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Citation	Abazov, V. M., Abbott, B., Acharya, B. S., Adams, M., Adams, T., & Zivkovic, L. (2015). Inclusive Production of the X(4140) State in $p\bar{p}$ Collisions at D0. Physical Review Letters, 115(23), 232001. doi:10.1103/PhysRevLett.115.232001
DOI	10.1103/PhysRevLett.115.232001
Publisher	American Physical Society
Version	Version of Record
Terms of Use	http://cdss.library.oregonstate.edu/sa-termsofuse

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V. M. Abazov,[31] B. Abbott,[67] B. S. Acharya,[25] M. Adams,[46] T. Adams,[44] J. P. Agnew,[41] G. D. Alexeev,[31] G. Alkhazov,[35] A. Alton,[a,56] A. Askew,[44] S. Atkins,[54] K. Augsten,[7] C. Avila,[5] F. Badaud,[10] L. Bagby,[45] B. Baldin,[45] D. V. Bandurin,[74] S. Banerjee,[25] E. Barberis,[55] P. Baringer,[53] J. F. Bartlett,[45] U. Bassler,[15] V. Bazterra,[46] A. Bean,[53] M. Begalli,[2] L. Bellantoni,[45] S. B. Beri,[23] G. Bernardi,[14] R. Bernhard,[19] I. Bertram,[39] M. Besançon,[15] R. Beuselinck,[40] P. C. Bhat,[45] S. Bhatia,[58] V. Bhatnagar,[23] G. Blazey,[47] S. Blessing,[44] K. Bloom,[59] A. Boehnlein,[45] D. Boline,[64] E. E. Boos,[33] G. Borissov,[39] M. Borysova,[l,38] A. Brandt,[71] O. Brandt,[20] R. Brock,[57] A. Bross,[45] D. Brown,[14] X. B. Bu,[45] M. Buehler,[45] V. Buescher,[21] V. Bunichev,[33] S. Burdin,[b,39] C. P. Buszello,[37] E. Camacho-Pérez,[28] B. C. K. Casey,[45] H. Castilla-Valdez,[28] S. Caughron,[57] S. Chakrabarti,[64] K. M. Chan,[51] A. Chandra,[73] E. Chapon,[15] G. Chen,[53] S. W. Cho,[27] S. Choi,[27] B. Choudhary,[24] S. Cihangir,[45] D. Claes,[59] J. Clutter,[53] M. Cooke,[k,45] W. E. Cooper,[45] M. Corcoran,[73] F. Couderc,[15] M.-C. Cousinou,[12] J. Cuth,[21] D. Cutts,[70] A. Das,[72] G. Davies,[40] S. J. de Jong,[29,30] E. De La Cruz-Burelo,[28] F. Déliot,[15] R. Demina,[63] D. Denisov,[45] S. P. Denisov,[34] S. Desai,[45] C. Deterre,[c,41] K. DeVaughan,[59] H. T. Diehl,[45] M. Diesburg,[45] P. F. Ding,[41] A. Dominguez,[59] A. Dubey,[24] L. V. Dudko,[33] A. Duperrin,[12] S. Dutt,[23] M. Eads,[47] D. Edmunds,[57] J. Ellison,[43] V. D. Elvira,[45] Y. Enari,[14] H. Evans,[49] A. Evdokimov,[46] V. N. Evdokimov,[34] A. Fauré,[15] L. Feng,[47] T. Ferbel,[63] F. Fiedler,[21] F. Filthaut,[29,30] W. Fisher,[57] H. E. Fisk,[45] M. Fortner,[47] H. Fox,[39] S. Fuess,[45] P. H. Garbincius,[45] A. Garcia-Bellido,[63] J. A. García-González,[28] V. Gavrilov,[32] W. Geng,[12,57] C. E. Gerber,[46] Y. Gershtein,[60] G. Ginther,[45] O. Gogota,[38] G. Golovanov,[31] P. D. Grannis,[64] S. Greder,[16] H. Greenlee,[45] G. Grenier,[17] Ph. Gris,[10] J.-F. Grivaz,[13] A. Grohsjean,[c,15] S. Grünendahl,[45] M. W. Grünewald,[26] T. Guillemin,[13] G. Gutierrez,[45] P. Gutierrez,[67] J. Haley,[68] L. Han,[4] K. Harder,[41] A. Harel,[63] J. M. Hauptman,[52] J. Hays,[40] T. Head,[41] T. Hebbeker,[18] D. Hedin,[47] H. Hegab,[68] A. P. Heinson,[43] U. Heintz,[70] C. Hensel,[1] I. Heredia-De La