Observation of the B_c Meson in the Exclusive Decay $B\_c \to J/\psi\pi$

V.M. Abazov, B. Abbott, M. Abolins, B.S. Acharya, M. Adams, T. Adams, E. Aguilo, S.H. Ahn, M. Ahsan, G.D. Alexeev, et al.

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Measurement of the B_c meson mass in the exclusive decay $B_c \to J/\psi\ \pi$

V.M. Abazov[36], B. Abbott[75], M. Abolins[65], B.S. Acharya[29], M. Adams[51], T. Adams[49], E. Aguilo[6], S.H. Ahn[31], M. Ahsan[59], G.D. Alexeev[36], G. Alkhazov[40], A. Alton[64,a], G. Alverson[63], G.A. Alves[2], M. Anastasoaie[35], L.S. Ancu[35], T. Andeen[53], S. Anderson[45], B. Andrieu[17], M.S. Anzelc[53], M. Aoki[50], Y. Arnoud[14], M. Arov[60], M. Arthaud[18], A. Askew[49], B. Åsman[41], A.C.S. Assis Jesus[3], O. Atramentov[49], C. Avila[8], C. Ay[24], F. Badaud[13], A. Baden[61], L. Bagby[50], B. Baldin[50], D.V. Bandurin[59], P. Banerjee[29], S. Banerjee[29], E. Barberis[63], A.-F. Barfuss[15], P. Bargassa[80], P. Baringer[58], J. Barreto[2], J.F. Bartlett[50], U. Bassler[18], D. Bauer[43], S. Beale[6], A. Bean[58], M. Begalli[3], M. Begel[73], C. Belanger-Champagne[41], L. Bellantoni[50], A. Bellavance[50], J.A. Benitez[65], S.B. Beri[27], G. Bernardi[17], R. Bernhard[23], I. Bertram[42], M. Besançon[18], R. Beuselinck[43], V.A. Bezzubov[39], P.C. Bhat[50], V. Bhatnagar[27], C. Biscarat[20], G. Blazey[52], F. Blekman[43], S. Blessing[49], D. Bloch[19], K. Bloom[67], A. Boehnlein[50], D. Boline[62], T.A. Bolton[59], G. Borissov[42], T. Bose[77], A. Brandt[78], R. Brock[65], G. Brooijmans[70], A. Bross[50], D. Brown[81], N.J. Buchanan[49], D. Buchholz[53], M. Buehler[81], V. Buescher[22], V. Bunichev[38], S. Burdin[42,b], S. Burke[45], T.H. Burnett[82], C.P. Buszello[43], J.M. Butler[62], P. Calfayan[25], S. Calvet[16], J. Cammin[71], W. Carvalho[3], B.C.K. Casey[50], H. Castilla-Valdez[33], S. Chakrabarti[18], D. Chakraborty[52], K. Chan[6], K.M. Chan[55], A. Chandra[48], F. Charles[19,‡], E. Cheu[45], F. Chevallier[14], D.K. Cho[62], S. Choi[32], B. Choudhary[28], L. Christofek[77], T. Christoudias[43], S. Cihangir[50], D. Claes[67], Y. Coadou[6], M. Cooke[80], W.E. Cooper[50], M. Corcoran[80], F. Couderc[18], M.-C. Cousinou[15], S. Crépé-Renaudin[14], D. Cutts[77], M. Ćwiok[30], H. da Motta[2], A. Das[45], G. Davies[43], K. De[78], S.J. de Jong[35], E. De La Cruz-Burelo[64], C. De Oliveira Martins[3], J.D. Degenhardt[64], F. Déliot[18], M. Demarteau[50], R. Demina[71], D. Denisov[50], S.P. Denisov[39], S. Desai[50], H.T. Diehl[50], M. Diesburg[50], A. Dominguez[67], H. Dong[72], L.V. Dudko[38], L. Duflot[16], S.R. Dugad[29], D. Duggan[49], A. Duperrin[15], J. Dyer[65], A. Dyshkant[52], M. Eads[67], D. Edmunds[65], J. Ellison[48], V.D. Elvira[50], Y. Enari[77], S. Eno[61], P. Ermolov[38], H. Evans[54], A. Evdokimov[73], V.N. Evdokimov[39], A.V. Ferapontov[59], T. Ferbel[71], F. Fiedler[24], F. Filthaut[35], W. Fisher[50], H.E. Fisk[50], M. Fortner[52], H. Fox[42], S. Fu[50], S. Fuess[50], T. Gadfort[70], C.F. Galea[35], E. Gallas[50], C. Garcia[71], A. Garcia-Bellido[82], V. Gavrilov[37], P. Gay[13], W. Geist[19], D. Gelé[19], C.E. Gerber[51], Y. Gershtein[49], D. Gillberg[6], G. Ginther[71], N. Gollub[41], B. Gómez[8], A. Goussiou[82], P.D. Grannis[72], H. Greenlee[50], Z.D. Greenwood[60], E.M. Gregores[4], G. Grenier[20], Ph. Gris[13], J.