Fermilab

FERMILAB-PUB-09-064-E

Evidence for a Narrow Near-Threshold Structure in the $J/\psi\phi$ Mass Spectrum in $B^+ \to J/\psi\phi K^+$ Decays

T. Aaltonen,[24] J. Adelman,[14] T. Akimoto,[56] B. Álvarez González[t],[12] S. Amerio[z],[44] D. Amidei,[35] A. Anastassov,[39] A. Annovi,[20] J. Antos,[15] G. Apollinari,[18] A. Apresyan,[49] T. Arisawa,[58] A. Artikov,[16] W. Ashmanskas,[18] A. Attal,[4] A. Aurisano,[54] F. Azfar,[43] W. Badgett,[18] A. Barbaro-Galtieri,[29] V.E. Barnes,[49] B.A. Barnett,[26] P. Barria[bb],[47] V. Bartsch,[31] G. Bauer,[33] P.-H. Beauchemin,[34] F. Bedeschi,[47] D. Beecher,[31] S. Behari,[26] G. Bellettini[aa],[47] J. Bellinger,[60] D. Benjamin,[17] A. Beretvas,[18] J. Beringer,[29] A. Bhatti,[51] M. Binkley,[18] D. Bisello[z],[44] I. Bizjak[ff],[31] R.E. Blair,[2] C. Blocker,[7] B. Blumenfeld,[26] A. Bocci,[17] A. Bodek,[50] V. Boisvert,[50] G. Bolla,[49] D. Bortoletto,[49] J. Boudreau,[48] A. Boveia,[11] B. Brau[a],[11] A. Bridgeman,[25] L. Brigliadori[y],[6] C. Bromberg,[36] E. Brubaker,[14] J. Budagov,[16] H.S. Budd,[50] S. Budd,[25] S. Burke,[18] K. Burkett,[18] G. Busetto[z],[44] P. Bussey,[22] A. Buzatu,[34] K. L. Byrum,[2] S. Cabrera[v],[17] C. Calancha,[32] M. Campanelli,[36] M. Campbell,[35] F. Canelli[14],[18] A. Canepa,[46] B. Carls,[25] D. Carlsmith,[60] R. Carosi,[47] S. Carrillo[n],[19] S. Carron,[34] B. Casal,[12] M. Casarsa,[18] A. Castro[y],[6] P. Catastini[bb],[47] D. Cauz[ee],[55] V. Cavaliere[bb],[47] M. Cavalli-Sforza,[4] A. Cerri,[29] L. Cerrito[p],[31] S.H. Chang,[28] Y.C. Chen,[1] M. Chertok,[8] G. Chiarelli,[47] G. Chlachidze,[18] F. Chlebana,[18] K. Cho,[28] D. Chokheli,[16] J.P. Chou,[23] G. Choudalakis,[33] S.H. Chuang,[53] K. Chung,[13] W.H. Chung,[60] Y.S. Chung,[50] T. Chwalek,[27] C.I. Ciobanu,[45] M.A. Ciocci[bb],[47] A. Clark,[21] D. Clark,[7] G. Compostella,[44] M.E. Convery,[18] J. Conway,[8] M. Cordelli,[20] G. Cortiana[z],[44] C.A. Cox,[8] D.J. Cox,[8] F. Crescioli[aa],[47] C. Cuenca Almenar[v],[8] J. Cuevas[t],[12] R. Culbertson,[18] J.C. Cully,[35] D. Dagenhart,[18] M. Datta,[18] T. Davies,[22] P. de Barbaro,[50] S. De Cecco,[52] A. Deisher,[29] G. De Lorenzo,[4] M. Dell'Orso[aa],[47] C. Deluca,[4] L. Demortier,[51] J. Deng,[17] M. Deninno,[6] P.F. Derwent,[18] A. Di Canto[aa],[47] G.P. di Giovanni,[45] C. Dionisi[dd],[52] B. Di Ruzza[ee],[55] J.R. Dittmann,[5] M. D'Onofrio,[4] S. Donati[aa],[47] P. Dong,[9] J. Donini,[44] T. Dorigo,[44] S. Dube,[53] J. Efron,[40] A. Elagin,[54] R. Erbacher,[8] D. Errede,[25] S. Errede,[25] R. Eusebi,[18] H.C. Fang,[29] S. Farrington,[43] W.T. Fedorko,[14] R.G. Feild,[61] M. Feindt,[27] J.P. Fernandez,[32] C. Ferrazza[cc],[47] R. Field,[19] G. Flanagan,[49] R. Forrest,[8] M.J. Frank,[5] M. Franklin,[23] J.C. Freeman,[18] I. Furic,[19] M. Gallinaro,[52] J. Galyardt,[13] F. Garberson,[11] J.E. Garcia,[21] A.F. Garfinkel,[49] P. Garosi[bb],[47] K. Genser,[18] H. Gerberich,[25] D. Gerdes,[35] A. Gessler,[27] S. Giagu[dd],[52] V. Giakoumopoulou,[3] P. Giannetti,[47] K. Gibson,[48] J.L. Gimmell,[50] C.M. Ginsburg,[18] N. Giokaris,[3] M. Giordani[ee],[55] P. Giromini,[20] M. Giunta,[47] G. Giurgiu,[26] V. Glagolev,[16] D. Glenzinski,[18] M. Gold,[38] N. Goldschmidt,[19] A. Golossanov,[18] G. Gomez,[12] G. Gomez-Ceballos,[33] M. Goncharov,[33] O. González,[32] I. Gorelov,[38] A.T. Goshaw,[17] K. Goulianos,[51] A. Gresele[z],[44] S. Grinstein,[23] C. Grosso-Pilcher,[14] R.C. Group,[18] U. Grundler,[25] J. Guimaraes da Costa,[23] Z. Gunay-Unalan,[36] C. Haber,[29] K. Hahn,[33] S.R. Hahn,[18] E. Halkiadakis,[53] B.-Y. Han,[50] J.Y. Han,[50] F. Happacher,[20] K. Hara,[56] D. Hare,[53] M. Hare,[57] S. Harper,[43] R.F. Harr,[59] R.M. Harris,[18] M. Hartz,[48] K. Hatakeyama,[51] C. Hays,[43] M. Heck,[27] A. Heijboer,[46] J. Heinrich,[46] C. Henderson,[33] M. Herndon,[60] J. Heuser,[27] S. Hewamanage,[5] D. Hidas,[17] C.S. Hill[c],[11] D. Hirschbuehl,[27] A. Hocker,[18] S. Hou,[1] M. Houlden,[30] S.-C. Hsu,[29] B.T. Huffman,[43] R.E. Hughes,[40] U. Husemann,[61] M. Hussein,[36] J. Huston,[36] J. Incandela,[11] G. Introzzi,[47] M. Iori[dd],[52] A. Ivanov,[8] E. James,[18] D. Jang,[13] B. Jayatilaka,[17] E.J. Jeon,[28] M.K. Jha,[6] S. Jindariani,[18] W. Johnson,[8] M. Jones,[49] K.K. Joo,[28] S.Y. Jun,[13] J.E. Jung,[28] T.R. Junk,[18] T. Kamon,[54] D. Kar,[19] P.E. Karchin,[59] Y. Kato[l],[42] R. Kephart,[18] W. Ketchum,[14] J. Keung,[46] V. Khotilovich,[54] B. Kilminster,[18] D.H. Kim,[28] H.S. Kim,[28] H.W. Kim,[28] J.E. Kim,[28] M.J. Kim,[20] S.B. Kim,[28] S.H. Kim,[56] Y.K. Kim,[14] N. Kimura,[56] L. Kirsch,[7] S. Klimenko,[19] B. Knuteson,[33] B.R. Ko,[17] K. Kondo,[58] D.J. Kong,[28] J. Konigsberg,[19] A. Korytov,[19] A.V. Kotwal,[17] M. Kreps,[27] J. Kroll,[46] D. Krop,[14] N. Krumnack,[5] M. Kruse,[17] V. Krutelyov,[11] T. Kubo,[56] T. Kuhr,[27] N.P. Kulkarni,[59] M. Kurata,[56] S. Kwang,[14] A.T. Laasanen,[49] S. Lami,[47] S. Lammel,[18] M. Lancaster,[31] R.L. Lander,[8] K. Lannon[s],[40] A. Lath,[53] G. Latino[bb],[47] I. Lazzizzera[z],[44] T. LeCompte,[2] E. Lee,[54] H.S. Lee,[14] S.W. Lee[u],[54] S. Leone,[47] J.D. Lewis,[18] C.-S. Lin,[29] J. Linacre,[43] M. Lindgren,[18] E. Lipeles,[46] A. Lister,[8] D.O. Litvintsev,[18] C. Liu,[48] T. Liu,[18] N.S. Lockyer,[46] A. Loginov,[61] M. Loreti[z],[44] L. Lovas,[15] D. Lucchesi[z],[44] C. Luci[dd],[52] J. Lueck,[27] P. Lujan,[29] P. Lukens,[18] G. Lungu,[51] L. Lyons,[43] J. Lys,[29] R. Lysak,[15] D. MacQueen,[34] R. Madrak,[18] K. Maeshima,[18] K. Makhoul,[33] T. Maki,[24] P. Maksimovic,[26] S. Malde,[43] S. Malik,[31] G. Manca[e],[30] A. Manousakis-Katsikakis,[3] F. Margaroli,[49] C. Marino,[27] C.P. Marino,[25] A. Martin,[61] V. Martin[k],[22] M. Martínez,[4] R. Martínez-Ballarín,[32] T. Maruyama,[56] P. Mastrandrea,[52] T. Masubuchi,[56] M. Mathis,[26] M.E. Mattson,[59] P. Mazzanti,[6] K.S. McFarland,[50]