Cruz,[d,28] K. Herner,[45] G. Hesketh,[f,41] M. D. Hildreth,[51] R. Hirosky,[74] T. Hoang,[44] J. D. Hobbs,[64] B. Hoeneisen,[9] J. Hogan,[73] M. Hohlfeld,[21] J. L. Holzbauer,[58] I. Howley,[71] Z. Hubacek,[7,15] V. Hynek,[7] I. Iashvili,[62] Y. Ilchenko,[72] R. Illingworth,[45] A. S. Ito,[45] S. Jabeen,[m,45] M. Jaffré,[13] A. Jayasinghe,[67] M. S. Jeong,[27] R. Jesik,[40] P. Jiang,[4] K. Johns,[42] E. Johnson,[57] M. Johnson,[45] A. Jonckheere,[45] P. Jonsson,[40] J. Joshi,[43] A. W. Jung,[45] A. Juste,[36] E. Kajfasz,[12] D. Karmanov,[33] I. Katsanos,[59] M. Kaur,[23] R. Kehoe,[72] S. Kermiche,[12] N. Khalatyan,[45] A. Khanov,[68] A. Kharchilava,[62] Y. N. Kharzheev,[31] I. Kiselevich,[32] J. M. Kohli,[23] A. V. Kozelov,[34] J. Kraus,[58] A. Kumar,[62] A. Kupco,[8] T. Kurča,[17] V. A. Kuzmin,[33] S. Lammers,[49] P. Lebrun,[17] H. S. Lee,[27] S. W. Lee,[52] W. M. Lee,[45] X. Lei,[42] J. Lellouch,[14] D. Li,[14] H. Li,[74] L. Li,[43] Q. Z. Li,[45] J. K. Lim,[27] D. Lincoln,[45] J. Linnemann,[57] V. V. Lipaev,[34] R. Lipton,[45] H. Liu,[72] Y. Liu,[4] A. Lobodenko,[35] M. Lokajicek,[8] R. Lopes de Sa,[45] R. Luna-Garcia,[g,28] A. L. Lyon,[45] A. K. A. Maciel,[1] R. Madar,[19] R. Magaña-Villalba,[28] S. Malik,[59] V. L. Malyshev,[31] J. Mansour,[20] J. Martínez-Ortega,[28] R. McCarthy,[64] C. L. McGivern,[41] M. M. Meijer,[29,30] A. Melnitchouk,[45] D. Menezes,[47] P. G. Mercadante,[3] M. Merkin,[33] A. Meyer,[18] J. Meyer,[i,20] F. Miconi,[16] N. K. Mondal,[25] M. Mulhearn,[74] E. Nagy,[12] M. Narain,[70] R. Nayyar,[42] H. A. Neal,[56] J. P. Negret,[5] P. Neustroev,[35] H. T. Nguyen,[74] T. Nunnemann,[22] J. Orduna,[73] N. Osman,[12] J. Osta,[51] A. Pal,[71] N. Parashar,[50] V. Parihar,[70] S. K. Park,[27] R. Partridge,[e,70] N. Parua,[49] A. Patwa,[j,65] B. Penning,[40] M. Perfilov,[33] Y. Peters,[41] K. Petridis,[41] G. Petrillo,[63] P. Pétroff,[13] M.-A. Pleier,[65] V. M. Podstavkov,[45] A. V. Popov,[34] M. Prewitt,[73] D. Price,[41] N. Prokopenko,[34] J. Qian,[56] A. Quadt,[20] B. Quinn,[58] P. N. Ratoff,[39] I. Razumov,[34] I. Ripp-Baudot,[16] F. Rizatdinova,[68] M. Rominsky,[45] A. Ross,[39] C. Royon,[8] P. Rubinov,[45] R. Ruchti,[51] G. Sajot,[11] A. Sánchez-Hernández,[28] M. P. Sanders,[22] A. S. Santos,[h,1] G. Savage,[45] M. Savitskyi,[38] L. Sawyer,[54] T. Scanlon,[40] R. D. Schamberger,[64] Y. Scheglov,[35] H. Schellman,[69,48] M. Schott,[21] C. Schwanenberger,[41] R. Schwienhorst,[57] J. Sekaric,[53] H. Severini,[67] E. Shabalina,[20] V. Shary,[15] S. Shaw,[41] A. A. Shchukin,[34] V. Simak,[7] P. Skubic,[67] P. Slattery,[63] D. Smirnov,[51] G. R. Snow,[59] J. Snow,[66] S. Snyder,[65] S. Söldner-Rembold,[41] L. Sonnenschein,[18] K. Soustruznik,[6] J. Stark,[11] D. A. Stoyanova,[34] M. Strauss,[67] L. Suter,[41] P. Svoisky,[67] M. Titov,[15] V. V. Tokmenin,[31] Y.-T. Tsai,[63] D. Tsybychev,[64] B. Tuchming,[15] C. Tully,[61] L. Uvarov,[35] S. Uvarov,[35] S. Uzunyan,[47] R. Van Kooten,[49] W. M. van Leeuwen,[29] N. Varelas,[46] E. W. Varnes,[42] I. A. Vasilyev,[34] A. Y. Verkheev,[31] L. S. Vertogradov,[31] M. Verzocchi,[45] M. Vesterinen,[41] D. Vilanova,[15] P. Vokac,[7] H. D. Wahl,[44] M. H. L. S. Wang,[45] J. Warchol,[51] G. Watts,[75] M. Wayne,[51] J. Weichert,[21] L. Welty-Rieger,[48] M. R. J. Williams,[n,49] G. W. Wilson,[53] M. Wobisch,[54] D. R. Wood,[55] T. R. Wyatt,[41] Y. Xie,[45] R. Yamada,[45] S. Yang,[4] T. Yasuda,[45] Y. A. Yatsunenko,[31] W. Ye,[64] Z. Ye,[45] H. Yin,[45] K. Yip,[65] S. W. Youn,[45] J. M. Yu,[56] J. Zennamo,[62] T. G. Zhao,[41] B. Zhou,[56] J. Zhu,[56] M. Zielinski,[63] D. Zieminska,[49] and L. Zivkovic[14]

(D0 Collaboration)