-F. Grivaz[16], A. Grohsjean[25], S. Grünendahl[50], M.W. Grünewald[30], F. Guo[72], J. Guo[72], G. Gutierrez[50], P. Gutierrez[75], A. Haas[70], N.J. Hadley[61], P. Haefner[25], S. Hagopian[49], J. Haley[68], I. Hall[65], R.E. Hall[47], L. Han[7], K. Harder[44], A. Harel[71], R. Harrington[63], J.M. Hauptman[57], R. Hauser[65], J. Hays[43], T. Hebbeker[21], D. Hedin[52], J.G. Hegeman[34], J.M. Heinmiller[51], A.P. Heinson[48], U. Heintz[62], C. Hensel[58], K. Herner[72], G. Hesketh[63], M.D. Hildreth[55], R. Hirosky[81], J.D. Hobbs[72], B. Hoeneisen[12], H. Hoeth[26], M. Hohlfeld[22], S.J. Hong[31], S. Hossain[75], P. Houben[34], Y. Hu[72], Z. Hubacek[10], V. Hynek[9], I. Iashvili[69], R. Illingworth[50], A.S. Ito[50], S. Jabeen[62], M. Jaffré[16], S. Jain[75], K. Jakobs[23], C. Jarvis[61], R. Jesik[43], K. Johns[45], C. Johnson[70], M. Johnson[50], A. Jonckheere[50], P. Jonsson[43], A. Juste[50], E. Kajfasz[15], A.M. Kalinin[36], J.M. Kalk[60], S. Kappler[21], D. Karmanov[38], P.A. Kasper[50], I. Katsanos[70], D. Kau[49], V. Kaushik[78], R. Kehoe[79], S. Kermiche[15], N. Khalatyan[50], A. Khanov[76], A. Kharchilava[69], Y.M. Kharzheev[36], D. Khatidze[70], T.J. Kim[31], M.H. Kirby[53], M. Kirsch[21], B. Klima[50], J.M. Kohli[27], J.-P. Konrath[23], V.M. Korablev[39], A.V. Kozelov[39], J. Kraus[65], D. Krop[54], T. Kuhl[24], A. Kumar[69], A. Kupco[11], T. Kurča[20], J. Kvita[9], F. Lacroix[13], D. Lam[55], S. Lammers[70], G. Landsberg[77], P. Lebrun[20], W.M. Lee[50], A. Leflat[38], J. Lellouch[17], J. Leveque[45], J. Li[78], L. Li[48], Q.Z. Li[50], S.M. Lietti[5], J.G.R. Lima[52], D. Lincoln[50], J. Linnemann[65], V.V. Lipaev[39], R. Lipton[50], Y. Liu[7], Z. Liu[6], A. Lobodenko[40], M. Lokajicek[11], P. Love[42], H.J. Lubatti[82], R. Luna[3], A.L. Lyon[50], A.K.A. Maciel[2], D. Mackin[80], R.J. Madaras[46], P. Mättig[26], C. Magass[21], A. Magerkurth[64], P.K. Mal[82], H.B. Malbouisson[3], S. Malik[67], V.L. Malyshev[36], H.S. Mao[50], Y. Maravin[59], B. Martin[14], R. McCarthy[72], A. Melnitchouk[66], L. Mendoza[8], P.G. Mercadante[5], M. Merkin[38], K.W. Merritt[50], A. Meyer[21], J. Meyer[22,d], T. Millet[20], J. Mitrevski[70], J. Molina[3], R.K. Mommsen[44], N.K. Mondal[29], R.W. Moore[6], T. Moulik[58], G.S. Muanza[20], M. Mulders[50], M. Mulhearn[70], O. Mundal[22], L. Mundim[3], E. Nagy[15], M. Naimuddin[50], M. Narain[77], N.A. Naumann[35], H.A. Neal[64], J.P. Negret[8], P. Neustroev[40], H. Nilsen[23], H. Nogima[3], S.F. Novaes[5], T. Nunnemann[25], V. O'Dell[50], D.C. O'Neil[6], G. Obrant[40], C. Ochando[16], D. Onoprienko[59], N. Oshima[50], N. Osman[43], J. Osta[55], R. Otec[10], G.J. Otero y Garzón[50], M. Owen[44], P. Padley[80], M. Pangilinan[77], N. Parashar[56], S.-J. Park[71], S.K. Park[31], J. Parsons[70], R. Partridge[77], N. Parua[54], A. Patwa[73], G. Pawloski[80], B. Penning[23], M. Perfilov[38], K. Peters[44],

