



# Observation of a $B_c^{*+}$ meson with the ATLAS detector

The ATLAS Collaboration

The first observation of a new meson state decaying into  $B_c^+$  and a photon is presented using a dataset of  $pp$  collisions at a centre-of-mass energy  $\sqrt{s} = 13$  TeV collected by the ATLAS detector at the Large Hadron Collider, corresponding to an integrated luminosity of  $140 \text{ fb}^{-1}$ . The  $B_c^+$  mesons are reconstructed from a three-muon final state from  $B_c^+ \rightarrow J/\psi(\mu^+\mu^-)\mu^+\nu_\mu X$  decays, along with photons reconstructed via conversions to electron–positron pairs in the detector material. The new state is observed with a significance that exceeds 8 standard deviations. The mass difference between the new meson state and the ground-state  $B_c^+$  meson is measured to be  $64.5 \pm 1.4$  (stat.) $_{-1.4}^{+1.0}$  (syst.) MeV. This corresponds to a mass for the observed state of  $6339.0 \pm 1.4$  (stat.) $_{-1.4}^{+1.0}$  (syst.)  $\pm 0.3$  ( $m_{B_c^+}$ ) MeV, where the last uncertainty is due to the precision of the best knowledge of the  $B_c^+$  meson mass. The low mass difference value matches the theory expectations for the lowest vector state of the  $\bar{b}c$  quarkonium system, the  $B_c^{*+}$  meson.

The  $B_c^+$  meson represents the ground state of a family of mesons consisting of a  $b$ -antiquark and a  $c$ -quark. These states share some properties of other heavy quarkonium systems, such as charmonium ( $\bar{c}c$ ) and bottomonium ( $\bar{b}b$ ), and similar approaches are often used to theoretically study their mass spectrum [1]. However, the asymmetry in the masses of the constituent quarks can provide further insights on heavy-quark bound-state dynamics. Extensive predictions of the  $\bar{b}c$  excitation spectrum exist in the literature [2–31], while the experimental knowledge is relatively limited, mainly due to the suppressed production rate of the states, which requires simultaneous production of two heavy quark–antiquark pairs.

The first observation of an excited  $\bar{b}c$  state was reported by the ATLAS experiment [32] in  $pp$  collision data collected during Large Hadron Collider (LHC) Run 1. The mass of the structure observed in the  $B_c^+\pi^+\pi^-$  mass spectrum is consistent with expectations for the first radial excitation of  $S$ -wave  $\bar{b}c$  states ( $2S$ ). Later, the CMS [33] and LHCb [34] collaborations reported an observation of two distinct signals compatible with the predictions for the pseudoscalar and vector components of that excitation,  $B_c(2S)^+$  and  $B_c^*(2S)^+$ , using the full dataset collected during LHC Run 2. Recently, the LHCb collaboration reported a new observation of a broad peaking structure in the  $B_c^+\gamma$  mass spectrum, consistent with theory predictions for the lowest excited  $P$ -wave  $\bar{b}c$  states,  $B_c(1P)^+$  [35, 36]. In the case of all of the aforementioned excitations, the mass difference relative to the pseudoscalar ground state,  $B_c^+$ , is between 400 and 600 MeV.

Lattice QCD [6–8] and other calculations based on QCD potential models [9–31] predict the mass difference between the lightest excited state of the  $\bar{b}c$  system, the vector  $B_c^{*+}$  meson, and the ground state to be between 50 and 70 MeV. The  $B_c^{*+}$  meson is expected to decay into  $B_c^+$  by emitting a photon with almost 100% probability. No other  $\bar{b}c$  excitation is expected to exhibit such a low mass splitting relative to  $B_c^+$ . The small mass difference complicates the experimental search for the  $B_c^{*+}$  due to the very soft energy spectrum of the emitted photon, which is difficult to detect at LHC experiments.

This Letter presents the first observation of a state consistent with theoretical expectations for the  $B_c^{*+}$  meson, decaying into  $B_c^+\gamma$  (for simplicity, charge conjugated states are implied from here onwards). The study is performed with the ATLAS detector [37].  $B_c^+$  mesons are reconstructed in the  $B_c^+ \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\mu^+\nu_\mu X$  decay chain, where  $X$  corresponds to any other particles which are not reconstructed. This choice is motivated by the approximately 20 times larger branching fraction compared to the  $B_c^+ \rightarrow J/\psi\pi^+$  decay, used in the earlier  $\bar{b}c$  excited state searches at the LHC. The resulting gain in acceptance overcompensates for the complications related to the presence of the neutrino and hence the partially reconstructed final state. Because of the significant  $B_c^+$  lifetime the decay candidates are reconstructed from a displaced vertex. Photons are reconstructed via conversions to  $e^+e^-$  in the detector material as vertices of two charged particle tracks. Typical values of photon transverse momentum relevant to this study are below 1–2 GeV and not accessible to reconstruction approaches based on calorimeter energy clusters.