P. McIntyre,[54] R. McNulty[j],[30] A. Mehta,[30] P. Mehtala,[24] A. Menzione,[47] P. Merkel,[49] C. Mesropian,[51] T. Miao,[18]
N. Miladinovic,[7] R. Miller,[36] C. Mills,[23] M. Milnik,[27] A. Mitra,[1] G. Mitselmakher,[19] H. Miyake,[56] N. Moggi,[6]
C.S. Moon,[28] R. Moore,[18] M.J. Morello,[47] J. Morlock,[27] P. Movilla Fernandez,[18] J. Mülmenstädt,[29] A. Mukherjee,[18]
Th. Muller,[27] R. Mumford,[26] P. Murat,[18] M. Mussini[y],[6] J. Nachtman[o],[18] Y. Nagai,[56] A. Nagano,[56] J. Naganoma,[56]
K. Nakamura,[56] I. Nakano,[41] A. Napier,[57] V. Necula,[17] J. Nett,[60] C. Neu[w],[46] M.S. Neubauer,[25] S. Neubauer,[27]
J. Nielsen[g],[29] L. Nodulman,[2] M. Norman,[10] O. Norniella,[25] E. Nurse,[31] L. Oakes,[43] S.H. Oh,[17] Y.D. Oh,[28]
I. Oksuzian,[19] T. Okusawa,[42] R. Orava,[24] K. Osterberg,[24] S. Pagan Griso[z],[44] E. Palencia,[18] V. Papadimitriou,[18]
A. Papaikonomou,[27] A.A. Paramonov,[14] B. Parks,[40] S. Pashapour,[34] J. Patrick,[18] G. Pauletta[ee],[55] M. Paulini,[13]
C. Paus,[33] T. Peiffer,[27] D.E. Pellett,[8] A. Penzo,[55] T.J. Phillips,[17] G. Piacentino,[47] E. Pianori,[46] L. Pinera,[19]
K. Pitts,[25] C. Plager,[9] L. Pondrom,[60] O. Poukhov*,[16] N. Pounder,[43] F. Prakoshyn,[16] A. Pronko,[18] J. Proudfoot,[2]
F. Ptohos[i],[18] E. Pueschel,[13] G. Punzi[aa],[47] J. Pursley,[60] J. Rademacker[c],[43] A. Rahaman,[48] V. Ramakrishnan,[60]
N. Ranjan,[49] I. Redondo,[32] P. Renton,[43] M. Renz,[27] M. Rescigno,[52] S. Richter,[27] F. Rimondi[y],[6] L. Ristori,[47]
A. Robson,[22] T. Rodrigo,[12] T. Rodriguez,[46] E. Rogers,[25] S. Rolli,[57] R. Roser,[18] M. Rossi,[55] R. Rossin,[11]
P. Roy,[34] A. Ruiz,[12] J. Russ,[13] V. Rusu,[18] B. Rutherford,[18] H. Saarikko,[24] A. Safonov,[54] W.K. Sakumoto,[50]
O. Saltó,[4] L. Santi[ee],[55] S. Sarkar[dd],[52] L. Sartori,[47] K. Sato,[18] A. Savoy-Navarro,[45] P. Schlabach,[18] A. Schmidt,[27]
E.E. Schmidt,[18] M.A. Schmidt,[14] M.P. Schmidt*,[61] M. Schmitt,[39] T. Schwarz,[8] L. Scodellaro,[12] A. Scribano[bb],[47]
F. Scuri,[47] A. Sedov,[49] S. Seidel,[38] Y. Seiya,[42] A. Semenov,[16] L. Sexton-Kennedy,[18] F. Sforza[aa],[47] A. Sfyrla,[25]
S.Z. Shalhout,[59] T. Shears,[30] P.F. Shepard,[48] M. Shimojima[r],[56] S. Shiraishi,[14] M. Shochet,[14] Y. Shon,[60]
I. Shreyber,[37] P. Sinervo,[34] A. Sisakyan,[16] A.J. Slaughter,[18] J. Slaunwhite,[40] K. Sliwa,[57] J.R. Smith,[8] F.D. Snider,[18]
R. Snihur,[34] A. Soha,[8] S. Somalwar,[53] V. Sorin,[36] T. Spreitzer,[34] P. Squillacioti[bb],[47] M. Stanitzki,[61] R. St. Denis,[22]
B. Stelzer,[34] O. Stelzer-Chilton,[34] D. Stentz,[39] J. Strologas,[38] G.L. Strycker,[35] J.S. Suh,[28] A. Sukhanov,[19]
I. Suslov,[16] T. Suzuki,[56] A. Taffard[f],[25] R. Takashima,[41] Y. Takeuchi,[56] R. Tanaka,[41] M. Tecchio,[35] P.K. Teng,[1]
K. Terashi,[51] J. Thom[h],[18] A.S. Thompson,[22] G.A. Thompson,[25] E. Thomson,[46] P. Tipton,[61] P. Ttito-Guzmán,[32]
S. Tkaczyk,[18] D. Toback,[54] S. Tokar,[15] K. Tollefson,[36] T. Tomura,[56] D. Tonelli,[18] S. Torre,[20] D. Torretta,[18]
P. Totaro[ee],[55] S. Tourneur,[45] M. Trovato[cc],[47] S.-Y. Tsai,[1] Y. Tu,[46] N. Turini[bb],[47] F. Ukegawa,[56] S. Vallecorsa,[21]
N. van Remortel[b],[24] A. Varganov,[35] E. Vataga[cc],[47] F. Vázquez[n],[19] G. Velev,[18] C. Vellidis,[3] M. Vidal,[32] R. Vidal,[18]
I. Vila,[12] R. Vilar,[12] T. Vine,[31] M. Vogel,[38] I. Volobouev[u],[29] G. Volpi[aa],[47] P. Wagner,[46] R.G. Wagner,[2]
R.L. Wagner,[18] W. Wagner[x],[27] J. Wagner-Kuhr,[27] T. Wakisaka,[42] R. Wallny,[9] S.M. Wang,[1] A. Warburton,[34]
D. Waters,[31] M. Weinberger,[54] J. Weinelt,[27] W.C. Wester III,[18] B. Whitehouse,[57] D. Whiteson[f],[46] A.B. Wicklund,[2]
E. Wicklund,[18] S. Wilbur,[14] G. Williams,[34] H.H. Williams,[46] P. Wilson,[18] B.L. Winer,[40] P. Wittich[h],[18]
S. Wolbers,[18] C. Wolfe,[14] T. Wright,[35] X. Wu,[21] F. Würthwein,[10] S. Xie,[33] A. Yagil,[10] K. Yamamoto,[42]
J. Yamaoka,[17] U.K. Yang[q],[14] Y.C. Yang,[28] W.M. Yao,[29] G.P. Yeh,[18] K. Yi[o],[18] J. Yoh,[18] K. Yorita,[58] T. Yoshida[m],[42]
G.B. Yu,[50] I. Yu,[28] S.S. Yu,[18] J.C. Yun,[18] L. Zanello[dd],[52] A. Zanetti,[55] X. Zhang,[25] Y. Zheng[d],[9] and S. Zucchelli[y],[6]
(CDF Collaboration†)

