

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)



CERN-PH-EP-2014-061

LHCb-PAPER-2014-014

7 April 2014

Observation of the resonant character of the $Z(4430)^-$ state

The LHCb collaboration[†]

Abstract

Resonant structures in $B^0 \rightarrow \psi' \pi^- K^+$ decays are analyzed by performing a four-dimensional fit of the decay amplitude, using pp collision data corresponding to 3 fb^{-1} collected with the LHCb detector. The data cannot be described with $K^+ \pi^-$ resonances alone, which is confirmed with a model-independent approach. A highly significant $Z(4430)^- \rightarrow \psi' \pi^-$ component is required, thus confirming the existence of this state. The observed evolution of the $Z(4430)^-$ amplitude with the $\psi' \pi^-$ mass establishes the resonant nature of this particle. The mass and width measurements are substantially improved. The spin-parity is determined unambiguously to be 1^+ .

Submitted to Physical Review Letters

© CERN on behalf of the LHCb collaboration, license CC-BY-3.0.

[†]Authors are listed on the following pages.

LHCb collaboration

R. Aaij⁴¹, B. Adeva³⁷, M. Adinolfi⁴⁶, A. Affolder⁵², Z. Ajaltouni⁵, J. Albrecht⁹, F. Alessio³⁸, M. Alexander⁵¹, S. Ali⁴¹, G. Alkhazov³⁰, P. Alvarez Cartelle³⁷, A.A. Alves Jr^{25,38}, S. Amato², S. Amerio²², Y. Amhis⁷, L. An³, L. Anderlini^{17,g}, J. Anderson⁴⁰, R. Andreassen⁵⁷, M. Andreotti^{16,f}, J.E. Andrews⁵⁸, R.B. Appleby⁵⁴, O. Aquines Gutierrez¹⁰, F. Archilli³⁸, A. Artamonov³⁵, M. Artuso⁵⁹, E. Aslanides⁶, G. Auriemma^{25,n}, M. Baalouch⁵, S. Bachmann¹¹, J.J. Back⁴⁸, A. Badalov³⁶, V. Balagura³¹, W. Baldini¹⁶, R.J. Barlow⁵⁴, C. Barschel³⁸, S. Barsuk⁷, W. Barter⁴⁷, V. Batozskaya²⁸, Th. Bauer⁴¹, A. Bay³⁹, L. Beaucourt⁴, J. Beddow⁵¹, F. Bedeschi²³, I. Bediaga¹, S. Belogurov³¹, K. Belous³⁵, I. Belyaev³¹, E. Ben-Haim⁸, G. Bencivenni¹⁸, S. Benson³⁸, J. Benton⁴⁶, A. Berezhnoy³², R. Bernet⁴⁰, M.