The ATLAS experiment [37] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near  $4\pi$  coverage in solid angle.<sup>1</sup> It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS). The ID covers the pseudorapidity range  $|\eta| < 2.5$ . It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. The MS surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The MS includes a system of precision tracking chambers up to  $|\eta| = 2.7$  and fast detectors

<sup>1</sup> ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the  $z$ -axis along the beam line. Polar coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the  $z$ -axis. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ , and the transverse momentum is defined relative to the beam line as  $p_T = p \sin \theta$ .

for triggering up to  $|\eta| = 2.4$ . A two-level trigger system was used to select events [38]. A software suite [39] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

This analysis is based on the full Run 2 dataset of  $\sqrt{s} = 13$  TeV  $pp$  collisions collected by ATLAS between 2015 and 2018 at the LHC. The data are required to satisfy criteria ensuring that the detector was in good operating condition [40]. Events are triggered on the basis of the muons present in the final state of the targeted decay channel [41]. Several trigger configurations were used to maximise the signal yield. Most of the triggers were based on the identification of two muons, with various muon transverse momentum thresholds from 4 to 11 GeV, requiring opposite charge for the muons in the pair, to form a good vertex and to have an invariant mass compatible with a  $J/\psi \rightarrow \mu^+\mu^-$  decay. Other triggers required the presence of a third muon, typically lowering the thresholds down to 4 GeV for all three while still keeping acceptable rates. The total trigger efficiency is above 60% for  $B_c^+$  mesons with  $p_T$  above 25 GeV.

To model inelastic  $pp$  events containing the  $B_c^{*+} \rightarrow B_c^+\gamma$  decays, followed by the decays  $B_c^+ \rightarrow J/\psi\mu^+\nu_\mu X$ , large samples of Monte Carlo (MC) simulated events were prepared using BCVEGPY 2.2 generator [42] to model  $\bar{b}c$  state production, interfaced to PYTHIA 8.244 [43] to simulate parton showers and hadronisation, and EVTGEN [44] to model heavy-flavour decays. All generated MC events undergo the full ATLAS detector simulation [39] using GEANT4 [45].

Events are required to contain at least three muons reconstructed using information from the MS and the ID and satisfying the *Loose* identification working point [46]. The  $J/\psi$  candidates are built from two oppositely charged muons, which are required to have  $p_T(\mu^\pm) > 4$  GeV and  $|\eta(\mu^\pm)| < 2.4$ , and that have their tracks fitted to a common vertex [47]. Candidates in the dimuon invariant mass window  $2.8 \text{ GeV} < m(\mu^+\mu^-) < 3.4 \text{ GeV}$  are retained for further analysis. The third muon track with  $p_T(\mu^\pm) > 3$  GeV and  $|\eta(\mu^\pm)| < 2.5$  is fitted to a common vertex with the muon tracks of the  $J/\psi$  candidate. In this fit the  $J/\psi$  candidate mass is constrained to the world average value [48]. The combination of the  $J/\psi$  candidate with the third muon is referred to as the  $B_c^+$  candidate below. Because of the presence of the neutrino in the  $B_c^+$  decay, the invariant mass of the signal candidates is expected to have a smooth distribution in the kinematically allowed range of roughly 3.2–6.3 GeV.

Primary vertices (PV) are reconstructed from at least two charged-particle tracks with  $p_T > 0.5$  GeV and  $|\eta| < 2.5$  [49, 50]. The  $B_c^+$  candidate is associated to a PV by choosing the one giving the smallest three-dimensional impact parameter of the  $B_c^+$  candidate trajectory. The position of the PV is determined from a refit of the vertex, following the removal of the muon tracks used to reconstruct the  $B_c^+$  candidate. The  $B_c^+$  vertex fit quality must be  $\chi^2(B_c^+)/N_{\text{dof}} < 2$ , where the number of degrees of freedom  $N_{\text{dof}} = 4$ . The contribution of the third muon track to the  $\chi^2(B_c^+)$  is required to be less than 4, to suppress background from a genuine  $J/\psi$  combined with a randomly-associated muon. The projection of the  $B_c^+$  candidate transverse momentum on the direction from the PV to the candidate decay vertex is required to be positive, to further suppress the background from prompt  $J/\psi$ , produced at the PV. The  $B_c^+$  candidates are required to satisfy the criterion  $p_T(B_c^+)/\sum p_T(\text{track}) > 0.2$ , where the scalar sum in the denominator is taken over all tracks with  $p_T > 0.5$  GeV originating from the PV, including the tracks of the  $B_c^+$  candidate. The  $B_c^+$  candidates must have  $p_T(B_c^+) > 25$  GeV and  $|\eta(B_c^+)| < 2.4$ . If the same triplet of muons allows the formation of two  $B_c^+$  candidates passing the selection above (with different muons considered as the  $J/\psi$  daughters), only the candidate with the lowest  $\chi^2(B_c^+)$  is retained. Multiple  $B_c^+$  candidates in a single event are kept if they share up to two muons. This happens in less than 0.2% of events, for both data and simulated event samples.