Y. Peters[26], P. Pétroff[16], M. Petteni[43], R. Piegaia[1], J. Piper[65], M.-A. Pleier[22], P.L.M. Podesta-Lerma[33,c], V.M. Podstavkov[50], Y. Pogorelov[55], M.-E. Pol[2], P. Polozov[37], B.G. Pope[65], A.V. Popov[39], C. Potter[6], W.L. Prado da Silva[3], H.B. Prosper[49], S. Protopopescu[73], J. Qian[64], A. Quadt[22,d], B. Quinn[66], A. Rakitine[42], M.S. Rangel[2], K. Ranjan[28], P.N. Ratoff[42], P. Renkel[79], S. Reucroft[63], P. Rich[44], J. Rieger[54], M. Rijssenbeek[72], I. Ripp-Baudot[19], F. Rizatdinova[76], S. Robinson[43], R.F. Rodrigues[3], M. Rominsky[75], C. Royon[18], P. Rubinov[50], R. Ruchti[55], G. Safronov[37], G. Sajot[14], A. Sánchez-Hernández[33], M.P. Sanders[17], A. Santoro[3], G. Savage[50], L. Sawyer[60], T. Scanlon[43], D. Schaile[25], R.D. Schamberger[72], Y. Scheglov[40], H. Schellman[53], T. Schliephake[26], C. Schwanenberger[44], A. Schwartzman[68], R. Schwienhorst[65], J. Sekaric[49], H. Severini[75], E. Shabalina[51], M. Shamim[59], V. Shary[18], A.A. Shchukin[39], R.K. Shivpuri[28], V. Siccardi[19], V. Simak[10], V. Sirotenko[50], P. Skubic[75], P. Slattery[71], D. Smirnov[55], G.R. Snow[67], J. Snow[74], S. Snyder[73], S. Söldner-Rembold[44], L. Sonnenschein[17], A. Sopczak[42], M. Sosebee[78], K. Soustruznik[9], B. Spurlock[78], J. Stark[14], J. Steele[60], V. Stolin[37], D.A. Stoyanova[39], J. Strandberg[64], S. Strandberg[41], M.A. Strang[69], E. Strauss[72], M. Strauss[75], R. Ströhmer[25], D. Strom[53], L. Stutte[50], S. Sumowidagdo[49], P. Svoisky[55], A. Sznajder[3], P. Tamburello[45], A. Tanasijczuk[1], W. Taylor[6], J. Temple[45], B. Tiller[25], F. Tissandier[13], M. Titov[18], V.V. Tokmenin[36], T. Toole[61], I. Torchiani[23], T. Trefzger[24], D. Tsybychev[72], B. Tuchming[18], C. Tully[68], P.M. Tuts[70], R. Unalan[65], L. Uvarov[40], S. Uvarov[40], S. Uzunyan[52], B. Vachon[6], P.J. van den Berg[34], R. Van Kooten[54], W.M. van Leeuwen[34], N. Varelas[51], E.W. Varnes[45], I.A. Vasilyev[39], M. Vaupel[26], P. Verdier[20], L.S. Vertogradov[36], M. Verzocchi[50], F. Villeneuve-Seguier[43], P. Vint[43], P. Vokac[10], E. Von Toerne[59], M. Voutilainen[68,e], R. Wagner[68], H.D. Wahl[49], L. Wang[61], M.H.L.S. Wang[50], J. Warchol[55], G. Watts[82], M. Wayne[55], G. Weber[24], M. Weber[50], L. Welty-Rieger[54], A. Wenger[23,f], N. Wermes[22], M. Wetstein[61], A. White[78], D. Wicke[26], G.W. Wilson[58], S.J. Wimpenny[48], M. Wobisch[60], D.R. Wood[63], T.R. Wyatt[44], Y. Xie[77], S. Yacoob[53], R. Yamada[50], M. Yan[61], T. Yasuda[50], Y.A. Yatsunenko[36], K. Yip[73], H.D. Yoo[77], S.W. Youn[53], J. Yu[78], A. Zatserklyaniy[52], C. Zeitnitz[26], T. Zhao[82], B. Zhou[64], J. Zhu[72], M. Zielinski[71], D. Zieminska[54], A. Zieminski[54,‡], L. Zivkovic[70], V. Zutshi[52], and E.G. Zverev[38]