-O. Bettler⁴⁷, M. van Beuzekom⁴¹, A. Bien¹¹, S. Bifani⁴⁵, T. Bird⁵⁴, A. Bizzeti^{17,i}, P.M. Bjørnstad⁵⁴, T. Blake⁴⁸, F. Blanc³⁹, J. Blouw¹⁰, S. Blusk⁵⁹, V. Bocci²⁵, A. Bondar³⁴, N. Bondar^{30,38}, W. Bonivento^{15,38}, S. Borghi⁵⁴, A. Borgia⁵⁹, M. Borsato⁷, T.J.V. Bowcock⁵², E. Bowen⁴⁰, C. Bozzi¹⁶, T. Brambach⁹, J. van den Brand⁴², J. Bressieux³⁹, D. Brett⁵⁴, M. Britsch¹⁰, T. Britton⁵⁹, J. Brodzicka⁵⁴, N.H. Brook⁴⁶, H. Brown⁵², A. Bursche⁴⁰, G. Busetto^{22,q}, J. Buytaert³⁸, S. Cadeddu¹⁵, R. Calabrese^{16,f}, M. Calvi^{20,k}, M. Calvo Gomez^{36,o}, A. Camboni³⁶, P. Campana^{18,38}, D. Campora Perez³⁸, A. Carbone^{14,d}, G. Carboni^{24,l}, R. Cardinale^{19,38,j}, A. Cardini¹⁵, H. Carranza-Mejia⁵⁰, L. Carson⁵⁰, K. Carvalho Akiba², G. Casse⁵², L. Cassina²⁰, L. Castillo Garcia³⁸, M. Cattaneo³⁸, Ch. Cauet⁹, R. Cenci⁵⁸, M. Charles⁸, Ph. Charpentier³⁸, S. Chen⁵⁴, S.-F. Cheung⁵⁵, N. Chiapolini⁴⁰, M. Chrzaszcz^{40,26}, K. Ciba³⁸, X. Cid Vidal³⁸, G. Ciezarek⁵³, P.E.L. Clarke⁵⁰, M. Clemencic³⁸, H.V. Cliff⁴⁷, J. Closier³⁸, V. Coco³⁸, J. Cogan⁶, E. Cogneras⁵, P. Collins³⁸, A. Comerma-Montells¹¹, A. Contu^{15,38}, A. Cook⁴⁶, M. Coombes⁴⁶, S. Coquereau⁸, G. Corti³⁸, M. Corvo^{16,f}, I. Counts⁵⁶, B. Couturier³⁸, G.A. Cowan⁵⁰, D.C. Craik⁴⁸, M. Cruz Torres⁶⁰, S. Cunliffe⁵³, R. Currie⁵⁰, C. D'Ambrosio³⁸, J. Dalsen⁴⁶, P. David⁸, P.N.Y. David⁴¹, A. Davis⁵⁷, K. De Bruyn⁴¹, S. De Capua⁵⁴, M. De Cian¹¹, J.M. De Miranda¹, L. De Paula², W. De Silva⁵⁷, P. De Simone¹⁸, D. Decamp⁴, M. Deckenhoff⁹, L. Del Buono⁸, N. Déleage⁴, D. Derkach⁵⁵, O. Deschamps⁵, F. Dettori⁴², A. Di