Figure 1 shows the distribution of invariant mass,  $m(J/\psi\mu^+)$ , for all  $B_c^+$  candidates with  $4.0 < m(J/\psi\mu^+) < 6.25$  GeV. Studies performed with simulation suggest that the distribution contains sizeable contributions from signal  $B_c^+ \rightarrow J/\psi\mu^+\nu_\mu X$  decays and from background  $J/\psi$  mesons combined with either a true muon or a hadron mis-identified as a muon, due to punch-through to the MS or decays in flight. A narrow peak with  $m(J/\psi\mu^+) \sim 5.2$  GeV is produced by  $B^+ \rightarrow J/\psi K^+$  decays where  $K^+$  is mis-identified as a muon. The structure near 4.5 GeV arises due to various  $B^+ \rightarrow (\psi/\chi)K^+ \rightarrow J/\psi K^+ X$  decays with the same kaon mis-identification and where some of the decay products of the heavier charmonium state, such as  $\psi(2S)$  or  $\chi_{cJ}$ , are not reconstructed. Many other partially reconstructed  $B \rightarrow J/\psi X$  decays can contribute to the mass range below about 5 GeV. Figure 1 also shows the expected contribution from the  $B_c^+ \rightarrow J/\psi\mu^+\nu_\mu X$  signal. Its shape is taken from the simulation and its normalisation is obtained from the fitted yield of  $B_c^{*+}$  signal in data discussed below. The normalisation also uses the ratio of  $B_c^{*+}$  and  $B_c^+$  reconstruction efficiencies, obtained from simulation, and the assumption that 3/4 of the inclusive  $B_c^+$  mesons are produced in decays of the vector  $B_c^{*+}$  state. The latter assumption is motivated by the ratio of the spin states involved in the production (naive spin counting). It is used only for the illustrative purposes and no further aspects of the analysis rely on this normalisation. The contribution of the  $B^+ \rightarrow J/\psi K^+$  decay with the shape taken from the simulation and the normalisation extracted by fitting the invariant mass distribution assuming a kaon mass hypothesis for the third muon track, is also shown in Figure 1.

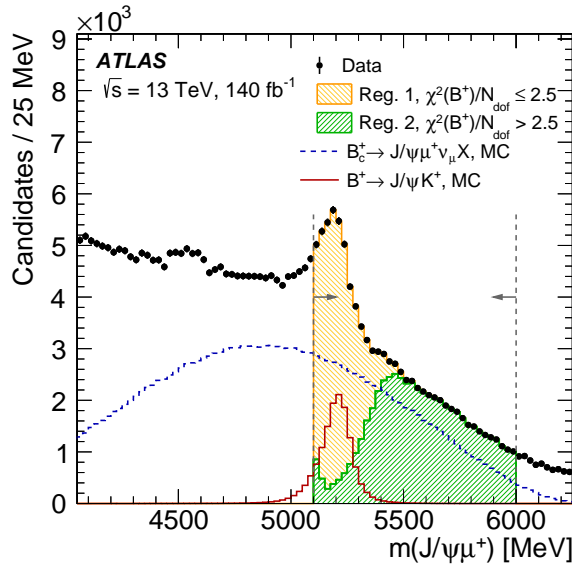


Figure 1: The distribution of  $B_c^+$  candidate invariant mass. The colour-filled areas show the  $B_c^+$  candidates in the mass window selected for further analysis: from (orange) Region 1 – candidates with  $\chi^2(B^+)/N_{\text{dof}} \leq 2.5$ , and (green) Region 2 – candidates with  $\chi^2(B^+)/N_{\text{dof}} > 2.5$ , where the quantity  $\chi^2(B^+)$  is defined in the text. The blue dashed line shows the expected contribution of  $B_c^+ \rightarrow J/\psi\mu^+\nu_\mu X$  decays, with the normalisation calculated from the fitted  $B_c^{*+}$  signal yield and simulated ratio of reconstruction efficiencies of  $B_c^{*+}$  and  $B_c^+$  candidates, and extrapolated to the total expected  $B_c^+$  inclusive production. The red solid line shows the contribution of  $B^+ \rightarrow J/\psi K^+$  decay. The grey vertical dashed lines and arrows indicate the mass range of  $B_c^+$  candidates used for  $B_c^{*+}$  reconstruction.