[1]*LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*
[2]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[3]*Universidade Federal do ABC, Santo André, Brazil*
[4]*University of Science and Technology of China, Hefei, People's Republic of China*
[5]*Universidad de los Andes, Bogotá, Colombia*
[6]*Center for Particle Physics, Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic*
[7]*Czech Technical University in Prague, Prague, Czech Republic*
[8]*Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic*
[9]*Universidad San Francisco de Quito, Quito, Ecuador*
[10]*LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France*
[11]*LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France*
[12]*CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
[13]*LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France*
[14]*LPNHE, Universités Paris VI and VII, CNRS/IN2P3, Paris, France*
[15]*CEA, Irfu, SPP, Saclay, France*
[16]*IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France*
[17]*IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France*
[18]*III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany*
[19]*Physikalisches Institut, Universität Freiburg, Freiburg, Germany*
[20]*II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany*
[21]*Institut für Physik, Universität Mainz, Mainz, Germany*
[22]*Ludwig-Maximilians-Universität München, München, Germany*
[23]*Panjab University, Chandigarh, India*
[24]*Delhi University, Delhi, India*
[25]*Tata Institute of Fundamental Research, Mumbai, India*
[26]*University College Dublin, Dublin, Ireland*
[27]*Korea Detector Laboratory, Korea University, Seoul, Korea*
[28]*CINVESTAV, Mexico City, Mexico*
[29]*Nikhef, Science Park, Amsterdam, Netherlands*
[30]*Radboud University Nijmegen, Nijmegen, Netherlands*
[31]*Joint Institute for Nuclear Research, Dubna, Russia*
[32]*Institute for Theoretical and Experimental Physics, Moscow, Russia*
[33]*Moscow State University, Moscow, Russia*
[34]*Institute for High Energy Physics, Protvino, Russia*
[35]*Petersburg Nuclear Physics Institute, St. Petersburg, Russia*
[36]*Institució Catalana de Recerca i Estudis Avançats (ICREA) and Institut de Física d'Altes Energies (IFAE), Barcelona, Spain*
[37]*Uppsala University, Uppsala, Sweden*
[38]*Taras Shevchenko National University of Kyiv, Kiev, Ukraine*
[39]*Lancaster University, Lancaster LA1 4YB, United Kingdom*
[40]*Imperial College London, London SW7 2AZ, United Kingdom*
[41]*The University of Manchester, Manchester M13 9PL, United Kingdom*
[42]*University of Arizona, Tucson, Arizona 85721, USA*
[43]*University of California Riverside, Riverside, California 92521, USA*
[44]*Florida State University, Tallahassee, Florida 32306, USA*
[45]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[46]*University of Illinois at Chicago, Chicago, Illinois 60607, USA*
[47]*Northern Illinois University, DeKalb, Illinois 60115, USA*
[48]*Northwestern University, Evanston, Illinois 60208, USA*
[49]*Indiana University, Bloomington, Indiana 47405, USA*
[50]*Purdue University Calumet, Hammond, Indiana 46323, USA*
[51]*University of Notre Dame, Notre Dame, Indiana 46556, USA*
[52]*Iowa State University, Ames, Iowa 50011, USA*
[53]*University of Kansas, Lawrence, Kansas 66045, USA*
[54]*Louisiana Tech University, Ruston, Louisiana 71272, USA*
[55]*Northeastern University, Boston, Massachusetts 02115, USA*
[56]*University of Michigan, Ann Arbor, Michigan 48109, USA*
[57]*Michigan State University, East Lansing, Michigan 48824, USA*
[58]*University of Mississippi, University, Mississippi 38677, USA*
[59]*University of Nebraska, Lincoln, Nebraska 68588, USA*
[60]*Rutgers University, Piscataway, New Jersey 08855, USA*

[61]Princeton University, Princeton, New Jersey 08544, USA
[62]State University of New York, Buffalo, New York 14260, USA
[63]University of Rochester, Rochester, New York 14627, USA
[64]State University of New York, Stony Brook, New York 11794, USA
[65]Brookhaven National Laboratory, Upton, New York 11973, USA
[66]Langston University, Langston, Oklahoma 73050, USA
[67]University of Oklahoma, Norman, Oklahoma 73019, USA
[68]Oklahoma State University, Stillwater, Oklahoma 74078, USA
[69]Oregon State University, Corvallis, Oregon 97331, USA
[70]Brown University, Providence, Rhode Island 02912, USA
[71]University of Texas, Arlington, Texas 76019, USA
[72]Southern Methodist University, Dallas, Texas 75275, USA
[73]Rice University, Houston, Texas 77005, USA
[74]University of Virginia, Charlottesville, Virginia 22904, USA
[75]University of Washington, Seattle, Washington 98195, USA

(Received 31 August 2015; revised manuscript received 23 October 2015; published 2 December 2015)

We present a study of the inclusive production of the $X(4140)$ state with the decay to the $J/\psi\phi$ final state in hadronic collisions. Based on 10.4 fb^{-1} of $p\bar{p}$ collision data collected by the D0 experiment at the Fermilab Tevatron collider, we report the first evidence for the prompt production of an $X(4140)$ state and find the fraction of $X(4140)$ events originating from b hadrons to be $f_b = 0.39 \pm 0.07(\text{stat}) \pm 0.10(\text{syst})$. The ratio of the nonprompt $X(4140)$ production rate to the B_s^0 yield in the same channel is $R = 0.19 \pm 0.05(\text{stat}) \pm 0.07(\text{syst})$. The values of the mass $M = 4152.5 \pm 1.7(\text{stat})^{+6.2}_{-5.4}(\text{syst})$ MeV and width $\Gamma = 16.3 \pm 5.6(\text{stat}) \pm 11.4(\text{syst})$ MeV are consistent with previous measurements.