[1]*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*
[2]*Argonne National Laboratory, Argonne, Illinois 60439*
[3]*University of Athens, 157 71 Athens, Greece*
[4]*Institut de Fisica d'Altes Energies, Universitat Autonoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain*
[5]*Baylor University, Waco, Texas 76798*
[6]*Istituto Nazionale di Fisica Nucleare Bologna,* [y]*University of Bologna, I-40127 Bologna, Italy*
[7]*Brandeis University, Waltham, Massachusetts 02254*
[8]*University of California, Davis, Davis, California 95616*
[9]*University of California, Los Angeles, Los Angeles, California 90024*
[10]*University of California, San Diego, La Jolla, California 92093*
[11]*University of California, Santa Barbara, Santa Barbara, California 93106*
[12]*Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*
[13]*Carnegie Mellon University, Pittsburgh, PA 15213*
[14]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637*
[15]*Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia*
[16]*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
[17]*Duke University, Durham, North Carolina 27708*
[18]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[19]*University of Florida, Gainesville, Florida 32611*
[20]*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[21]*University of Geneva, CH-1211 Geneva 4, Switzerland*

[22]*Glasgow University, Glasgow G12 8QQ, United Kingdom*
[23]*Harvard University, Cambridge, Massachusetts 02138*
[24]*Division of High Energy Physics, Department of Physics,*
University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland
[25]*University of Illinois, Urbana, Illinois 61801*
[26]*The Johns Hopkins University, Baltimore, Maryland 21218*
[27]*Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany*
[28]*Center for High Energy Physics: Kyungpook National University,*
Daegu 702-701, Korea; Seoul National University, Seoul 151-742,
Korea; Sungkyunkwan University, Suwon 440-746,
Korea; Korea Institute of Science and Technology Information, Daejeon,
305-806, Korea; Chonnam National University, Gwangju, 500-757, Korea
[29]*Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[30]*University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[31]*University College London, London WC1E 6BT, United Kingdom*
[32]*Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain*
[33]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
[34]*Institute of Particle Physics: McGill University, Montréal, Québec,*
Canada H3A 2T8; Simon Fraser University, Burnaby, British Columbia,
Canada V5A 1S6; University of Toronto, Toronto, Ontario,
Canada M5S 1A7; and TRIUMF, Vancouver, British Columbia, Canada V6T 2A3
[35]*University of Michigan, Ann Arbor, Michigan 48109*
[36]*Michigan State University, East Lansing, Michigan 48824*
[37]*Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia*
[38]*University of New Mexico, Albuquerque, New Mexico 87131*
[39]*Northwestern University, Evanston, Illinois 60208*
[40]*The Ohio State University, Columbus, Ohio 43210*
[41]*Okayama University, Okayama 700-8530, Japan*
[42]*Osaka City University, Osaka 588, Japan*
[43]*University of Oxford, Oxford OX1 3RH, United Kingdom*
[44]*Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento,* [z]*University of Padova, I-35131 Padova, Italy*
[45]*LPNHE, Universite Pierre et Marie Curie/IN2P3-CNRS, UMR7585, Paris, F-75252 France*
[46]*University of Pennsylvania, Philadelphia, Pennsylvania 19104*
[47]*Istituto Nazionale di Fisica Nucleare Pisa,* [aa]*University of Pisa,*
[bb]*University of Siena and* [cc]*Scuola Normale Superiore, I-56127 Pisa, Italy*
[48]*University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[49]*Purdue University, West Lafayette, Indiana 47907*
[50]*University of Rochester, Rochester, New York 14627*
[51]*The Rockefeller University, New York, New York 10021*
[52]*Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1,*
[dd]*Sapienza Università di Roma, I-00185 Roma, Italy*
[53]*Rutgers University, Piscataway, New Jersey 08855*
[54]*Texas A&M University, College Station, Texas 77843*
[55]*Istituto Nazionale di Fisica Nucleare Trieste/Udine,*
I-34100 Trieste, [ee]*University of Trieste/Udine, I-33100 Udine, Italy*
[56]*University of Tsukuba, Tsukuba, Ibaraki 305, Japan*
[57]*Tufts University, Medford, Massachusetts 02155*
[58]*Waseda University, Tokyo 169, Japan*
[59]*Wayne State University, Detroit, Michigan 48201*
[60]*University of Wisconsin, Madison, Wisconsin 53706*
[61]*Yale University, New Haven, Connecticut 06520*

(Dated: March 5, 2009)

Evidence is reported for a narrow structure near the $J/\psi\phi$ threshold in exclusive $B^+ \rightarrow J/\psi\phi K^+$ decays produced in $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV. A signal of 14 ± 5 events, with statistical significance in excess of 3.8 standard deviations, is observed in a data sample corresponding to an integrated luminosity of 2.7 fb^{-1}, collected by the CDF II detector. The mass and natural width of the structure are measured to be $4143.0 \pm 2.9(\text{stat}) \pm 1.2(\text{syst})$ MeV/c^2 and $11.7^{+8.3}_{-5.0}(\text{stat}) \pm 3.7(\text{syst})$ MeV/c^2.

PACS numbers: 14.40.Gx, 13.25.Gv, 12.39.Mk

---

[*] Deceased

[†] With visitors from [a]University of Massachusetts Amherst,

Heavy quarkonium spectroscopy provides insight into strong interactions that are not precisely predictable by QCD theory. The recently discovered states that have charmonium-like decay modes [1–4] but are difficult to place in the overall charmonium system have introduced new challenges. The possible interpretations beyond quark-antiquark states ($q\bar{q}$) such as hybrid ($q\bar{q}g$) and four-quark states ($q\bar{q}q\bar{q}$) have revitalized interest in exotic mesons in the charm sector [5–8]. An important tool in unraveling the nature of the states in the charmonium-mass region is the exploration of states in diverse channels. The $J/\psi\phi$ final state, with positive C-parity, and two $\mathrm{J^{PC}} = 1^{--}$ vector mesons (VV), is a good channel for an exotic meson search. First, the discovery of the $X(3872)$ (proposed as a four-quark state ($c\bar{c}q\bar{q}$) [7, 8]) and $Y(3930)$ [2], both decaying into VV [9], suggests searching for other possible VV states [10]. In addition, the observation of $Y(3930)$ near the $J/\psi\omega$ threshold motivates searches for similar phenomena near the $J/\psi\phi$ threshold. Second, the observation of the $Y(4260)$, a potential hybrid candidate [6], leads to an expectation of a triplet of positive C-parity states to lie nearby in mass [11, 12], which would be accessible in the $J/\psi\phi$ channel. Finally, other possibilities such as glueballs [12] and nuclear-bound quarkonium [13] also motivate a search in this channel. The $J/\psi\phi$ channel is accessible in the decay mode $B^+ \rightarrow J/\psi\phi K^+$, which has been observed [14]. However, to date no results have been reported for substructure in the $J/\psi\phi$ channel.