(The DØ Collaboration)

[1] *Universidad de Buenos Aires, Buenos Aires, Argentina*
[2] *LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*
[3] *Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[4] *Universidade Federal do ABC, Santo André, Brazil*
[5] *Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil*
[6] *University of Alberta, Edmonton, Alberta, Canada, Simon Fraser University, Burnaby, British Columbia, Canada, York University, Toronto, Ontario, Canada, and McGill University, Montreal, Quebec, Canada*
[7] *University of Science and Technology of China, Hefei, People's Republic of China*
[8] *Universidad de los Andes, Bogotá, Colombia*
[9] *Center for Particle Physics, Charles University, Prague, Czech Republic*
[10] *Czech Technical University, Prague, Czech Republic*
[11] *Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic*
[12] *Universidad San Francisco de Quito, Quito, Ecuador*
[13] *LPC, Univ Blaise Pascal, CNRS/IN2P3, Clermont, France*
[14] *LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, France*
[15] *CPPM, IN2P3/CNRS, Université de la Méditerranée, Marseille, France*
[16] *LAL, Univ Paris-Sud, IN2P3/CNRS, Orsay, France*
[17] *LPNHE, IN2P3/CNRS, Universités Paris VI and VII, Paris, France*
[18] *DAPNIA/Service de Physique des Particules, CEA, Saclay, France*
[19] *IPHC, Université Louis Pasteur et Université de Haute Alsace, CNRS/IN2P3, Strasbourg, France*
[20] *IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France*
[21] *III. Physikalisches Institut A, RWTH Aachen, Aachen, Germany*
[22] *Physikalisches Institut, Universität Bonn, Bonn, Germany*
[23] *Physikalisches Institut, Universität Freiburg, Freiburg, Germany*
[24] *Institut für Physik, Universität Mainz, Mainz, Germany*
[25] *Ludwig-Maximilians-Universität München, München, Germany*
[26] *Fachbereich Physik, University of Wuppertal, Wuppertal, Germany*
[27] *Panjab University, Chandigarh, India*
[28] *Delhi University, Delhi, India*