DOI: 10.1103/PhysRevLett.115.232001 PACS numbers: 14.40.Rt

The $X(4140)$ state [1] was first seen in 2009 as a narrow structure in the $J/\psi\phi$ system near threshold. The CDF Collaboration reported the first evidence [2] for this state [then designated $Y(4140)$] in the decay $B^+ \to X(4140)K^+ \to J/\psi\phi K^+$ (charge conjugation is implied throughout this Letter) and measured the invariant mass $M = 4143.0 \pm 2.9(\text{stat}) \pm 1.2(\text{syst})$ MeV and width $\Gamma = 11.7^{+8.3}_{-5.0}(\text{stat}) \pm 3.7(\text{syst})$ MeV. The LHCb Collaboration found no evidence for the $X(4140)$ state [3] in a 2.4 standard deviation disagreement with the CDF measurement. However, the presence of the $X(4140)$ state in B^+ decay was later confirmed by the CMS [4] and D0 [5] collaborations. The *BABAR* Collaboration searched for resonant production in the $J/\psi\phi$ mass spectrum in $B^{\pm,0}$ decays and obtained a significance below 2σ, but it noted that the hypothesis that the events are distributed uniformly on the Dalitz plot gives a poorer description of the data [6]. The quantum numbers of the $X(4140)$ state have not been measured. Since both the J/ψ and ϕ mesons have $I^G J^{PC} = 0^- 1^{--}$, the state has positive G and C parities.

A meson decaying into a charmed quark pair might be an excited charmonium state. However, the standard nonrelativistic quark model of a single $c\bar{c}$ pair does not predict a narrow hadronic state at this mass. Also, at masses above the open-charm threshold of 3740 MeV, such states are expected to decay predominantly to pairs of charmed mesons and to have a much larger width than is experimentally observed. It has been suggested that the $X(4140)$ state could be a molecular structure made of two charmed mesons, e.g., $(D_s, \bar{D}_s)$. Other possible states are hybrids composed of two quarks and a valence gluon ($q\bar{q}g$), four-quark combinations ($c\bar{c}s\bar{s}$), or states with higher Fock components [7]. For details, see the reviews in Refs. [8] and [9] and the references therein. The Belle Collaboration found no evidence for the $X(4140)$ state in the process $\gamma\gamma \to J/\psi\phi$ [10], making its interpretation as a hadronic molecule with spin-parity $J^P = 0^+$ or 2^+ unlikely.

In addition to the $X(4140)$ state, the CDF Collaboration reported [2] seeing a second enhancement in the same channel, located near 4280 MeV. A similar structure is seen by the CMS Collaboration [4] at a slightly higher mass of $4316.7 \pm 3.0(\text{stat}) \pm 7.3(\text{syst})$ MeV. Belle also reports [10] a new structure at $M = 4350.6^{+4.6}_{-5.1}(\text{stat}) \pm 0.7(\text{syst})$ MeV.

In this Letter we present results of a search for the $X(4140)$ resonance in the $J/\psi\phi$ system produced inclusively in $p\bar{p}$ collisions, either promptly, by pure QCD, or through weak decays of b hadrons. The measured production rates are normalized to the rate of the process $B_s^0 \to J/\psi\phi$ measured with the same data set. The data sample corresponds to an integrated luminosity of 10.4 fb^{-1} collected with the D0 detector in $p\bar{p}$ collisions at 1.96 TeV at the Fermilab Tevatron collider.

The D0 detector consists of a central tracking system, calorimeters, and muon detectors [11]. The central tracking system comprises a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located inside a 1.9 T superconducting solenoidal magnet. The tracking system is designed to optimize tracking and vertexing for pseudorapidities $|\eta| < 3$, where $\eta = -\ln[\tan(\theta/2)]$, and θ is the polar angle with respect to the proton beam direction. The SMT can reconstruct the $p\bar{p}$ interaction vertex (the primary vertex) for interactions with at least three tracks with a precision of 0.004 cm in the plane transverse to the beam direction. The muon detector, positioned outside the calorimeter, consists of a central muon system covering the pseudorapidity region $|\eta| < 1$ and a forward muon system covering the pseudorapidity region $1 < |\eta| < 2$. Both central and forward systems consist of a layer of drift tubes and scintillators inside 1.8 T iron toroidal magnets with two similar layers outside the toroids [12].

Events used in this analysis are collected with both single-muon and dimuon triggers. Muon triggers require a coincidence of signals in trigger elements inside and outside the toroidal magnets. Dimuon triggers in the central rapidity region require at least one muon to penetrate the toroid. In the forward region, both muons are required to penetrate the toroid.

We study a wide range of the $J/\psi\phi$ invariant mass, from threshold to 5.7 GeV, covering both the $X(4140)$ state and the decay $B_s^0 \to J/\psi\phi$. Candidate events are required to include a pair of oppositely charged muons in the invariant mass range $2.9 < M(\mu^+\mu^-) < 3.3$ GeV, consistent with J/ψ decay, accompanied by two additional particles of opposite charge, assumed to be kaons, with $p_T > 0.4$ GeV and $1.011 < M(K^+K^-) < 1.030$ GeV. In the event selection, both muons are required to be detected in the muon chambers inside the toroidal magnet, and at least one of the muons is required to be also detected outside the iron toroid [12]. Each muon candidate is required to match a track found in the central tracking system, and each of the four final-state tracks is required to have at least one SMT hit and at least one CFT hit. The J/ψ signal purity and the ϕ signal purity in the selected sample are approximately 75% and 20%, respectively.