In this Letter, we report an investigation of the $J/\psi\phi$ system produced in exclusive $B^+ \rightarrow J/\psi\phi K^+$ decays with $J/\psi \rightarrow \mu^+\mu^-$ and $\phi \rightarrow K^+K^-$. The search in exclusive B^+ decays is more sensitive than an inclusive search since the additional B^+ mass constraint on the $J/\psi\phi K^+$ system helps to reduce background. This analysis is based on a data sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV with an integrated luminosity of 2.7 fb^{-1} collected by the CDF II detector at the Tevatron. Charge conjugate modes are included implicitly in this Letter.

The CDF II detector has been described in detail elsewhere [15]. The important components for this analysis include the tracking, muon, and time-of-flight (TOF) systems. The tracking system is composed of a silicon-strip vertex detector (SVX) surrounded by an open-cell drift chamber system called the central outer tracker (COT) located inside a solenoid with a 1.4 T magnetic field. The COT and SVX are used for the measurement of charged-particle trajectories and vertex positions. In addition, the COT provides ionization energy loss information, dE/dx, used for particle identification (PID), while the TOF system provides complementary PID information. The muon system is located radially outside the electromagnetic and hadronic calorimeters and consists of two sets of drift chambers and scintillation counters. The central part covers the pseudorapidity region $|\eta| \leq 0.6$ and detects muons with $p_T \geq 1.4$ GeV/c [16], and the second part covers the region $0.6 < |\eta| < 1.0$ and detects muons with $p_T \geq 2.0$ GeV/c.

In this analysis, $J/\psi \rightarrow \mu^+\mu^-$ events are recorded using a dedicated three-level dimuon trigger. The first trigger level requires two muon candidates with matching tracks in the COT and muon systems. The second level applies additional kinematic requirements to the muon pair candidate. The third level requires the invariant mass of the $\mu^+\mu^-$ pair to be within the range of 2.7 to 4.0 GeV/c^2.

Offline reconstruction of $B^+ \rightarrow J/\psi\phi K^+$ candidates uses only tracks that pass standard CDF quality requirements and which have been corrected for ionization energy loss for the muon or kaon hypothesis, as appropriate. The $B^+ \rightarrow J/\psi\phi K^+$ candidates are reconstructed by combining a $J/\psi \rightarrow \mu^+\mu^-$ candidate, a $\phi \rightarrow K^+K^-$ candidate, and an additional charged track. All five tracks must form a good quality 3D vertex, using *a priori* requirements typical for B hadron reconstruction at CDF [18]. Preliminary event selection requires a J/ψ candidate reconstructed using opposite-sign muon candidates and a ϕ candidate formed from opposite-sign tracks to which we assign the kaon mass. The reconstructed mass of each vector meson candidate must lie within a suitable range from the nominal values (50 MeV/c^2 for the J/ψ and 7 MeV/c^2 for the ϕ). In the final B^+ reconstruction the J/ψ is mass constrained, and the B^+ candidates must have $p_T > 4$ GeV/c.

To suppress combinatorial background, we use dE/dx and TOF information to identify all three kaons in the final state. The information is summarized in a log-likelihood ratio (LLR), which reflects how well a candidate track can be positively identified as a kaon relative

---

Amherst, Massachusetts 01003, [b]Universiteit Antwerpen, B-2610 Antwerp, Belgium, [c]University of Bristol, Bristol BS8 1TL, United Kingdom, [d]Chinese Academy of Sciences, Beijing 100864, China, [e]Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, 09042 Monserrato (Cagliari), Italy, [f]University of California Irvine, Irvine, CA 92697, [g]University of California Santa Cruz, Santa Cruz, CA 95064, [h]Cornell University, Ithaca, NY 14853, [i]University of Cyprus, Nicosia CY-1678, Cyprus, [j]University College Dublin, Dublin 4, Ireland, [k]University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom, [l]University of Fukui, Fukui City, Fukui Prefecture, Japan 910-0017 [m]Kinki University, Higashi-Osaka City, Japan 577-8502 [n]Universidad Iberoamericana, Mexico D.F., Mexico, [o]University of Iowa, Iowa City, IA 52242, [p]Queen Mary, University of London, London, E1 4NS, England, [q]University of Manchester, Manchester M13 9PL, England, [r]Nagasaki Institute of Applied Science, Nagasaki, Japan, [s]University of Notre Dame, Notre Dame, IN 46556, [t]University de Oviedo, E-33007 Oviedo, Spain, [u]Texas Tech University, Lubbock, TX 79609, [v]IFIC(CSIC-Universitat de Valencia), 46071 Valencia, Spain, [w]University of Virginia, Charlottesville, VA 22904, [x]Bergische Universität Wuppertal, 42097 Wuppertal, Germany, [ff]On leave from J. Stefan Institute, Ljubljana, Slovenia,