[29] Tata Institute of Fundamental Research, Mumbai, India
[30] University College Dublin, Dublin, Ireland
[31] Korea Detector Laboratory, Korea University, Seoul, Korea
[32] SungKyunKwan University, Suwon, Korea
[33] CINVESTAV, Mexico City, Mexico
[34] FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands
[35] Radboud University Nijmegen/NIKHEF, Nijmegen, The Netherlands
[36] Joint Institute for Nuclear Research, Dubna, Russia
[37] Institute for Theoretical and Experimental Physics, Moscow, Russia
[38] Moscow State University, Moscow, Russia
[39] Institute for High Energy Physics, Protvino, Russia
[40] Petersburg Nuclear Physics Institute, St. Petersburg, Russia
[41] Lund University, Lund, Sweden, Royal Institute of Technology and Stockholm University, Stockholm, Sweden, and Uppsala University, Uppsala, Sweden
[42] Lancaster University, Lancaster, United Kingdom
[43] Imperial College, London, United Kingdom
[44] University of Manchester, Manchester, United Kingdom
[45] University of Arizona, Tucson, Arizona 85721, USA
[46] Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA
[47] California State University, Fresno, California 93740, USA
[48] University of California, Riverside, California 92521, USA
[49] Florida State University, Tallahassee, Florida 32306, USA
[50] Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
[51] University of Illinois at Chicago, Chicago, Illinois 60607, USA
[52] Northern Illinois University, DeKalb, Illinois 60115, USA
[53] Northwestern University, Evanston, Illinois 60208, USA
[54] Indiana University, Bloomington, Indiana 47405, USA
[55] University of Notre Dame, Notre Dame, Indiana 46556, USA
[56] Purdue University Calumet, Hammond, Indiana 46323, USA
[57] Iowa State University, Ames, Iowa 50011, USA
[58] University of Kansas, Lawrence, Kansas 66045, USA
[59] Kansas State University, Manhattan, Kansas 66506, USA
[60] Louisiana Tech University, Ruston, Louisiana 71272, USA
[61] University of Maryland, College Park, Maryland 20742, USA
[62] Boston University, Boston, Massachusetts 02215, USA
[63] Northeastern University, Boston, Massachusetts 02115, USA
[64] University of Michigan, Ann Arbor, Michigan 48109, USA
[65] Michigan State University, East Lansing, Michigan 48824, USA
[66] University of Mississippi, University, Mississippi 38677, USA
[67] University of Nebraska, Lincoln, Nebraska 68588, USA
[68] Princeton University, Princeton, New Jersey 08544, USA
[69] State University of New York, Buffalo, New York 14260, USA
[70] Columbia University, New York, New York 10027, USA
[71] University of Rochester, Rochester, New York 14627, USA
[72] State University of New York, Stony Brook, New York 11794, USA
[73] Brookhaven National Laboratory, Upton, New York 11973, USA
[74] Langston University, Langston, Oklahoma 73050, USA
[75] University of Oklahoma, Norman, Oklahoma 73019, USA
[76] Oklahoma State University, Stillwater, Oklahoma 74078, USA
[77] Brown University, Providence, Rhode Island 02912, USA
[78] University of Texas, Arlington, Texas 76019, USA
[79] Southern Methodist University, Dallas, Texas 75275, USA
[80] Rice University, Houston, Texas 77005, USA
[81] University of Virginia, Charlottesville, Virginia 22901, USA and
[82] University of Washington, Seattle, Washington 98195, USA

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A fully reconstructed $B_c \to J/\psi + \pi$ signal is observed with the D0 detector at the Fermilab Tevatron $p\overline{p}$ collider. Using 1.3 fb^{-1} of integrated luminosity, the signal is extracted with a significance more than five standard deviations above background. The measured B_c meson mass is $6300 \pm 14\,(\text{stat}) \pm 5\,(\text{sys})$ MeV/c^2.

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B_c mesons are predicted by the quark model to be members of the $J^P = 0^-$ pseudo-scalar ground-state multiplet and to have zero isospin as the lowest-lying bound state of a bottom anti-quark and a charm quark [1]. B_c properties are of special interest because of this meson's unique status as a short-lifetime bound state of heavy but (unlike quarkonia) different flavor quarks. Measurements of its mass, production, and decay therefore allow for tests of theories under new approximation regimes or extended validity ranges beyond quarkonia.

This analysis uses data collected by the D0 detector between April 2002 and March 2006 at the Fermilab Tevatron $p\overline{p}$ collider operating at $\sqrt{s} = 1.96$ TeV. The data sample corresponds to approximately 1.3 fb^{-1} of integrated luminosity. At the Tevatron the most easily identified decay modes of the B_c have a J/ψ meson in the final state and are either the semileptonic mode $B_c \to J/\psi \ell \nu$ $(\ell = e, \mu)$, a signal with much higher statistics and thus more suitable for lifetime measurements, or the hadronic mode $B_c \to J/\psi\pi$, more suitable for mass measurements given its fully exclusive reconstruction without the loss of an escaping neutrino.

The CDF collaboration has published results on both decay modes [2, 3], and has recently updated the B_c mass measurement to $M(B_c) = 6275.6 \pm 2.9\,(\text{stat}) \pm 2.5\,(\text{sys})$ MeV/c^2 [4]. The present Letter is the first report by the D0 collaboration of a fully reconstructed hadronic decay mode of this state. The measured lifetime [3] is consistent with the expectation of a shorter B_c lifetime than for other B mesons due to the presence of a charm quark. The B_c mass has been predicted by various theoretical models [5] and most recently [6] with a three-flavor (unquenched) lattice QCD numerical algorithm that yielded the smallest theoretical uncertainty, with the result $M(B_c) = 6304 \pm 12\ ^{+18}_{-0}$ MeV/c^2, where the first error is the sum in quadrature of statistical and systematic uncertainties, and the second is due to heavy quark discretization effects.