Canto³⁸, H. Dijkstra³⁸, S. Donleavy⁵², F. Dordei¹¹, M. Dorigo³⁹, A. Dosil Suárez³⁷, D. Dossett⁴⁸, A. Dovbnya⁴³, G. Dujany⁵⁴, F. Dupertuis³⁹, P. Durante³⁸, R. Dzhelyadin³⁵, A. Dziurda²⁶, A. Dzyuba³⁰, S. Easo^{49,38}, U. Egede⁵³, V. Egorychev³¹, S. Eidelman³⁴, S. Eisenhardt⁵⁰, U. Eitschberger⁹, R. Ekelhof⁹, L. Eklund^{51,38}, I. El Rifai⁵, Ch. Elsasser⁴⁰, S. Ely⁵⁹, S. Esen¹¹, T. Evans⁵⁵, A. Falabella^{16,f}, C. Färber¹¹, C. Farinelli⁴¹, N. Farley⁴⁵, S. Farry⁵², D. Ferguson⁵⁰, V. Fernandez Albor³⁷, F. Ferreira Rodrigues¹, M. Ferro-Luzzi³⁸, S. Filippov³³, M. Fiore^{16,f}, M. Fiorini^{16,f}, M. Firlej²⁷, C. Fitzpatrick³⁸, T. Fiutowski²⁷, M. Fontana¹⁰, F. Fontanelli^{19,j}, R. Forty³⁸, O. Francisco², M. Frank³⁸, C. Frei³⁸, M. Frosini^{17,38,g}, J. Fu^{21,38}, E. Furfaro^{24,l}, A. Gallas Torreira³⁷, D. Galli^{14,d}, S. Gallorini²², S. Gambetta^{19,j}, M. Gandelman², P. Gandini⁵⁹, Y. Gao³, J. Garofoli⁵⁹, J. Garra Tico⁴⁷, L. Garrido³⁶, C. Gaspar³⁸, R. Gauld⁵⁵, L. Gavardi⁹, E. Gersabeck¹¹, M. Gersabeck⁵⁴, T. Gershon⁴⁸, Ph. Ghez⁴, A. Gianelle²², S. Giani³⁹, V. Gibson⁴⁷, L. Giubega²⁹, V.V. Gligorov³⁸, C. Göbel⁶⁰, D. Golubkov³¹, A. Golutvin^{53,31,38}, A. Gomes^{1,a}, H. Gordon³⁸, C. Gotti²⁰, M. Grabalosa Gándara⁵, R. Graciani Diaz³⁶, L.A. Granado Cardoso³⁸, E. Graugés³⁶, G. Graziani¹⁷, A. Grecu²⁹, E. Greening⁵⁵, S. Gregson⁴⁷, P. Griffith⁴⁵, L. Grillo¹¹, O. Grünberg⁶², B. Gui⁵⁹, E. Gushchin³³, Yu. Guz^{35,38}, T. Gys³⁸, C. Hadjivasiliou⁵⁹, G. Haefeli³⁹, C. Haen³⁸, S.C. Haines⁴⁷, S. Hall⁵³, B. Hamilton⁵⁸, T. Hampson⁴⁶, X. Han¹¹, S. Hansmann-Menzemer¹¹, N. Harnew⁵⁵, S.T. Harnew⁴⁶, J. Harrison⁵⁴, T. Hartmann⁶², J. He³⁸, T. Head³⁸, V. Heijne⁴¹, K. Hennessy⁵², P. Henrard⁵, L. Henry⁸,