To increase the fraction of  $B_c^+ \rightarrow J/\psi\mu^+\nu_\mu X$  decays and suppress contributions from other partially reconstructed  $b$ -hadron decays, only  $B_c^+$  candidates with  $5.1 < m(J/\psi\mu^+) < 6.0$  GeV are kept for further analysis. The contribution from  $B^+ \rightarrow J/\psi K^+$  decays can be isolated by performing a modified 3-muon vertex fit as follows. A kaon mass hypothesis is assigned to the third muon track, and the triplet is refitted to a common vertex with the following constraints: the  $J/\psi$  candidate muon pair and whole

triplet masses are constrained to the world average values for  $J/\psi$  and  $B^+$  masses [48], respectively, and the reconstructed candidate momentum is required to point back to the PV. The quality of this modified vertex fit,  $\chi^2(B^+)/N_{\text{dof}}$  with  $N_{\text{dof}} = 7$ , is used to define two non-overlapping regions: Region 1 includes candidates with  $\chi^2(B^+)/N_{\text{dof}} \leq 2.5$  and is expected to contain a significant contribution from  $B^+ \rightarrow J/\psi K^+$  and from combinatorial background; Region 2 includes candidates with  $\chi^2(B^+)/N_{\text{dof}} > 2.5$  and should be practically free of the  $B^+ \rightarrow J/\psi K^+$  contribution. Both regions are kept for further analysis and are shown in Figure 1 for the data sample.

Candidates for  $B_c^{*+}$  mesons decaying into  $B_c^+ \gamma$  are reconstructed by combining  $B_c^+$  candidates with a soft photon. To reconstruct the photons, the process of photon conversion in the detector material is exploited. Pairs of oppositely charged ID tracks (both assigned an electron mass hypothesis) are used for the reconstruction of conversion vertices. To increase the acceptance for the low-energy photons, each track is required have  $p_T(e^\pm) > 100$  MeV and  $|\eta(e^\pm)| < 2.5$ . This  $p_T$  threshold is much lower than a typical value of 400–500 MeV used in most ATLAS data analyses [51, 52]. A dedicated track reconstruction setup similar to that used in measurements with minimum-bias data [53] was employed, with certain computational adaptations made for the track multiplicity environment of nominal Run 2 data-taking conditions. This dedicated reconstruction was run on a preselected set of events containing a  $B_c^+$  candidate. Track pairs are fitted to a common vertex, with the quality of the fit with one degree of freedom required to satisfy  $\chi^2 < 3$ . The vertex radial and longitudinal positions are required to be  $20 < R_{xy}(e^+e^-) < 125$  mm and  $|z(e^+e^-)| < 425$  mm, respectively. This geometrical region roughly corresponds to the volume occupied by the beampipe and barrel layers of the silicon pixel detector. Photon conversion candidates are required to have an invariant mass  $m(e^+e^-) < 50$  MeV and transverse momentum with respect to the direction from the PV to the conversion vertex  $p_T^{\text{rel}} < 20$  MeV. To further suppress fake conversion candidates, a combined selection criterion is applied in the two-dimensional space of  $m(e^+e^-)$  and  $p_T^{\text{rel}}$ , where the signal is concentrated towards small values of both variables, and the background dominates at higher values. The reconstruction and selection efficiency for photons with  $p_T$  above 200 MeV is approximately 0.4% in the  $B_c^{*+}$  signal simulation. This is defined mainly by the radiation thickness of the traversed material, acceptance of the  $p_T(e^\pm)$  selection and the efficiency of low-energy electron track reconstruction.

Finally, the invariant mass of the muon triplet and the photon candidate with a kaon mass hypothesis assigned to the third muon is required to be  $m(J/\psi K^+ e^+ e^-) < 6050$  MeV. This requirement suppresses possible contributions from fully reconstructed  $B_c^+ \rightarrow J/\psi K^+$  and  $B_c^+ \rightarrow J/\psi \pi^+$  decays with soft photons from final-state radiation. If more than one  $B_c^{*+}$  candidate passes the selection in a single event, all of them are kept. This happens in about 2% of events in both data and  $B_c^{*+}$  signal simulation.