The D0 detector is described elsewhere [7], and the elements most relevant to this analysis are the tracking detectors inside a 2 T superconducting solenoidal magnet and the muon detection chambers. For enhanced preselection efficiency, no specific trigger requirements are applied, but all events satisfy one of a suite of muon triggers, typically requiring at least one muon with transverse momentum (p_T) above 3 GeV/c. The decay under study consists of a single detached secondary three-track vertex: $B_c \to J/\psi\pi \to \mu^+\mu^-\pi$ (charge conjugate modes, $\pi^\pm$, are always implied). Initial track selection extends to a pseudorapidity of $|\eta| < 2.0$ (where $\eta = -\ln[\tan(\theta/2)]$, and θ is the polar angle with respect to the beam line), and rejects tracks with $p_T < 1.5$ GeV/c. Selected final state tracks must satisfy quality requirements based on established minimal hit patterns and a goodness of track fit. Tracks identified as muons must have matching hits in all three layers of the muon detector.

Event selection starts with the requirement of an opposite-charge muon pair that forms a common vertex and whose mass is consistent with that of the J/ψ meson (between 2.85 and 3.35 GeV/c^2). There follows a search for a third track that, together with the muons, must form a common vertex with $\chi^2 < 16.0$ for the three degrees of freedom. The J/ψ candidate must have $p_T > 4$ GeV/c, and the third particle is assigned the pion mass. Thus formed, the B_c meson candidate is required to have $p_T > 5$ GeV/c.

Further B_c candidate selection places constraints on quantities that proved to be strong discriminators against combinatoric backgrounds. The impact parameter (IP) significance of any particle, reconstructed either from a single track or a combination of tracks, is $I_{\text{sig}} = \sqrt{[\epsilon_T/\sigma(\epsilon_T)]^2 + [\epsilon_L/\sigma(\epsilon_L)]^2}$, where ϵ_T (ϵ_L) is the transverse (longitudinal) projection (with respect to the beam direction) of the track IP relative to the $p\overline{p}$ interaction vertex, or primary vertex, and σ is the associated uncertainty. The primary vertex is determined event by event using a method described in Ref. [8]. The transverse decay length significance of a decay (or secondary) vertex is $S_{xy} = L_{xy}/\sigma(L_{xy})$ where L_{xy} is the distance separating that vertex from the beam line. The pointing cosine, C_{xy}, measures the alignment between $\vec{L}_{xy}$ and the transverse momentum direction of the decaying candidate particle. The isolation $\mathcal{I}$ of a B_c candidate is defined as the ratio of two p_T sums: that from the three candidate tracks, divided by that from all tracks with p_T above 0.3 GeV/c whose momenta are lying within a cone of radius $\Delta\mathcal{R} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.5$, where $\Delta\eta$ and $\Delta\phi$ are distances in pseudorapidity and azimuthal angle from the B_c momentum axis, respectively.

Throughout the background reduction process, a control procedure is used that tests the effect of each discriminator against a well-understood signal sample, either reconstructed $B^\pm \to J/\psi K^\pm$ candidates in data or candidates in a $B_c^\pm \to J/\psi\pi^\pm$ simulated Monte Carlo sample. The latter is generated using EvtGen [9] interfaced with pythia [10], followed by full modeling of the detector response with geant [11] and event reconstruction exactly as in data.

J/ψ candidates are mass constrained, i.e., their daughter muon momenta are corrected to yield the PDG [12] mass value. When the third track is assumed to be a kaon, a clean, high-statistics $B^\pm$ signal in invariant mass is observed in the data. This decay has a topology similar to the B_c signal and is used as a reference in an initial round of selection cuts shown in Table I as Stage 1. Here the $B^\pm$ signal and sideband regions are used as efficiency and rejection indicators of where to set selection thresholds. The $B^\pm$ study region extends from 4.98 to 5.58 GeV/c^2 in invariant mass, and the signal region is approximately $\pm 2\sigma$ wide from 5.20 to 5.36 GeV/c^2. Individual cuts are required to be about 95% efficient,

TABLE I: Discriminators and their values at the two selection stages (see text). $p_T^{\rm rel}(\pi)$ is introduced only for the second stage and represents the transverse momentum of the pion candidate with respect to the total B_c candidate momentum.