J.A. Hernando Morata³⁷, E. van Herwijnen³⁸, M. Heß⁶², A. Hicheur¹, D. Hill⁵⁵, M. Hoballah⁵,
 C. Hombach⁵⁴, W. Hulsbergen⁴¹, P. Hunt⁵⁵, N. Hussain⁵⁵, D. Hutchcroft⁵², D. Hynds⁵¹,
 M. Idzik²⁷, P. Ilten⁵⁶, R. Jacobsson³⁸, A. Jaeger¹¹, J. Jalocha⁵⁵, E. Jans⁴¹, P. Jatón³⁹,
 A. Jawahery⁵⁸, M. Jezabek²⁶, F. Jing³, M. John⁵⁵, D. Johnson⁵⁵, C.R. Jones⁴⁷, C. Joram³⁸,
 B. Jost³⁸, N. Jurik⁵⁹, M. Kaballo⁹, S. Kandybei⁴³, W. Kanso⁶, M. Karacson³⁸, T.M. Karbach³⁸,
 M. Kelsey⁵⁹, I.R. Kenyon⁴⁵, T. Ketel⁴², B. Khanji²⁰, C. Khurewathanakul³⁹, S. Klaver⁵⁴,
 O. Kochebina⁷, M. Kolpin¹¹, I. Komarov³⁹, R.F. Koopman⁴², P. Koppenburg^{41,38}, M. Korolev³²,
 A. Kozlinskiy⁴¹, L. Kravchuk³³, K. Kreplin¹¹, M. Kreps⁴⁸, G. Krocker¹¹, P. Krokovny³⁴,
 F. Kruse⁹, M. Kucharczyk^{20,26,38,k}, V. Kudryavtsev³⁴, K. Kurek²⁸, T. Kvaratskheliya³¹,
 V.N. La Thi³⁹, D. Lacarrere³⁸, G. Lafferty⁵⁴, A. Lai¹⁵, D. Lambert⁵⁰, R.W. Lambert⁴²,
 E. Lanciotti³⁸, G. Lanfranchi¹⁸, C. Langenbruch³⁸, B. Langhans³⁸, T. Latham⁴⁸, C. Lazzeroni⁴⁵,
 R. Le Gac⁶, J. van Leerdam⁴¹, J.-P. Lees⁴, R. Lefèvre⁵, A. Leflat³², J. Lefrançois⁷, S. Leo²³,
 O. Leroy⁶, T. Lesiak²⁶, B. Leverington¹¹, Y. Li³, M. Liles⁵², R. Lindner³⁸, C. Linn³⁸,
 F. Lionetto⁴⁰, B. Liu¹⁵, G. Liu³⁸, S. Lohn³⁸, I. Longstaff⁵¹, J.H. Lopes², N. Lopez-March³⁹,
 P. Lowdon⁴⁰, H. Lu³, D. Lucchesi^{22,q}, H. Luo⁵⁰, A. Lupato²², E. Luppi^{16,f}, O. Lupton⁵⁵,
 F. Machefert⁷, I.V. Machikhiliyan³¹, F. Maciuc²⁹, O. Maev³⁰, S. Malde⁵⁵, G. Manca^{15,e},
 G. Mancinelli⁶, M. Manzali^{16,f}, J. Maratas⁵, J.F. Marchand⁴, U. Marconi¹⁴, C. Marin Benito³⁶,
 P. Marino^{23,s}, R. Märki³⁹, J. Marks¹¹, G. Martellotti²⁵, A. Martens⁸, A. Martín Sánchez⁷,
 M. Martinelli⁴¹, D. Martinez Santos⁴², F. Martinez Vidal⁶⁴, D. Martins Tostes², A. Massafferri¹,
 R. Matev³⁸, Z. Mathe³⁸, C. Matteuzzi²⁰, A. Mazurov^{16,f}, M. McCann⁵³, J. McCarthy⁴⁵,
 A. McNab⁵⁴, R. McNulty¹², B. McSkelly⁵², B. Meadows^{57,55}, F. Meier⁹, M. Meissner¹¹,
 M. Merk⁴¹, D.A. Milanes⁸, M.-N. Minard⁴, N. Moggi¹⁴, J. Molina Rodriguez⁶⁰, S. Monteil⁵,
 D. Moran⁵⁴, M. Morandin²², P. Morawski²⁶, A. Mordà⁶, M.J. Morello^{23,s}, J. Moron²⁷,