The dimuon invariant mass is constrained to the world-average J/ψ mass [1], and the four-track system is constrained to a common vertex. To reconstruct the primary vertex, tracks are selected that do not originate from the $J/\psi\phi$ candidate, and a constraint is applied to the average beam position in the transverse plane. We require $J/\psi\phi$ candidates to have $5 < p_T < 20$ GeV and rapidity $|y| < 2$.

We define the signed decay length of the $J/\psi\phi$ system, L_{xy}, to be the vector pointing from the primary vertex to the decay vertex, projected onto the direction of the transverse momentum. The distribution of L_{xy} for the selected events is shown in Fig. 1.

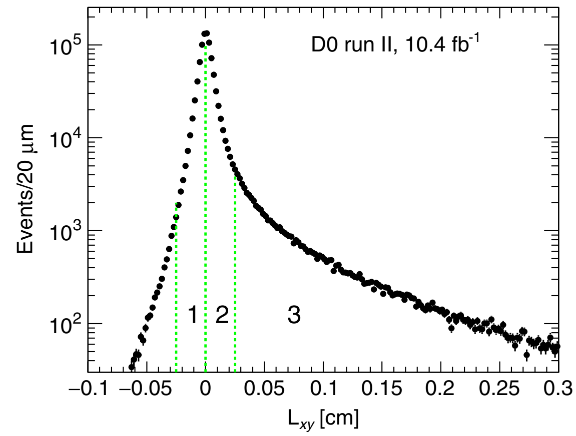

FIG. 1 (color online). Transverse decay length distribution of $J/\psi\phi$ candidates. The vertical lines define the three regions discussed in the text.

We focus on two ranges of the $J/\psi\phi$ invariant mass, $M(J/\psi\phi) < 4.36$ GeV and $4.8 < M(J/\psi\phi) < 5.7$ GeV. The low-mass range includes the $X(4140)$ state. The high-mass range includes the reference decay process, $B_s^0 \to J/\psi\phi$. Background arises primarily from nonresonant pairs in the ϕ mass window. At low L_{xy}, the background comes from J/ψ mesons directly produced in $p\bar{p}$ collisions combined with random particles from the underlying event. At higher values of L_{xy}, the background consists of J/ψ mesons paired with random products of b-hadron decays.

We divide the data in each mass range into three independent subsamples according to the value of L_{xy}: (1) $-0.025 \leq L_{xy} < 0$ cm, (2) $0 \leq L_{xy} \leq 0.025$ cm, and (3) $L_{xy} > 0.025$ cm. Region 1 includes half of the prompt events and almost no B-decay events (the fit result shown in Table I is 37 ± 26 events). Region 2 includes the remaining half of all prompt events and a fraction of nonprompt events. The rest of the nonprompt events populate region 3. Given the average resolution of 0.006 cm in L_{xy}, we assume that the fraction of prompt events in region 3 is negligible. We perform binned maximum likelihood fits to the distributions of the $J/\psi\phi$ invariant mass for events in the six subsamples

TABLE I. Summary of event yields in three L_{xy} regions and their sum for B_s^0 and $X(4140)$. For regions 1 and 2 the mass of $X(4140)$ is assumed to be 4152.5 MeV and the width is taken to be 16.3 MeV. Also shown are the deduced yields for the nonprompt and prompt production of $X(4140)$. The uncertainties are statistical.

Parent	$-0.025 < L_{xy} < 0$ cm	$0 < L_{xy} < 0.025$ cm	$L_{xy} > 0.025$ cm	Sum
B_s^0	191 ± 143	804 ± 169	3166 ± 81	4161 ± 236
$X(4140)$	511 ± 120	837 ± 135	616 ± 170	1964 ± 248
$X(4140)$ nonprompt	37 ± 26	156 ± 54	616 ± 170	809 ± 175
$X(4140)$ prompt	474 ± 123	681 ± 149	$\equiv 0$	1155 ± 193

defined above. In the fits in the B_s^0 mass region, the signal is described by a Gaussian function and the background is described by a second-order Chebychev polynomial. We also allow for the presence of the decay $B^0 \to J/\psi\phi$, where we set the mass to the world-average B^0 mass, and we find no evidence of a signal. The fit for region 3 yields 3166 ± 81 B_s^0 events.

In fitting the low-mass range, we assume a signal described by an $\mathcal{S}$-wave relativistic Breit-Wigner function convolved with a Gaussian resolution of $\sigma(M) = 4$ MeV. The background is parametrized by the function $f(m) \propto m(m^2/m_{\rm thr}^2 - 1)^{c_1} e^{-mc_2}$ where $m_{\rm thr}$ is the kinematic threshold, and c_1 and c_2 are free parameters. For events in the L_{xy} region 3, we allow the signal mass and width parameters to vary. The fit yields 616 ± 170 signal events, a mass of 4152.5 ± 1.7 MeV, and a width of 16.3 ± 5.6 MeV. The statistical significance of the signal, based on the increase of the likelihood with respect to the fit with no signal, $-2\Delta \ln \mathcal{L} = 42.5$ for 3 degrees of freedom, is 5.9 standard deviations. For the fits in L_{xy} regions 1 and 2, we set the mass and width to the region 3 values.