The signal of the  $B_c^{*+} \rightarrow B_c^+ \gamma$  decay is identified using the distribution of the mass difference  $\Delta m = m(J/\psi \mu^+ e^+ e^-) - m(J/\psi \mu^+)$ . Figure 2 shows the  $\Delta m$  distribution for the selected  $B_c^{*+}$  candidates in Region 1 and Region 2. This distribution features a structure in the region  $40 \text{ MeV} < \Delta m < 70 \text{ MeV}$  in both regions. The observed excess of events above the expected, smoothly rising, background distribution in Region 2 is attributed exclusively to the  $B_c^{*+} \rightarrow B_c^+ \gamma$  decay signal, while in Region 1 the same signal can be accompanied by  $B^{*+} \rightarrow B^+ \gamma$  decays, which are expected to produce a peaking contribution with a  $\Delta m$  value close to  $\Delta m_{B^{*+}} = m_{B^{*+}} - m_{B^+} = 45.34 \pm 0.20$  MeV [48]. According to simulation the residual contribution of  $B^+$  decays in Region 2 does not exceed 2% of its total contribution to both regions, thus making the expected contamination from the  $B^{*+}$  negligible.

An extended unbinned maximum-likelihood fit to the  $\Delta m$  distribution is performed simultaneously to the two regions. The  $B_c^{*+} \rightarrow B_c^+ \gamma$  decay signal contribution is modelled with a template made from the simulated event samples with the adaptive Gaussian kernel density estimation (KDE) technique [54]. Separate templates are used for Region 1 and 2. The dependence of the template on the true mass difference

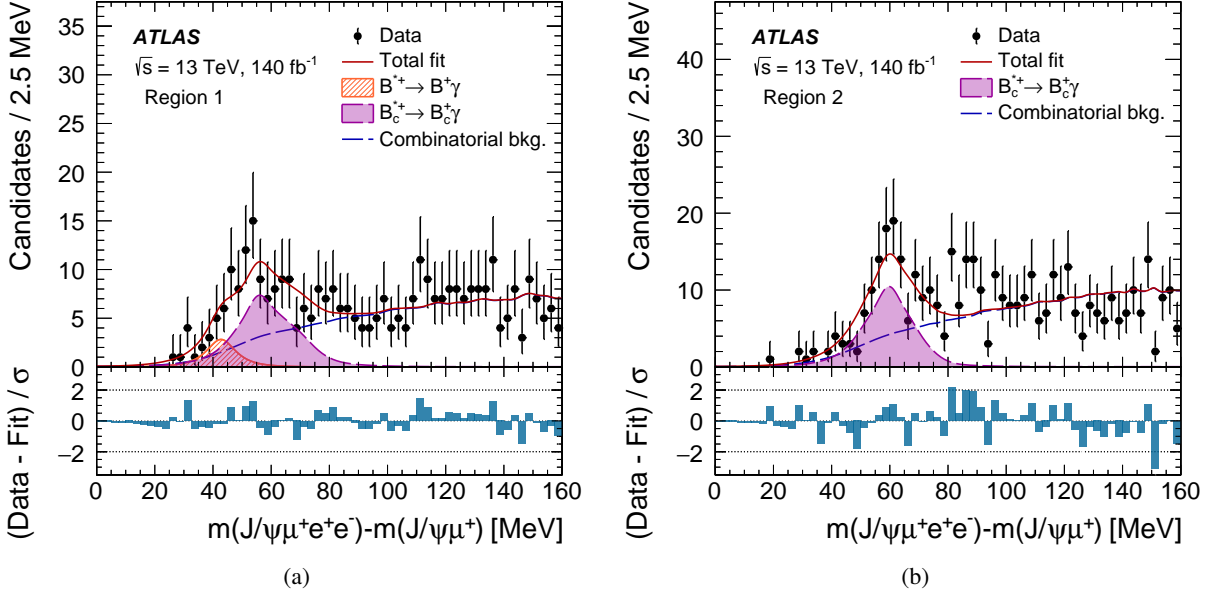


Figure 2: Distributions of the mass difference for the selected  $B_c^{*+}$  candidates in (a) Region 1 and (b) Region 2. Data are shown as points, and the overall result of the fit is given by the red solid line. The purple filled area shows the  $B_c^{*+}$  signal contribution, and the orange hatched area corresponds to the  $B^{*+}$  background. The combinatorial background is shown with the blue dashed line. The bottom panels show the pulls, defined as the difference between the data and the fit function divided by the statistical uncertainty of the data point.

value,  $\Delta m_{B_c^{*+}} = m_{B_c^{*+}} - m_{B_c^+}$ , was studied using simulated signal samples with different values of  $m_{B_c^{*+}}$ . Due to the lost neutrino in the  $B_c^+$  decay final state the mean  $\Delta m$  position of the template is shifted by a few MeV relative to  $\Delta m_{B_c^{*+}}$  and the templates are broader than would be expected from the photon energy resolution alone. Applying a rescaling proportional to  $\Delta m_{B_c^{*+}}$  to the  $\Delta m$  values of simulated events used in the KDE was shown to well reproduce the signal  $\Delta m$  shape for the  $\Delta m_{B_c^{*+}}$  values in the 60–70 MeV range. During the fit to data, the templates are allowed to scale in  $\Delta m$ , with  $\Delta m_{B_c^{*+}}$  being a free parameter of the fit.

