the $B_c^±$ family are predicted by nonrelativistic potential models, perturbative QCD, and lattice calculations [5]. Measurements of the ground and excited states through fully reconstructed channels will provide tests of the predictions of these models and ultimately the opportunity to extract information on the strong interaction potential.

The second $S$-wave state, $B_c^±(2S)$, is predicted to have a mass in the range 6835–6917 MeV [5]. The next $S$-wave state, $B_c^±(3S)$, is predicted to have a mass above the threshold for decay into a $BD$ meson pair. Both the $1S$ and $2S$ states have pseudoscalar ($0^−$) and vector ($1^−$) spin states that are predicted to differ in mass by about 20–50 MeV. Transitions between the spin states occur through soft photon radiation that escapes identification in ATLAS; the spin states cannot be separated by this analysis.

This Letter presents the observation of a new state whose mass is consistent with predictions for the $B_c^±(2S)$, the second $S$-wave state of the $B_c^±$ meson. The $B_c^±(2S)$ state is reconstructed in the decay to the $B_c^±$ meson and two oppositely charged pions, with the $B_c^±$ reconstructed through its decay to $J/ψπ^±, J/ψ → μ^+μ^-$. The ATLAS Collaboration at the Large Hadron Collider (LHC) uses a general-purpose particle detector [6] consisting of several subsystems including the inner detector (ID), the electromagnetic and hadronic calorimeters, and the muon spectrometer (MS). Muon reconstruction at ATLAS makes use of both the ID and the MS.

Muons pass through the calorimeters and reach the MS if their momentum is above approximately 3 GeV. The inner detector features a three-component tracking system, consisting of two silicon-based detectors, the pixel detector and the microstrip semiconductor tracker (SCT), and the transition radiation tracker (TRT). ID tracks are reconstructed if their transverse momentum $p_T$ [7] is greater than 400 MeV and the magnitude of their pseudorapidity $|η|$ is less than 2.5. Muon candidates are formed from a standalone MS track that is matched to an ID track [8]. In this analysis the MS is only used to identify muons, while their momentum is measured using the ID information only.

The trigger system [9] comprises three levels: the hardware-based Level-1 trigger and the High-Level Triggers (HLT), consisting of the Level-2 trigger and the Event Filter (EF). The Level-1 trigger uses resistive plate chambers (RPC) and thin gap chambers (TGC) to trigger muons in the pseudorapidity ranges of $|η| < 1.05$ and $1.05 < |η| < 2.5$, respectively. One or more regions of interest identified by the Level-1 muon trigger seed the HLT muon online reconstruction algorithms, where the responses from both the ID and the MS are combined. For this analysis the HLT muon selection for the $J/ψ$ requires two muons, respectively, $μ_1$ and $μ_2$, originating at a common vertex, with the invariant mass of the muon pair lying between 2.5 and 4.3 GeV. The individual muon $p_T$ thresholds are $p_T(μ_1) > 6 GeV$ and $p_T(μ_2) > 4 GeV$.

This study uses $pp$ collision data collected in the years 2011 ($\sqrt{s} = 7$ TeV) and 2012 ($\sqrt{s} = 8$ TeV) by the ATLAS experiment. The data sets correspond to an integrated luminosity of 4.9 and 19.2 fb⁻¹, respectively. The luminosity estimate has an uncertainty of 1.8% in 2011 [10] and 2.8% in 2012.

To improve the resolution, peaks are sought in the distribution of the variable $Q = m(B_c^±π^-) - m(B_c^±) - 2m(π^±)$, where $m(B_c^±)$ is the offline reconstructed invariant
mass of the $B_c^±$ candidate, $m(B_c^±π)$ is the invariant mass of the $B_c^±$ candidate combined with two charged pion candidates, and $m(π^±)$ is the charged pion mass [11]. The $B_c^±$ candidates are reconstructed through the decay $B_c^± → J/ψ(μ^±μ^-)π^±$. 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 $B_c^±$ 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 √s and the number of simultaneous $pp$ interactions per bunch crossing, hereafter called pileup. The increase in the $B_c^±$ 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 $B_c^±$ meson production, based on calculations from Ref. [17]. The following MC samples are used to optimize the event selection criteria (charge conjugates implied): $B_c^±$ decay modes $J/ψπ^±$, $J/ψK^±$, $J/ψπ^0ν$, $J/ψπ^0π^±$, $J/ψπ^+π^−π^0$, as well as $J/ψX$ 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 ($B_c^±$) channels are generated with PYTHIA 6, and inclusive ($J/ψX$) channels are generated with PYTHIA 8.

This analysis involves several steps. First the $J/ψ$ candidates are formed as described below. Then a pion track candidate from the same vertex is added to form a $B_c^±$ meson candidate. Finally, the $B_c^±$ candidates are formed by adding two pion candidates originating at the primary vertex (PV); the selection of the primary vertex is defined below.

The $J/ψ$ 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 $J/ψ$ 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 $J/ψ$ vertex fit chi-square per degree of freedom $χ^2$/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 $J/ψ$ 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 $|η| < 1.05$, (ii) one muon has $|η| < 1.05$ and the other one has $1.05 < |η| < 2.5$, (iii) both muons have $1.05 < |η| < 2.5$. The invariant mass $m(μ^+μ^-)$ is calculated from the track parameters adjusted by the common-vertex fit to be in a three standard deviation ($±3σ$) mass window around the world average mass $m(J/ψ)$ [11], where the $J/ψ$ reconstructed width $σ$ 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 $B_c^±$ were chosen by maximizing $S/√S+B$, 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 $B_c^±$ 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.