The mass distributions with superimposed fits for both mass regions and for all three L_{xy}'s are shown in Fig. 2. The $X(4140)$ and B_s^0 yields are presented in Table I. We also show the expected number of $X(4140)$ events originating from b-hadron decays in the two low L_{xy} regions, assuming

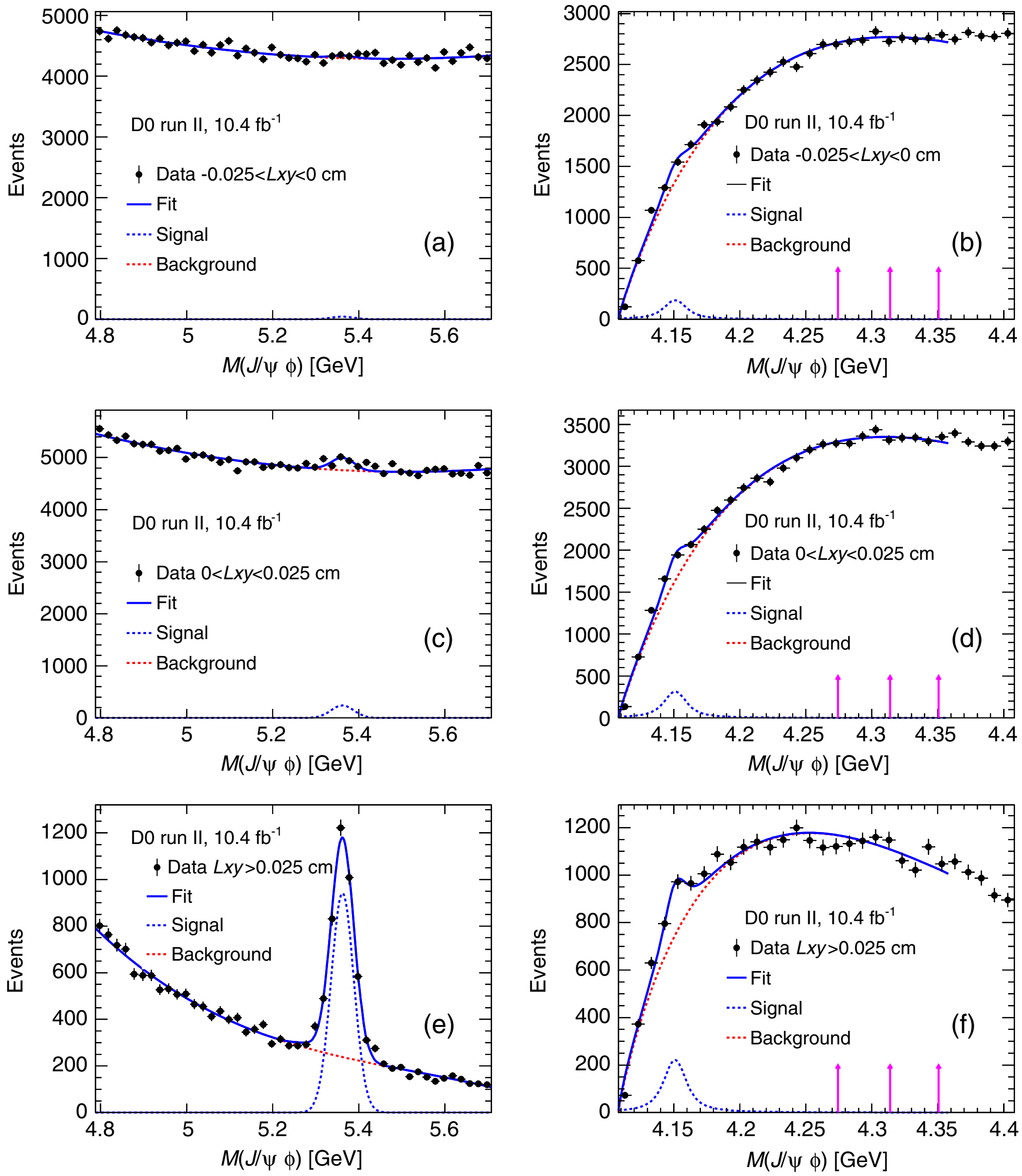

FIG. 2 (color online). Invariant mass distribution of the $J/\psi\phi$ candidates in the mass window around (left panels) B_s^0 and (right panels) $X(4140)$, for events with (a),(b) $-0.025 < L_{xy} < 0$ cm, (c), (d) $0 < L_{xy} < 0.025$ cm and (e),(f) $L_{xy} > 0.025$ cm. The arrows indicate the structures seen by CDF [2], CMS [4], and Belle [10]. The signal and background models are described in the text.

that the L_{xy} distribution of the "nonprompt" $X(4140)$ state is similar to that of B_s^0. For the regions 1 and 2, we find an excess of signal events, indicating prompt production of the $X(4140)$ state. For events in region 2, the increase in the likelihood between the fit with a free signal yield and the fit with the expected nonprompt contribution only, $-2\Delta \ln \mathcal{L} = 23.6$, corresponds to a statistical significance of 4.9σ for the net prompt signal. The statistical significance of the total signal in this L_{xy} region is 6.2σ. For region 1, the corresponding values of statistical significance are 3.9σ and 4.2σ. If the mass and width parameters are allowed to vary, the fit for region 2 gives the total yield $N = 932 \pm 216$, $M = 4146.8 \pm 2.4$ MeV, and $\Gamma = 15.8 \pm 3.8$ MeV. The data in region 1 do not yield a stable fit. Fixing the $X(4140)$ mass at 4152.5 MeV in this region, as obtained in region 3, we fit a total yield of $N = 601 \pm 205$ and Γ of 19.8 ± 5.9 MeV. A common fit to all three regions yields $N = 2312 \pm 343$, $M = 4149.6 \pm 1.2$ MeV, and $\Gamma = 17.7 \pm 2.5$ MeV.