 A.-B. Morris⁵⁰, R. Mountain⁵⁹, F. Muheim⁵⁰, K. Müller⁴⁰, R. Muresan²⁹, M. Mussini¹⁴,
 B. Muster³⁹, P. Naik⁴⁶, T. Nakada³⁹, R. Nandakumar⁴⁹, I. Nasteva², M. Needham⁵⁰, N. Neri²¹,
 S. Neubert³⁸, N. Neufeld³⁸, M. Neuner¹¹, A.D. Nguyen³⁹, T.D. Nguyen³⁹, C. Nguyen-Mau^{39,p},
 M. Nicol⁷, V. Niess⁵, R. Niet⁹, N. Nikitin³², T. Nikodem¹¹, A. Novoselov³⁵,
 A. Oblakowska-Mucha²⁷, V. Obraztsov³⁵, S. Oggero⁴¹, S. Ogilvy⁵¹, O. Okhrimenko⁴⁴,
 R. Oldeman^{15,e}, G. Onderwater⁶⁵, M. Orlandea²⁹, J.M. Otalora Goicochea², P. Owen⁵³,
 A. Oyanguren⁶⁴, B.K. Pal⁵⁹, A. Palano^{13,c}, F. Palombo^{21,t}, M. Palutan¹⁸, J. Panman³⁸,
 A. Papanestis^{49,38}, M. Pappagallo⁵¹, C. Parkes⁵⁴, C.J. Parkinson⁹, G. Passaleva¹⁷, G.D. Patel⁵²,
 M. Patel⁵³, C. Patrignani^{19,j}, A. Pazos Alvarez³⁷, A. Pearce⁵⁴, A. Pellegrino⁴¹,
 M. Pepe Altarelli³⁸, S. Perazzini^{14,d}, E. Perez Trigo³⁷, P. Perret⁵, M. Perrin-Terrin⁶,
 L. Pescatore⁴⁵, E. Pesen⁶⁶, K. Petridis⁵³, A. Petrolini^{19,j}, E. Picatoste Olloqui³⁶, B. Pietrzyk⁴,
 T. Pilar⁴⁸, D. Pinci²⁵, A. Pistone¹⁹, S. Playfer⁵⁰, M. Plo Casasus³⁷, F. Polci⁸, A. Poluektov^{48,34},
 E. Polcarpo², A. Popov³⁵, D. Popov¹⁰, B. Popovici²⁹, C. Potterat², A. Powell⁵⁵,
 J. Prisciandaro³⁹, A. Pritchard⁵², C. Prouve⁴⁶, V. Pugatch⁴⁴, A. Puig Navarro³⁹, G. Punzi^{23,r},
 W. Qian⁴, B. Rachwal²⁶, J.H. Rademacker⁴⁶, B. Rakotomiaramanana³⁹, M. Rama¹⁸,
 M.S. Rangel², I. Raniuk⁴³, N. Rauschmayr³⁸, G. Raven⁴², S. Reichert⁵⁴, M.M. Reid⁴⁸,
 A.C. dos Reis¹, S. Ricciardi⁴⁹, A. Richards⁵³, M. Rihl³⁸, K. Rinnert⁵², V. Rives Molina³⁶,
 D.A. Roa Romero⁵, P. Robbe⁷, A.B. Rodrigues¹, E. Rodrigues⁵⁴, P. Rodriguez Perez⁵⁴,
 S. Roiser³⁸, V. Romanovsky³⁵, A. Romero Vidal³⁷, M. Rotondo²², J. Rouvinet³⁹, T. Ruf³⁸,
 F. Ruffini²³, H. Ruiz³⁶, P. Ruiz Valls⁶⁴, G. Sabatino^{25,l}, J.J. Saborido Silva³⁷, N. Sagidova³⁰,
 P. Sail⁵¹, B. Saitta^{15,e}, V. Salustino Guimaraes², C. Sanchez Mayordomo⁶⁴,
 B. Sanmartin Sedes³⁷, R. Santacesaria²⁵, C. Santamarina Rios³⁷, E. Santovetti^{24,l}, M. Sapunov⁶,
 A. Sarti^{18,m}, C. Satriano^{25,n}, A. Satta²⁴, M. Savrie^{16,f}, D. Savrina^{31,32}, M. Schiller⁴²,