The  $B^{*+} \rightarrow B^+\gamma$  decay is modelled with a modified Gaussian function,  $G_{\text{mod}} \propto \exp(-0.5 \times x^{2-x/(x+2)})$  [55, 56], where  $x = |\Delta m - \Delta m_{B^{*+}}|/\sigma_{B^{*+}}$  with the mean  $\Delta m_{B^{*+}}$  and width  $\sigma_{B^{*+}}$  fixed to the values obtained from simulated samples. This component only contributes to Region 1 and is absent in Region 2.

For combinatorial background modelling, a data-driven method, referred to as event mixing below, is applied.  $B_c^{*+}$  candidates in data with  $80 < \Delta m < 160$  MeV are used to build synthetic background candidates by combining the  $B_c^+$  and photon from different events. The  $\Delta m$  range below 80 MeV is excluded to avoid contamination from the signal. The use of the partial  $\Delta m$  range biases the background  $p_T(\gamma)$  spectrum, as does the mixing procedure itself, favouring “mixed” candidates with low  $p_T(\gamma)$  which are more likely to have  $\Delta m < 160$  MeV. These biases should be corrected since the  $p_T(\gamma)$  spectrum is highly correlated with the  $\Delta m$  shape. Corrections for the partial  $\Delta m$  range are derived using the  $B_c^{*+}$  candidates in the signal simulation where a reconstructed photon is not matched to the true photon from  $B_c^{*+}$  (unmatched candidates). The bias due to the mixing procedure itself is corrected by comparing the  $p_T(\gamma)$  spectra in data candidates used for the mixing and in the “mixed” candidates. The  $\Delta m$  templates for the combinatorial background are made from the corrected “mixed” candidates using the KDE technique.

Separate templates are made for the Region 1 and Region 2 by using the corresponding  $B_c^+$  candidate selections. The background yields in each region are allowed to float independently in the fit.

The total  $B_c^{*+}$  signal yield in Region 1 and 2,  $N_{B_c^{*+}}$ , and  $B^{*+}$  yield in Region 1,  $N_{B^{*+}}$ , are free parameters of the fit. The ratio of the  $B_c^{*+}$  yields in Region 1 and 2,  $N_{B_c^{*+}}^{R1}/N_{B_c^{*+}}^{R2}$ , is fixed to the value extracted from the signal simulation.

The results of the simultaneous fit are shown in Figure 2. The total  $B_c^{*+}$  signal yield in data is found to be  $N_{B_c^{*+}} = 163 \pm 19$ , where this uncertainty is statistical only. The yield of the  $B^{*+}$ ,  $N_{B^{*+}} = 17 \pm 8$ , is consistent with expectations based on the amount of  $B^+$  mesons in the peak in the  $m(J/\psi\mu^+)$  distribution and the simulated efficiency for  $B^{*+} \rightarrow B^+\gamma$  events. The signal significance relative to the background-only hypothesis is evaluated using the asymptotic distribution of the profile likelihood ratio [57]. The method of Ref. [58] is used to account for the look-elsewhere effect. Both the local and global significance exceed 10 standard deviations assuming the nominal fit model and stay above 8 standard deviations for all systematic variations described below. The fit yields a  $B_c^{*+}$  mass difference value of  $\Delta m_{B_c^{*+}} = 64.5 \pm 1.4$  MeV, where the uncertainty is statistical. Separate fits of Region 1 and 2 individually yield consistent  $\Delta m_{B_c^{*+}}$  values.

Systematic uncertainties in the value of  $\Delta m_{B_c^{*+}}$  arise due to detector-related and modelling effects, affecting the shape of signal templates used in the  $\Delta m$  fit, and the signal extraction procedure itself. Each source of systematic uncertainty is considered individually, either by repeating the analysis with an appropriate change in the methodology implemented, or by means of MC pseudo-experiments to assess the sensitivity of the fit to the input assumptions. The uncertainty sources that have a significant impact on the  $\Delta m_{B_c^{*+}}$  measurement are listed below and their contributions are summarised in Table 1. Contributions of individual sources are treated as uncorrelated and added in quadrature.