There are several uncertainties that may affect measurements of the $X(4140)$ yield, mass, and width, the ratio R of the yields of nonprompt $X(4140)$ and B_s^0 events, and the fraction f_b of all $X(4140)$ events that originate from weak decays of b hadrons.

The mass resolution of 4.0 MeV obtained in the simulations is in agreement with an approximately linear rise with the released kinetic energy for decays with a similar topology: $\psi(2S) \to J/\psi\pi^+\pi^-$, $X(3872) \to J/\psi\pi^+\pi^-$, and the decay $B_s^0 \to J/\psi\phi$. We assign an uncertainty of ± 0.1 MeV to the resolution at the $X(4140)$ mass.

We assign an asymmetric uncertainty of 3 MeV to the $J/\psi\phi$ mass scale in the vicinity of $X(4140)$, based on the range of the mass deficit between 1 and 5 MeV compared to world-average values, found in several channels with this topology. We assign the uncertainty in the signal model, taken from the range of results obtained with relativistic and nonrelativistic Breit-Wigner shapes and a relativistic P-wave Breit-Wigner shape. Simulations show the event reconstruction and selection efficiency to be independent of the $M(J/\psi\phi)$ invariant mass, with a possible variation of $\pm 10\%$ [5]. The possible variation of the efficiency within the $X(4140)$ mass range affects the mass, width, and yield of the signal. We have assessed the effects of the fitting procedure and the background size and shape by lowering the upper edge to 4.28 GeV and raising it to 4.4 GeV, and by using 8-MeV instead of 10-MeV bins. For each of the measured quantities, we assign a symmetric uncertainty equal to one half of the difference between the extreme results.

Some of the single-muon triggers include a trigger term requiring a presence of tracks with a nonzero impact parameter. Events recorded solely by such triggers constitute approximately 5% of all events. Assuming that such triggers are 100% efficient for events originating from weak decays of b hadrons and reject all prompt events, we apply a 5% correction to the prompt yield. We assign a systematic uncertainty of $\pm 5\%$ on the fraction f_b due to this correction. Finally, our assumption of the equality of the relative rates in regions 1–3 for the nonprompt $X(4140)$ and B_s^0 events is based on an expectation of the equality of the average lifetime of b-hadron parents of the $X(4140)$ event and that of the B_s^0 event in the $J/\psi\phi$ channel. The world average of the B_s^0 lifetime is 6% lower than the lifetime averaged over all b hadron species [1]. We assign an asymmetric uncertainty in the ratio R and the fraction f_b based on this difference. The systematic uncertainties are summarized in Table II.

We test the stability of the results of the event selection by changing the ϕ mass window to $1.012 < M(K^+K^-) < 1.029$ GeV. As additional cross-checks, we perform fits to subsamples corresponding to the transverse momentum ranges $5 < p_T < 10$ GeV and $10 < p_T < 20$ GeV, to early and late data-taking periods, and to events in the central ($|y| < 1$) and forward rapidity regions. In each case, the background shape in the two subsamples is well described by the same functional form, although it requires different values of the parameters. In all cases the sums of the resulting signal yields agree with the total yield within a few events.

Our measured values of the mass and width of the $X(4140)$ state are compared with earlier measurements in Table III. The ratio of the $X(4140)$ to B_s^0 yield for events with $L_{xy} > 0.025$ cm is $R = 0.19 \pm 0.05(\text{stat}) \pm 0.07(\text{syst})$. After correcting for the efficiency of this L_{xy} cut and for the trigger bias, we find the fraction of $X(4140)$ events originating from b hadrons to be $f_b = 0.39 \pm 0.07(\text{stat}) \pm 0.10(\text{syst})$. The yield for the $X(4140)$ state at $L_{xy} > 0.025$ cm can also be compared with the yield of 52 ± 19 events of $X(4140)$ from the decay process $B^+ \to J/\psi\phi K^+$ obtained by D0 [5] for the same data set. After correcting for a factor of 2.5 ± 0.5 for the efficiency of the full reconstruction of the B^+ decay and lower kaon p_T threshold, we expect the yield from the B^+ decay to be $\approx 130 \pm 60$ events in this analysis. Our observed yield of 616 ± 170 events exceeds this estimate, suggesting that decays of b hadrons other than the decay $B^+ \to J/\psi\phi K^+$ contribute to the nonprompt production of an $X(4140)$ state.

TABLE II. Summary of systematic uncertainties.