H. Schindler³⁸, M. Schlupp⁹, M. Schmelling¹⁰, B. Schmidt³⁸, O. Schneider³⁹, A. Schopper³⁸, M.-H. Schune⁷, R. Schwemmer³⁸, B. Sciascia¹⁸, A. Sciubba²⁵, M. Seco³⁷, A. Semennikov³¹, K. Senderowska²⁷, I. Sepp⁵³, N. Serra⁴⁰, J. Serrano⁶, L. Sestini²², P. Seyfert¹¹, M. Shapkin³⁵, I. Shapoval^{16,43,f}, Y. Shcheglov³⁰, T. Shears⁵², L. Shekhtman³⁴, V. Shevchenko⁶³, A. Shires⁹, R. Silva Coutinho⁴⁸, G. Simi²², M. Sirendi⁴⁷, N. Skidmore⁴⁶, T. Skwarnicki⁵⁹, N.A. Smith⁵², E. Smith^{55,49}, E. Smith⁵³, J. Smith⁴⁷, M. Smith⁵⁴, H. Snoek⁴¹, M.D. Sokoloff⁵⁷, F.J.P. Soler⁵¹, F. Soomro³⁹, D. Souza⁴⁶, B. Souza De Paula², B. Spaan⁹, A. Sparkes⁵⁰, F. Spinella²³, P. Spradlin⁵¹, F. Stagni³⁸, S. Stahl¹¹, O. Steinkamp⁴⁰, O. Stenyakin³⁵, S. Stevenson⁵⁵, S. Stoica²⁹, S. Stone⁵⁹, B. Storaci⁴⁰, S. Stracka^{23,38}, M. Straticiu²⁹, U. Straumann⁴⁰, R. Stroili²², V.K. Subbiah³⁸, L. Sun⁵⁷, W. Sutcliffe⁵³, K. Swientek²⁷, S. Swientek⁹, V. Syropoulos⁴², M. Szczekowski²⁸, P. Szczypka^{39,38}, D. Szilard², T. Szumlak²⁷, S. T’Jampens⁴, M. Teklishyn⁷, G. Tellarini^{16,f}, F. Teubert³⁸, C. Thomas⁵⁵, E. Thomas³⁸, J. van Tilburg⁴¹, V. Tisserand⁴, M. Tobin³⁹, S. Tolck⁴², L. Tomassetti^{16,f}, D. Tonelli³⁸, S. Topp-Joergensen⁵⁵, N. Torr⁵⁵, E. Tournefier⁴, S. Tourneur³⁹, M.T. Tran³⁹, M. Tresch⁴⁰, A. Tsaregorodtsev⁶, P. Tsopelas⁴¹, N. Tuning⁴¹, M. Ubeda Garcia³⁸, A. Ukleja²⁸, A. Ustyuzhanin⁶³, U. Uwer¹¹, V. Vagnoni¹⁴, G. Valenti¹⁴, A. Vallier⁷, R. Vazquez Gomez¹⁸, P. Vazquez Regueiro³⁷, C. Vázquez Sierra³⁷, S. Vecchi¹⁶, J.J. Velthuis⁴⁶, M. Veltri^{17,h}, G. Veneziano³⁹, M. Vesterinen¹¹, B. Viaud⁷, D. Vieira², M. Vieites Diaz³⁷, X. Vilasis-Cardona^{36,o}, A. Vollhardt⁴⁰, D. Volyansky¹⁰, D. Voong⁴⁶, A. Vorobyev³⁰, V. Vorobyev³⁴, C. Vob⁶², H. Voss¹⁰, J.A. de Vries⁴¹, R. Waldi⁶², C. Wallace⁴⁸, R. Wallace¹², J. Walsh²³, S. Wandernoth¹¹, J. Wang⁵⁹, D.R. Ward⁴⁷, N.K. Watson⁴⁵, D. Websdale⁵³, M. Whitehead⁴⁸, J. Wicht³⁸, D. Wiedner¹¹, G. Wilkinson⁵⁵, M.P. Williams⁴⁵, M. Williams⁵⁶, F.F. Wilson⁴⁹, J. Wimberley⁵⁸, J. Wishahi⁹, W. Wislicki²⁸, M. Witek²⁶, G. Wormser⁷, S.A. Wotton⁴⁷, S. Wright⁴⁷, S. Wu³, K. Wyllie³⁸, Y. Xie⁶¹, Z. Xing⁵⁹, Z. Xu³⁹, Z. Yang³, X. Yuan³, O. Yushchenko³⁵, M. Zangoli¹⁴, M. Zavertyaev^{10,b}, F. Zhang³, L. Zhang⁵⁹, W.C. Zhang¹², Y. Zhang³, A. Zhelezov¹¹, A. Zhokhov³¹, L. Zhong³, A. Zvyagin³⁸.