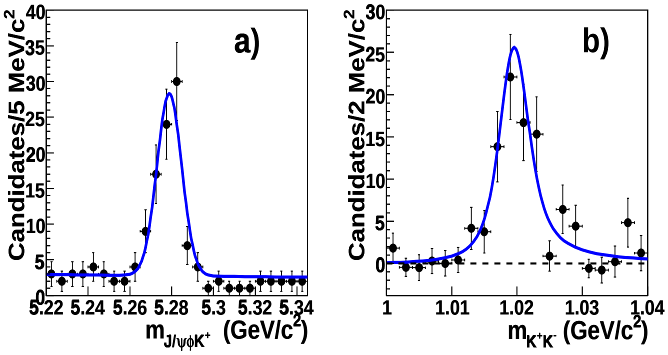

FIG. 1: (a) The mass distribution of $J/\psi\phi K^+$ after minimum $L_{xy}(B^+)$, minimum LLR, and the J/ψ and ϕ mass window requirements; the solid line is a fit to the data with a Gaussian signal function and flat background function. (b) The B^+ sideband-subtracted mass distribution of K^+K^- for candidates with the $J/\psi K^+K^-K^+$ mass within 3σ of the B^+ mass, without the ϕ mass window requirement. The solid curve is a P-wave relativistic Breit-Wigner fit to the data; for clarity, the dashed line shows the zero-candidate level.

to other hadrons [19]. In addition, we require a minimum $L_{xy}(B^+)$ for the $B^+ \to J/\psi\phi K^+$ candidate, where $L_{xy}(B^+)$ is the projection onto $\vec{p}_T(B^+)$ of the vector connecting the primary vertex to the B^+ decay vertex. The primary vertex is determined for each event using prompt tracks.

The $L_{xy}(B^+)$ and LLR requirements for $B^+ \to J/\psi\phi K^+$ are then chosen to maximize $S/\sqrt{S+B}$, where S is the number of $B^+ \to J/\psi\phi K^+$ signal events and B is the number of background events in the $J/\psi\phi K^+$ mass range of 5.0 to 5.6 GeV/c^2 in the data. The values of S and B are determined from an unbinned log-likelihood fit to the mass spectrum of $J/\psi\phi K^+$, for a given set of values of $L_{xy}(B^+)$ and LLR. A Gaussian function is used to represent the $B^+ \to J/\psi\phi K^+$ signal, where the mean value of the Gaussian is fixed to the B^+ world-average mass value [17]. The B^+ mass resolution is fixed to the value 5.9 MeV/c^2 obtained from Monte Carlo (MC) simulation [20]. A linear function is used to model the background in the fit. The requirements obtained by maximizing $S/\sqrt{S+B}$ are $L_{xy}(B^+) > 500$ μm and $LLR > 0.2$. In order to study the efficiency of the $L_{xy}(B^+)$ and LLR selections, we also reconstruct $B^+ \to J/\psi K^+$ and $B_s^0 \to J/\psi\phi$ as control channels. We select approximately 50 000 $B^+ \to J/\psi K^+$ and 3000 $B_s^0 \to J/\psi\phi$ events by applying similar requirements as for the $J/\psi\phi K^+$ channel but without the $L_{xy}(B^+)$ and LLR requirements. The efficiency for PID with the $LLR > 0.2$ requirement is approximately 80% per kaon and is reasonably flat as a function of kaon p_T; the efficiency for $L_{xy}(B^+) > 500$ μm is approximately 60%, based on the $B^+ \to J/\psi K^+$ control sample.

The invariant mass of $J/\psi\phi K^+$ after the $L_{xy}(B^+)$ and LLR requirements and J/ψ and ϕ mass window requirements is shown in Fig. 1(a). A fit with a Gaussian signal function and a flat background function to the mass spectrum of $J/\psi\phi K^+$ returns a B^+ signal of 75 ± 10(stat) events. This is the largest $B^+ \to J/\psi\phi K^+$ sample obtained to date [14]. The $L_{xy}(B^+)$ and LLR requirements reduce the background by a factor of approximately 20 000 while keeping a signal efficiency of approximately 20%, measured using the control channels. We select B^+ signal candidates with a mass within 3σ (17.7 MeV/c^2) of the nominal B^+ mass; the purity of the B^+ signal in that mass window is approximately 80%.

The combinatorial background under the B^+ peak includes B hadron decays such as $B_s^0 \to \psi(2S)\phi \to J/\psi\pi^+\pi^-\phi$, in which the pions are misidentified as kaons. However, background events with misidentified kaons cannot yield a Gaussian peak at the B^+ mass consistent with the 5.9 MeV/c^2mass resolution. The kinematics are such that for the hypothesis $B^+ \to J/\psi K^+K^-K^+$, only events with real kaons can produce the observed Gaussian signal. Thus, with the B^+ mass window selection the sample consists of real $B^+ \to J/\psi K^+K^-K^+$ decays over a small combinatorial background.

Figure 1(b) shows the invariant mass distribution of K^+K^- pairs from $\mu^+\mu^-K^+K^-K^+$ candidates within $\pm3\sigma$ of the nominal B^+ mass. The spectrum shown in this figure has had the sidebands subtracted, but the ϕ mass window selection has not been applied. By fitting the K^+K^- mass spectrum to a P-wave relativistic Breit-Wigner (BW) function [21] convoluted with a Gaussian resolution function with the rms fixed to 1.3 MeV/c^2 obtained from simulation, we obtain a mass of 1019.6 ± 0.3 MeV/c^2 and a width of 3.84 ± 0.65 MeV/c^2, consistent with the world-average values for the ϕ meson [17]. The fit χ^2 probability with only the $\phi \to K^+K^-$ contribution is 28%. This indicates that after the ±7 MeV/c^2 selection on the ϕ mass window, the $B^+ \to J/\psi K^+K^-K^+$ final state is well described as $J/\psi\phi K^+$, with negligible contributions from $J/\psi f_0(980)K^+$ or $J/\psi K^+K^-K^+$ phase space.

We examine the effects of detector acceptance and selection requirements using $B^+ \to J/\psi\phi K^+$ MC events simulated by phase space distributions. The MC events are smoothly distributed in the Dalitz plot and in the $J/\psi\phi$ mass spectrum. Figure 2(a) shows the Dalitz plot of $m^2(\phi K^+)$ versus $m^2(J/\psi\phi)$, and Fig. 2(b) shows the mass difference, $\Delta M = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$, for events in the B^+ mass window in our data sample. We examine the enhancement in the ΔM spectrum just above $J/\psi\phi$ threshold, using 73 events with $\Delta M < 1.56$ GeV/c^2. We exclude the high mass part of the spectrum to avoid combinatorial backgrounds that would be expected from misidentified $B_s^0 \to \psi(2S)\phi \to (J/\psi\pi^+\pi^-)\phi$ decays.