The largest systematic uncertainty is associated with the ID material modelling and photon momentum scale and resolution in simulation. Limited knowledge of the actual material distribution in the ID volume can affect the modelling the photon conversion probability and the efficiency of photon conversion reconstruction. This is investigated using a set of alternative  $B_c^{*+}$  signal simulations with varying detector geometry descriptions or GEANT4 physics models [59]. The accuracy of the simulation's modelling of the photon momentum scale and resolution is evaluated in a dedicated study with the  $B^{*+} \rightarrow B^+\gamma$  process with subsequent  $B^+ \rightarrow J/\psi K^+$  decay used as a control channel. The difference in the reconstructed position and width of the  $B^{*+}$  peak in the distribution of  $\Delta m' = m(J/\psi K^+ e^+ e^-) - m(J/\psi K^+)$  between data and simulation indicates a small discrepancy in both the simulated momentum scale and resolution. An associated systematic uncertainty is estimated by adjusting the detector  $\Delta m$  resolution and the photon  $p_T$  of the simulated candidates by factors that impose consistency of the  $B^{*+}$  peak width and position in the simulation and data. Both effects are added in quadrature resulting in a  $\Delta m_{B_c^{*+}}$  shift of  $-1.13$  MeV. Since they are partially caused by the uncertainty of the ID material modelling, the latter is not added in quadrature, but considered only for the positive-side  $\Delta m_{B_c^{*+}}$  uncertainty.

To evaluate the effect of the  $B_c^+$  production modelling, the simulated  $p_T$  and  $|\eta|$  spectra of the  $B_c^+$  in the signal simulation are varied based on the comparison between data and simulation performed with  $B_c^+ \rightarrow J/\psi\pi^+$  channel [60]. The effect of the modelling of the  $B_c^+ \rightarrow J/\psi\mu^+\nu_\mu$  decay, which uses the decay form factors outlined in Refs. [61–63] in the nominal simulation, is evaluated by using alternative models based on Refs. [64], [65], or the phase-space model. In addition to the dominant  $B_c^+ \rightarrow J/\psi\mu^+\nu_\mu$  channel, other decay chains yielding the  $J/\psi$  and a muon in the  $B_c^+$  decay final state contribute to the inclusive  $B_c^+ \rightarrow J/\psi\mu^+\nu_\mu X$  signal and are included in the nominal simulation. The total fraction of those decays in the simulated sample (about 6% after the selection) is varied between zero and twice the nominal value. These variations imply an effect on the  $N_{B_c^{*+}}^{R1}/N_{B_c^{*+}}^{R2}$  ratio, fixed in the data fit. Another variation

of the fit, where this ratio is treated as a free parameter, is used to conservatively account for a possible residual uncertainty associated with its modelling. Such a fit yields a value consistent with the expectation from the simulation. Muon reconstruction [46] and trigger efficiency [41] uncertainties are propagated to the signal  $\Delta m$  template shapes.

Several alternative approaches to describe the combinatorial background are used to estimate the systematic uncertainties associated with the modelling of its shape. Varying the event mixing procedure by keeping the  $z$  projection of the photon momentum from the real  $B_c^{*+}$  candidate, or by using exclusively the unmatched  $B_c^{*+}$  candidates in the signal MC sample to correct the  $p_T(\gamma)$  spectrum biases, yields tiny variations of the fit results. Using the background model based on the  $\Delta m$  shape of the unmatched candidates instead of the event mixing results in a sizeable change in the background shape, making this second largest contribution to the overall systematic uncertainty. Across all systematic variations, the fit with this alternative background description yields the smallest estimate of the signal significance and is associated with a signal yield reduction of about 15%.

Table 1: Systematic uncertainties associated with the measured value of  $\Delta m_{B_c^{*+}}$ .

Source	Uncertainty [MeV]
Material modelling and photon momentum scale & resolution	+0.44 -1.13
$B_c^+$ production modelling	$\pm 0.19$
$B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu X$ decay modelling	$\pm 0.05$
$N_{B_c^{*+}}^{R1} / N_{B_c^{*+}}^{R2}$ ratio	$\pm 0.12$
Muon reconstruction and trigger	$\pm 0.16$
Background shape modelling	$\pm 0.79$
Total	+0.95 -1.41