Discriminator	Condition	Stage 1	Stage 2
$I_{\rm sig}(B_c)$	$<$	3.5	3.5
$I_{\rm sig}(\pi)$	$>$	3.0	3.5
S_{xy}	$>$	3.0	4.5
C_{xy}	$>$	0.95	0.95
$\mathcal{I}$	$>$	0.5	0.64
$p_T(\pi)$ (GeV/c)	$>$	1.8	2.2
$p_T^{\rm rel}(\pi)$ (GeV/c)	$>$	–	1.5
$p_T^{\rm rel}(\pi)$ (GeV/c)	$<$	–	2.5

with typical background rejection of approximately 20%. The resulting thresholds are listed in Table I.

However, there are differences between the $B^\pm$ and B_c. Due to the lower (by about 1 GeV/c^2) invariant mass and the longer (b-like versus c-like) lifetime of the $B^\pm$, background reduction undergoes a second stage, in which the B_c Monte Carlo is used to model the signal. This second selection stage (Stage 2 in Table I) aims at re-optimizing, if needed, those cuts associated with B_c specific decay properties. With the third track now assumed to be a pion, the range in invariant mass from 5.6 to 7.2 GeV/c^2 is studied. A sub-range between 6.1 and 6.5 GeV/c^2 is treated as the B_c signal search window, and its invariant mass distribution in data is kept blinded throughout the analysis. This sub-range is approximately $\pm 3\sigma$ (mass resolution as determined from simulation) wide, and covers both the theory expectations for the B_c mass [6] as well as the observed values quoted in [2, 4]. Data in mass sidebands outside this sub-range are used as a model for backgrounds and to quantify background rejection. Table I lists those selections that were re-optimized (or introduced, in the case of $p_T^{\rm rel}(\pi)$) in Stage 2, and summarizes their evolution between the two selection stages. At this stage there remain no dimuon vertices with more than one candidate for the third track, and no events with more than one B_c candidate.

From B_c simulated events, the B_c mass signal is found to be well-modeled by a Gaussian function with a width of 55 MeV/c^2. The mass resolution of the $B^\pm \to J/\psi K^\pm$ signal observed in the data under similar conditions, after all selections have been applied, reproduces the same width when scaled by the ratio of the $B^\pm$ and B_c masses.

The resulting $J/\psi\pi$ invariant mass is shown in Fig. 1 where a clear excess is seen near 6.3 GeV/c^2. An unbinned maximum log-likelihood (UML) fit of the $J/\psi\pi$ invariant mass distribution is performed, where the signal is modeled by a Gaussian function with width fixed to a value of 55 MeV/c^2, and combinatoric backgrounds are modeled by a first-degree polynomial. The result of the UML fit is overlaid in Fig. 1 and yields a signal of 54 ± 12 events and a B_c mass value of 6300.7 ± 13.6 MeV/c^2. To

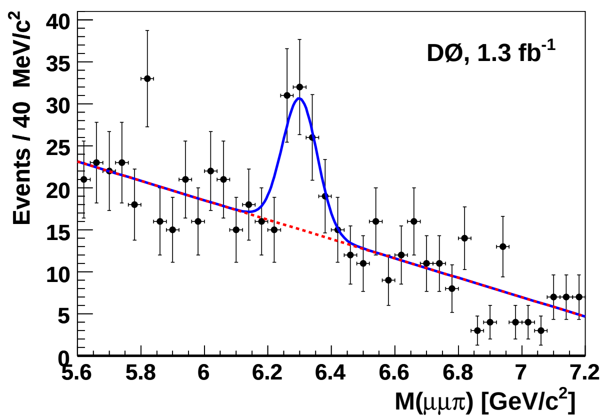

FIG. 1: $J/\psi\pi$ invariant mass distribution of B_c candidates after the final selection. A projection of the unbinned maximum likelihood fit to the distribution is shown overlaid.

estimate the signal significance, the same fit is repeated under the assumption that no signal is present. From the negative log-likelihoods of the signal plus background and background-only hypotheses, the signal significance is extracted [12] as $N_\sigma = \{2\ln[\mathcal{L}(s+b)/\mathcal{L}(b)]\}^{1/2} = 5.2$ standard deviations above background. For another estimate of signal significance, χ^2 fits to data (in the 40 MeV/c^2 bins of Fig. 1) under both hypotheses produce an increase in fit χ^2 of 27 units, again indicating $N_\sigma = 5.2$ standard deviations above background.