We model the enhancement by an S-wave relativistic BW function [22] convoluted with a Gaussian resolution

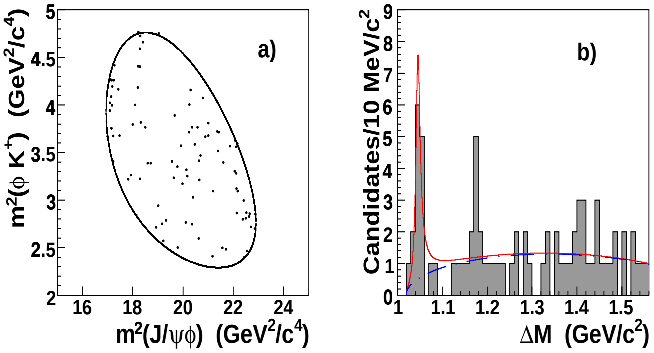

FIG. 2: (a) The Dalitz plot of $m^2(\phi K^+)$ versus $m^2(J/\psi\phi)$ in the B^+ mass window. The boundary shows the kinematic allowed region. (b) The mass difference, ΔM, between $\mu^+\mu^-K^+K^-$ and $\mu^+\mu^-$, in the B^+ mass window. The dash-dotted curve is the background contribution and the red solid curve is the total unbinned fit.

function with the rms fixed to 1.7 MeV/c^2 obtained from MC, and use three–body phase space [17] to describe the background shape. An unbinned likelihood fit to the ΔM distribution, as shown in Fig. 2(b), returns a yield of 14 ± 5 events, a ΔM of 1046.3 ± 2.9 MeV/c^2, and a width of $11.7^{+8.3}_{-5.0}$ MeV/c^2. We also fit the ΔM distribution to a single Gaussian with rms given by the mass resolution (1.7 MeV/c^2), plus phase space background, to test the hypothesis that the structure has zero width. The statistical significance for a non-zero width determined by the log-likelihood ratio between these two fits is 3.4σ, indicating a strong decay for this structure.

We use the log-likelihood ratio of $-2\ln(\mathcal{L}_0/\mathcal{L}_{max})$ to determine the significance of the structure at the $J/\psi\phi$ threshold, where $\mathcal{L}_0$ and $\mathcal{L}_{max}$ are the likelihood values for the null hypothesis fit and signal hypothesis fit. The $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{max})}$ value is 5.3 for a pure three–body phase space background shape assumption. We use MC simulations to estimate the probability that background fluctuations alone would give rise to signals as significant as that seen in the data. Since we do not have *a priori* expectations for the mass and width of the structure, we must consider a wide range of possible masses and widths. We generate ΔM spectra based on the background distribution alone, and search for the most significant fluctuation in each spectrum in the mass range of 1.02 to 1.56 GeV/c^2, with widths in the range of 1.7 (resolution) to 120 MeV/c^2 (ten times of the observed width). From these spectra we obtain the distribution for the quantity $-2\ln(\mathcal{L}_0/\mathcal{L}_{max})$ in pure background samples, and compare this with the signal in the data. We performed a total of 3.1 million simulations and found 29 trials with a $-2\ln(\mathcal{L}_0/\mathcal{L}_{max})$ value greater than or equal to the value obtained in the data. The resulting p-value is 9.3×10^{-6}, corresponding to a significance of 4.3σ. Thus, the significance is decreased from a simple estimate of 5.3σ to 4.3σ by taking into account the absence of a prior prediction for the mass and width [24].

In the analysis described above, we assumed that the backgrounds to the BW signal from both $B^+ \to J/\psi\phi K^+$ decays and combinatorial events in the B^+ mass window are described by three-body phase space. As a cross-check, we investigate the dependence of the BW signal on the modeling of the combinatorial events. For those events with $\Delta M < 1.56$ GeV/c^2, we estimate 15 ± 1 combinatorial background and 58 ± 8 B^+ events in the B^+ mass window. We model the B^+ events using three-body phase space as above, but use a flat spectrum to describe the combinatorial events; this increases the average background level at small ΔM. We fit the data again to the modified background distribution and the S-wave BW signal. This fit gives values for ΔM, width, and yield of 1046.6 ± 2.4 GeV/c^2, 10.8 ± 5.7 MeV/c^2, and 13 ± 5 events. The $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{max})}$ value with this modeling of background is 4.8. We performed a total of 1.1 million simulations and found 99 trials with a $-2\ln(\mathcal{L}_0/\mathcal{L}_{max})$ value greater than or equal to the value we obtained in the data. The p-value determined by this MC simulation is 9.0×10^{-5}, about 3.8σ significance.

We use the results obtained from the fit with a three–body phase space background shape as our central values. The mass of this structure is 4143.0 ± 2.9 MeV/c^2 after including the world-average J/ψ mass. To study the systematic uncertainties of the mass and width, we repeat the fit to the ΔM distribution while varying the background shapes as described above, and separately switching to a non–relativistic BW for signal. The largest deviation from the nominal values are 1.2 MeV/c^2 for ΔM and 3.7 MeV/c^2 for the width. Therefore we assign a systematic uncertainty of 1.2 MeV/c^2 to the mass and 3.7 MeV/c^2 to the width.

There is a small cluster of events approximately one pion mass higher than the first structure, located around 1.18 GeV/c^2 in Fig. 2(b). However, the statistical significance of this cluster is less than 3σ. To investigate possible reflections, we examine the Dalitz plot and projections into ϕK^+ and $J/\psi K^+$ spectrum. We find no evidence for any other structure in the ϕK^+ and $J/\psi K^+$ spectrum; the only structure [*i.e.* $K_2(1770)$] that has been claimed in the ϕK^+ spectrum by previous experiments is too broad to alter our analysis [23].