In summary, a new state decaying into  $B_c^+$  and a photon was observed by the ATLAS experiment at the LHC using  $pp$  collision data corresponding to an integrated luminosity of  $140 \text{ fb}^{-1}$  at 13 TeV centre-of-mass energy. The study was performed using the  $B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu X$  decay channel and an innovative approach to build photon conversion vertices from low- $p_T$  tracks reconstructed in a preselected event sample. The mass difference between the new state and ground-state  $B_c^+$  meson is measured to be  $\Delta m_{B_c^{*+}} = 64.5 \pm 1.4 \text{ (stat.)}_{-1.4}^{+1.0} \text{ (syst.) MeV}$ . This value matches the theory expectations for the lowest vector state of the  $\bar{b}c$  quarkonium system, the  $B_c^{*+}$  meson, which are generally in the range of 50–70 MeV [6–31]. However, it is larger than the values from the most recent precise lattice QCD calculations [6–8] which are below 60 MeV. The measured  $\Delta m_{B_c^{*+}}$  value corresponds to a mass for the new state of  $m(B_c^{*+}) = 6339.0 \pm 1.4 \text{ (stat.)}_{-1.4}^{+1.0} \text{ (syst.)} \pm 0.3 \text{ (} m_{B_c^+} \text{) MeV}$ , where the third uncertainty is due to the precision of the  $B_c^+$  meson mass knowledge [48]. The new state is observed with a significance that exceeds 8 standard deviations.

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

















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 M. Negrini <sup>24b</sup>, C. Nellist <sup>117</sup>, C. Nelson <sup>105</sup>, K. Nelson <sup>107</sup>, S. Nemecek <sup>133</sup>, M. Nessi <sup>37,g</sup>,  
 M.S. Neubauer <sup>165</sup>, J. Newell <sup>93</sup>, P.R. Newman <sup>21</sup>, Y.W.Y. Ng <sup>165</sup>, B. Ngair <sup>84b</sup>,  
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 A. Onofre <sup>132a,132e,e</sup>, P.U.E. Onyisi <sup>11</sup>, M.J. Oreglia <sup>40</sup>, D. Orestano <sup>77a,77b</sup>, R. Orlandini <sup>77a,77b</sup>,  
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 K. Pachal <sup>160a</sup>, A. Pacheco Pages <sup>13</sup>, C. Padilla Aranda <sup>13</sup>, G. Padovano <sup>75a,75b</sup>,  
 S. Pagan Griso <sup>18a</sup>, L. Pagani <sup>76a,76b</sup>, J. Pampel <sup>25</sup>, D.K. Panchal <sup>11</sup>, C.E. Pandini <sup>60</sup>,  
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 F. Parodi <sup>57b,57a</sup>, J.A. Parsons <sup>42</sup>, J.A. Partridge <sup>138</sup>, U. Parzefall <sup>54</sup>, B.A. Paschen <sup>18a</sup>,  
 B. Pascual Dias <sup>41</sup>, L. Pascual Dominguez <sup>100</sup>, E. Pasqualucci <sup>75a</sup>, S. Passaggio <sup>57b</sup>, F. Pastore <sup>96</sup>,  
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 A.G. Rennie <sup>59</sup>, M. Repik <sup>56</sup>, A.L. Rescia <sup>44b,44a</sup>, S. Resconi <sup>71a</sup>, M. Ressegotti <sup>57b</sup>,  
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 M. Romano <sup>24b</sup>, N. Rompotis <sup>93</sup>, L. Roos <sup>129</sup>, S. Rosati <sup>75a</sup>, L. Roscher <sup>48</sup>, B.J. Rosser <sup>40</sup>,  
 E. Rossi <sup>128</sup>, E. Rossi <sup>72a,72b</sup>, L.P. Rossi <sup>61</sup>, L. Rossini <sup>54</sup>, R. Rosten <sup>121</sup>, M. Rotaru <sup>28b</sup>,  
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 L. Santos Pereira Trigo <sup>48</sup>, E. Sanzani <sup>24b,24a</sup>, K.A. Saoucha <sup>84d</sup>, J.G. Saraiva <sup>132a,132d</sup>,  
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 D. Scheirich <sup>135</sup>, M. Schernau <sup>139f</sup>, C. Scheulen <sup>56</sup>, C. Schiavi <sup>57b,57a</sup>, M. Schioppa <sup>44b,44a</sup>,  
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 N.A. Schneider <sup>110</sup>, L. Schoeffel <sup>137</sup>, A. Schoening <sup>63b</sup>, P.G. Scholer <sup>35</sup>, E. Schopf <sup>145</sup>,  
 M. Schott <sup>25</sup>, S. Schramm <sup>56</sup>, T. Schroer <sup>56</sup>, H-C. Schultz-Coulon <sup>63a</sup>, M. Schumacher <sup>54</sup>,  
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 I. Silva Ferreira <sup>82b</sup>, M.V. Silva Oliveira <sup>30</sup>, S.B. Silverstein <sup>47a</sup>, S. Simion <sup>66</sup>, R. Simoniello <sup>37</sup>,  
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