$B_c^±$ candidates are reconstructed by fitting two muon tracks from the $J/ψ$ 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 $m(J/ψ)$. 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 $J/ψ$ candidates combined with candidate pions that are not associated with a $B_c^± → J/ψπ^±$ decay. This background is reduced by imposing a lower cut on $d_0/σ(d_0)$: $d_0$ here represents the projection of the pion track impact parameter relative to the primary vertex onto the transverse plane, and $σ(d_0)$ is the track-by-track uncertainty on $d_0$. Pion candidates are required to have $d_0/σ(d_0) > 5$ for 7 TeV data and $> 4.5$ for 8 TeV data. In 7 TeV data the $p_T$ of 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 $B_c^±$ candidate. All reconstructed $B_c^±$ candidates are also required to satisfy the following selection criteria:

(i) The $J/ψπ$ vertex fit $χ^2$/NDOF < 2 for 7 TeV and < 1.5 for 8 TeV data. (ii) The $p_T$ of the $B_c^±$ 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 $B_c^±$ 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
exclusive $B^\pm_c$ decay modes mentioned above are shown to have negligible contribution to the background shape. The results of the fits are summarized in Table I. The fitted mass values are consistent with the world average for the $B^\pm_c$ mass [11]. The signal yield per fb$^{-1}$ of the $B^\pm_c$ is lower in 8 TeV data due to the harder $p_T$ requirements. The stability of the $B^\pm_c$ yield was checked through its normalization to $B^\pm \rightarrow J/\psi \pi^\pm$ decays that were reconstructed with similar requirements.

The reconstruction of the excited state candidates uses the $B^\pm_c$ ground state candidates within $\pm 3\sigma$ 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 decay 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 ($B^+_c\pi^+\pi^-$ and $B^-_c\pi^-\pi^-$) 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 $m(B^+_c\pi\pi) - 2m(\pi)$ for the right-charge combinations $B^+_c\pi^+\pi^-$ 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 ($B^+_c\pi^+\pi^-$, $B^-_c\pi^-\pi^-$) combinations are shown in Fig. 2. The wrong-charge combinations, are normalized to the same yield as the right-charge background.

The relative $B^+_c(2S)/B^+_c$ 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 $\pm$ 5.1 MeV in the 7 TeV data and 288.4 $\pm$ 4.8 MeV in the 8 TeV data. The fit yields 22 $\pm$ 6 signal events in the 7 TeV data and 35 $\pm$ 13 events in the 8 TeV data. The Gaussian width of the structure is found to be 18.2 $\pm$ 3.8 MeV in the 7 TeV data and 17.6 $\pm$ 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 $\pm$ 23</td>
<td>6282 $\pm$ 8</td>
<td>49 $\pm$ 12</td>
</tr>
<tr>
<td>8 TeV</td>
<td>227 $\pm$ 25</td>
<td>6277 $\pm$ 6</td>
<td>50 $\pm$ 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 contribution from the uncertainty on the pion momentum procedure and estimated below to be about 3.6 MeV. The other involves systematic uncertainties in the fit of the mass difference introduced by the fitting procedure is the world average uncertainty on the candidate mass in the mass difference distribution for the right-charge combinations (points with error bars) and for the same (wrong) pion charge combinations (shaded histogram) in 7 TeV data (top) and in 8 TeV data (bottom). The wrong-charge combinations are normalized to the same yield as the right-charge background. The solid line is the projection of the results of the unbinned maximum likelihood fit to all candidates in the range 0–700 MeV. The dashed line is the projection of the background component of the same fit.

In conclusion, the distribution of the mass difference

\[ Q = m(B^+ \pi^-) - m(B^{0}) - 2m(\pi^\pm) \]

for events with the \( B^\pm \) meson reconstructed in its decay to \( J/\psi \pi^\pm \) has been investigated in \( pp \) collisions at the LHC using the ATLAS detector. The analysis is based on an integrated luminosity of 4.9 (19.2) \( fb^{-1} \) of \( pp \) collisions at a center-of-mass energy of 7 (8) TeV. A new state is observed at \( Q = 288.3 \pm 3.5 \pm 4.1 \) MeV (calculated as the error weighted mean of the 7 and 8 TeV mass values) corresponding to a mass of \( 6842 \pm 4 \pm 5 \) MeV, where the first error is statistical and the second is systematic. The significance of the observation is 5.2\( \sigma \) with the look elsewhere effect taken into account, and the local significance is 5.4\( \sigma \). Within the uncertainties, the mass of the resonance corresponding to the observed structure is consistent with the predicted mass of the \( B^\pm(2S) \) state.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions, without whom ATLAS could not be operated efficiently.
We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF 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; GUSTEC, Germany; INFN, Italy; INFN-TRIUMF, Canada; NDGF (Denmark, Norway, Sweden), from all WLCG partners is acknowledged gratefully, in Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Sweden; SER, SNSF and Cantons of Bern and Geneva, Africa; MINECO, Spain; SRC and Wallenberg Foundation, Slovakia; ARRS and MIZ Russian Federation; JINR; MSTD, Serbia; MSSR, MNE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, 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, ϕ) 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 $\eta = -\ln \tan(\theta/2)$.
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
Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
Institut de Física Corpuscular, Universitat de Valencia, Valencia, Spain
Institut de Física, Universitat de Barcelona, Barcelona, Spain
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 Maria, Valparaiso, 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, København, 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
Marien 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