Source	Mass (MeV)	Width (MeV)	Rate nonprompt (%)	Rate prompt (%)
Mass resolution	± 0.1	± 0.2	± 1	± 1
Mass bias	$^{+3}_{-0}$	...	...	...
Efficiency	± 4	± 5	± 4	± 4
Signal model	± 1	± 2.7	± 13	± 15
Fitting range	± 3	± 7.0	± 20	± 6
Bin size	± 1.6	± 7.0	± 25	± 10
Trigger bias	...	...	...	± 5
Mean lifetime	...	...	-1.5	$+1.5$
Total	$^{+6.2}_{-5.4}$	± 11.4	± 35	± 19

TABLE III. Summary of $X(4140)$ measurements.

Experiment	Process	Mass (MeV)	Width (MeV)
CDF [2]	$B^+ \to J/\psi\phi K^+$	$4143.0 \pm 2.9 \pm 1.2$	$11.7^{+8.3}_{-5.0} \pm 3.7$
CMS [4]	$B^+ \to J/\psi\phi K^+$	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$
D0 [5]	$B^+ \to J/\psi\phi K^+$	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+3.0}_{-8.0}$
D0 (this work)	$\bar{p}p \to J/\psi\phi$ + anything	$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$

The $J/\psi\phi$ invariant mass distributions presented in Fig. 2 show no evidence for states in the mass region $4250 < M(J/\psi\phi) < 4375$ MeV. Fits allowing for the states reported by CDF, CMS, and Belle, at $L_{xy} > -0.025$ cm, yield 351 ± 268, -283 ± 468, and -382 ± 247 events, respectively. Using the CL_s method [13], we obtain the 95% upper limits of 808, 750, and 296 events for the three states. In this upper limit calculation we did not account for systematic uncertainties, as they were checked to have a negligible impact. The corresponding 95% upper limits on the rate ratios relative to the total yield of the $X(4140)$ state are 0.48, 0.42, and 0.18, where the statistical and systematic uncertainties on the measured yield of the $X(4140)$ state are taken into account.

In summary, we have carried out the first search for inclusive production of the $X(4140)$ state in hadronic collisions. We find strong evidence for its direct, prompt production, and we observe its production in weak decays of b hadrons with a rate exceeding the expected rate for the known decay $B^+ \to J/\psi\phi K^+$. The significance of the prompt production, including systematic uncertainties, is 4.7σ. This is the first evidence for the prompt production of the $X(4140)$ state. The significance of the nonprompt production, including systematic uncertainties, is 5.6σ. The nonprompt production rate of the $X(4140)$ state relative to the B_s^0 value observed in the same final state is $R = 0.19 \pm 0.05(\text{stat}) \pm 0.07(\text{syst})$. Assuming a relativistic Breit-Wigner line shape, we measure the mass and width of the $X(4140)$ state to be $M = 4152.5 \pm 1.7(\text{stat})^{+6.2}_{-5.4}(\text{syst})$ MeV and width $\Gamma = 16.3 \pm 5.6(\text{stat}) \pm 11.4(\text{syst})$ MeV, consistent with previous measurements [2,4,5].

We thank the staffs at Fermilab and collaborating institutions, and we acknowledge support from the Department of Energy and the National Science Foundation (U.S.); the Alternative Energies and Atomic Energy Commission and the National Center for Scientific Research/National Institute of Nuclear and Particle Physics (France); the Ministry of Education and Science of the Russian Federation, the National Research Center "Kurchatov Institute" of the Russian Federation, and the Russian Foundation for Basic Research (Russia); the National Council for the Development of Science and Technology and the Carlos Chagas Filho Foundation for the Support of Research in the State of Rio de Janeiro (Brazil); the Department of Atomic Energy and the Department of Science and Technology (India); the Administrative Department of Science, Technology and Innovation (Colombia); the National Council of Science and Technology (Mexico); the National Research Foundation of Korea (Korea); the Foundation for Fundamental Research on Matter (Netherlands); the Science and Technology Facilities Council and The Royal Society (United Kingdom); the Ministry of Education, Youth and Sports (Czech Republic); Bundesministerium für Bildung und Forschung (the Federal Ministry of Education and Research) and Deutsche Forschungsgemeinschaft (the German Research Foundation) (Germany); Science Foundation Ireland (Ireland); the Swedish Research Council (Sweden); China Academy of Sciences and the National Natural Science Foundation of China (China); and the Ministry of Education and Science of Ukraine (Ukraine).

[a] Visitor from Augustana College, Sioux Falls, SD, USA.
[b] Visitor from The University of Liverpool, Liverpool, United Kingdom.
[c] Visitor from DESY, Hamburg, Germany.
[d] Visitor from CONACyT, Mexico City, Mexico.
[e] Visitor from SLAC, Menlo Park, CA, USA.
[f] Visitor from University College London, London, United Kingdom.
[g] Visitor from Centro de Investigacion en Computacion—IPN, Mexico City, Mexico.
[h] Visitor from Universidade Estadual Paulista, São Paulo, Brazil.
[i] Visitor from Karlsruher Institut für Technologie (KIT)—Steinbuch Centre for Computing (SCC), D-76128 Karlsruhe, Germany.
[j] Visitor from Office of Science, U.S. Department of Energy, Washington, D.C. 20585, USA.
[k] Visitor from American Association for the Advancement of Science, Washington, D.C. 20005, USA.
[l] Visitor from Kiev Institute for Nuclear Research, Kiev, Ukraine.
[m] Visitor from University of Maryland, College Park, Maryland 20742, USA.
[n] Visitor from European Orgnaization for Nuclear Research (CERN), Geneva, Switzerland.

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