In summary, the world's largest sample of $B^+ \to J/\psi\phi K^+$ decays (75 events) enables us to search for structure in the $J/\psi\phi$ mass spectrum, and we find evidence for a narrow structure near the $J/\psi\phi$ threshold with a significance in excess of 3.8σ. Assuming an S-wave relativistic BW, the mass and width of this structure, including systematic uncertainties, are measured to be $4143.0 \pm 2.9(\text{stat}) \pm 1.2(\text{syst})$ MeV/c^2 and $11.7^{+8.3}_{-5.0}(\text{stat}) \pm 3.7(\text{syst})$ MeV/c^2, respectively. It is well above the threshold for open charm decays, so a $c\bar{c}$ charmonium meson with this mass would be expected to decay into an open charm pair dominantly and to have a tiny branching fraction into $J/\psi\phi$ [5]. Thus, this structure does not fit conventional expectations for a charmonium state. We note that this structure decays to $J/\psi\phi$ just above the $J\psi\phi$ threshold, similar to the $Y(3930)$ [2], which decays to $J/\psi\omega$ near the $J/\psi\omega$ threshold. We therefore term it $Y(4140)$.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. We wish to thank E. Eichten for helpful discussions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; and the Academy of Finland.

[1] S.-K. Choi *et al.* (Belle Collaboration), Phys. Rev. Lett. **91**, 262001 (2003); D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **93**, 072001 (2004); V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **93**, 162002 (2004); B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **71**, 071103(R) (2005).

[2] S.-K. Choi *et al.* (Belle Collaboration), Phys. Rev. Lett. **94**, 182002 (2005); B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **101**, 082001 (2008).

[3] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **95**, 142001 (2005).

[4] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **98**, 212001 (2007); X. L. Wang *et al.* (Belle Collaboration), Phys. Rev. Lett. **99**, 142002 (2007); S.-K. Choi *et al.* (Belle Collaboration), Phys. Rev. Lett. **100**, 142001 (2008); R. Mizuk *et al.* (Belle Collaboration), Phys. Rev. D **78**, 072004 (2008); P. Pakhlov *et al.* (Belle Collaboration), Phys. Rev. Lett. **100**, 202001 (2008).

[5] E. Eichten, K. Lane, and C. Quigg, Phys. Rev. D **69**, 094019 (2004); E. Eichten, S. Godfrey, H. Mahlke, and J. Rosner, Rev. Mod. Phys. **80**, 1161 (2008).

[6] S. L. Zhu, Phys. Lett. B **625**, 212 (2005); F. Close and P. Page, Phys. Lett. B **628**, 215 (2005).

[7] E. S. Swanson, Phys. Lett. B **588**, 189 (2004).

[8] L. Maiani, F. Piccinini, A. D. Polosa, and V. Riquer, Phys. Rev. D **72**, 031502(R) (2005).

[9] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. Lett. **96**, 102002 (2006); B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **74**, 071101 (2006).

[10] N. V. Drenska, R. Faccini, and A. D. Polosa, arXiv:hep-ph/0902.2803v1.

[11] Yu. S. Kalashnikova and A. V. Nefediev, Phys. Rev. D **77**, 054025 (2008); E. J. Eichten, Private communication; P. Hasenfratz, R. R. Horgan, J. Kuti, and J. -M. Richard, Phys. Lett. B **95**, 299 (1980); S. Perantonis and C. Michael, Nucl. Phys. **B347**, 854 (1990); C. Bernard *et al.*, Phys. Rev. D **56**, 7039 (1997); X. Liao and T. Manke, arXiv:hep-lat/0210030.

[12] F. E. Close *et al.*, Phys. Rev. D **57**, 5653 (1998); F. E. Close and S. Godfrey, Phys. Lett. B **574** 210 (2003).

[13] S. J. Brodsky, I. Schmidt, and G. Téramond, Phys. Rev. Lett. **64**, 1011 (1990).

[14] A. Anastassov *et al.* (CLEO Collaboration), Phys. Rev. Lett. **84**, 1393 (2000); B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **91**, 071801 (2003).

[15] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 032001 (2005); A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. Lett. **97**, 242003 (2006).

[16] We use a coordinate system in which the proton beam direction is defined as the z axis. The angle θ is the usual polar angle. We define the pseudorapidity as $\eta \equiv -\ln(\tan\frac{\theta}{2})$. The transverse momentum is defined as $p_T = p\sin\theta$, where p is the momentum measured in the tracking system.

[17] C. Amsler *et al.* (Particle Data Group), Phys. Lett. B **667**, 1 (2008).

[18] T. Aaltonen, *et al.* (CDF Collaboration), Phys. Rev. Lett. **100**, 161802 (2008); D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **94**, 101803 (2005).

[19] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. Lett. **97**, 242003 (2006).

[20] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. Lett. **96**, 082002 (2006); T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **100** 182002 (2008).

[21] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **78**, 071103 (2008).

[22] $\frac{dN}{dm} \propto \frac{m\Gamma(m)}{(m^2-m_0^2)^2+m_0^2\Gamma^2(m)}$, where $\Gamma(m) = \Gamma_0\frac{q}{q_0}\frac{m_0}{m}$, and the 0 subscript indicates the value at the peak mass.

[23] T. Armstrong *et al.*, Nucl. Phys. **B221**, 1 (1983).

[24] Monte Carlo studies indicate that fits with small numbers of signal events tend to return statistical uncertainties that underestimate the true uncertainties, an effect that asymptotically decreases as the sample size becomes larger. We have not corrected for such an effect. Such an underestimate of the fitted parameter uncertainties does not influence the evaluation of the signal significance, which depends only on the background fluctuation probability.