Possible biases and systematic uncertainties affecting the B_c mass determination are estimated using both the $B^\pm$ signal in the data and the B_c signal in either the data or the simulation. Uncertainty assessments are made as these samples are re-fitted under various test hypotheses. Sources of systematic uncertainties are the event selection, the fitting procedure (input mass resolution and data modeling), and the reconstructed mass scale.

The fitted mass values are examined in the simulated signal sample as the value of the $p_T(\pi)$ threshold is varied from 1.9 to 2.5 GeV/c. No systematic mass bias is observed, but statistical fluctuations of ± 4.0 MeV/c^2 are observed and assigned as a systematic uncertainty. Similarly, the $p_T^{\rm rel}$ lower threshold is varied between no cut and 2.0 GeV/c, and the resultant mass variation indicates a small upward mass bias of 0.5 MeV/c^2 for the cut value adopted with respect to the no cut case. The observed B_c mass is corrected accordingly, and a 100% uncertainty is assigned to this correction. There is no indication of a bias in mass due to the upper $p_T^{\rm rel}$ limit.

The values of the selection cuts that are not directly related to the kinematics of the third particle (the pion or kaon candidates in the B_c or $B^\pm$ cases, respectively) are varied within reasonable values. No mass biases are observed, and from the range of mass values obtained, a systematic uncertainty of ± 2.5 MeV/c^2 is assigned due to the choice of these selection cuts.

TABLE II: Summary of systematic uncertainties in the B_c mass measurement.

Source	Component	Value (MeV/c^2)
Selection	π kinematics	4.0
	other	2.5
Data modeling	mass resolution	0.6
	background model	0.5
	signal shape	0.5
Mass scale		1.0
Total		4.9

To assess the systematic uncertainty due to the uncertainty of the mass resolution, the width of the Gaussian is allowed to float in the fit. The width input is also changed from the nominal value of 55 MeV/c^2 to other fixed values in the range from 45 to 65 MeV/c^2. From the variation of fitted mass results, a value of ± 0.6 MeV/c^2 is assigned to this uncertainty.

The background model is changed from a first-degree polynomial to a second-degree and third-degree polynomial, and to an exponential function. From the resulting change in mass observed, a systematic uncertainty of ± 0.5 MeV/c^2 is assigned due to uncertainty in the background model. The signal model is changed from a single Gaussian to a double Gaussian function, and the resulting shift of 0.5 MeV/c^2 is assigned as a systematic uncertainty.

Lastly, for an estimate of the mass scale uncertainty, a direct comparison is carried out between generated and reconstructed Monte Carlo masses, as well as between recent D0 mass measurements of well-known B states and the world averages of their measurements [12]. From the observed range of mass differences, a systematic uncertainty of ± 1.0 MeV/c^2 is assigned due to uncertainty in the D0 mass scale for the B_c decay.

A summary of all systematic uncertainties in the B_c mass measurement is shown in Table II. The overall systematic uncertainty is ± 4.9 MeV/c^2. The mass fit result of 6300.7 ± 13.6 MeV/c^2 is corrected by -0.5 MeV/c^2 for the $p_T^{\rm rel}$ bias. The final result for the B_c mass is $6300 \pm 14\,({\rm stat}) \pm 5\,({\rm sys})$ MeV/c^2.

In summary, using a dataset corresponding to 1.3 fb^{-1}, a signal for $B_c \to J/\psi\pi$ has been observed with a significance higher than five standard deviations above background. The mass of the B_c meson has been measured and found to be consistent with the latest and most precise lattice QCD prediction [6]. Besides its relevance in the development and tuning of heavy-quark bound-state models, the B_c sample described here, with added integrated luminosity, is expected to be used in the extraction of lifetime, relative branching ratio, and production rate.

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[a] Visitor from Augustana College, Sioux Falls, SD, USA.
[b] Visitor from The University of Liverpool, Liverpool, UK.
[c] Visitor from ICN-UNAM, Mexico City, Mexico.
[d] Visitor from II. Physikalisches Institut, Georg-August-University, Göttingen, Germany.
[e] Visitor from Helsinki Institute of Physics, Helsinki, Finland.
[f] Visitor from Universität Zürich, Zürich, Switzerland.
[‡] Deceased.

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