¹ Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil

² Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil

³ Center for High Energy Physics, Tsinghua University, Beijing, China

⁴ LAPP, Université de Savoie, CNRS/IN2P3, Annecy-Le-Vieux, France

⁵ Clermont Université, Université Blaise Pascal, CNRS/IN2P3, LPC, Clermont-Ferrand, France

⁶ CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France

⁷ LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France

⁸ LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France

⁹ Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany

¹⁰ Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany

¹¹ Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

¹² School of Physics, University College Dublin, Dublin, Ireland

¹³ Sezione INFN di Bari, Bari, Italy

¹⁴ Sezione INFN di Bologna, Bologna, Italy

¹⁵ Sezione INFN di Cagliari, Cagliari, Italy

¹⁶ Sezione INFN di Ferrara, Ferrara, Italy

¹⁷ Sezione INFN di Firenze, Firenze, Italy

¹⁸ Laboratori Nazionali dell’INFN di Frascati, Frascati, Italy

¹⁹ Sezione INFN di Genova, Genova, Italy

²⁰ Sezione INFN di Milano Bicocca, Milano, Italy

²¹ Sezione INFN di Milano, Milano, Italy

²² Sezione INFN di Padova, Padova, Italy

- ²³ *Sezione INFN di Pisa, Pisa, Italy*
- ²⁴ *Sezione INFN di Roma Tor Vergata, Roma, Italy*
- ²⁵ *Sezione INFN di Roma La Sapienza, Roma, Italy*
- ²⁶ *Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland*
- ²⁷ *AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland*
- ²⁸ *National Center for Nuclear Research (NCBJ), Warsaw, Poland*
- ²⁹ *Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania*
- ³⁰ *Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia*
- ³¹ *Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia*
- ³² *Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia*
- ³³ *Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia*
- ³⁴ *Budker Institute of Nuclear Physics (SB RAS) and Novosibirsk State University, Novosibirsk, Russia*
- ³⁵ *Institute for High Energy Physics (IHEP), Protvino, Russia*
- ³⁶ *Universitat de Barcelona, Barcelona, Spain*
- ³⁷ *Universidad de Santiago de Compostela, Santiago de Compostela, Spain*
- ³⁸ *European Organization for Nuclear Research (CERN), Geneva, Switzerland*
- ³⁹ *Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
- ⁴⁰ *Physik-Institut, Universität Zürich, Zürich, Switzerland*
- ⁴¹ *Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands*
- ⁴² *Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, The Netherlands*
- ⁴³ *NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine*
- ⁴⁴ *Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine*
- ⁴⁵ *University of Birmingham, Birmingham, United Kingdom*
- ⁴⁶ *H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
- ⁴⁷ *Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- ⁴⁸ *Department of Physics, University of Warwick, Coventry, United Kingdom*
- ⁴⁹ *STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ⁵⁰ *School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- ⁵¹ *School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- ⁵² *Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- ⁵³ *Imperial College London, London, United Kingdom*
- ⁵⁴ *School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- ⁵⁵ *Department of Physics, University of Oxford, Oxford, United Kingdom*
- ⁵⁶ *Massachusetts Institute of Technology, Cambridge, MA, United States*
- ⁵⁷ *University of Cincinnati, Cincinnati, OH, United States*
- ⁵⁸ *University of Maryland, College Park, MD, United States*
- ⁵⁹ *Syracuse University, Syracuse, NY, United States*
- ⁶⁰ *Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to ²*
- ⁶¹ *Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China, associated to ³*
- ⁶² *Institut für Physik, Universität Rostock, Rostock, Germany, associated to ¹¹*
- ⁶³ *National Research Centre Kurchatov Institute, Moscow, Russia, associated to ³¹*
- ⁶⁴ *Instituto de Fisica Corpuscular (IFIC), Universitat de Valencia-CSIC, Valencia, Spain, associated to ³⁶*
- ⁶⁵ *KVI - University of Groningen, Groningen, The Netherlands, associated to ⁴¹*
- ⁶⁶ *Celal Bayar University, Manisa, Turkey, associated to ³⁸*

^a *Universidade Federal do Triângulo Mineiro (UFMT), Uberaba-MG, Brazil*

^b *P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia*

^c *Università di Bari, Bari, Italy*

^d *Università di Bologna, Bologna, Italy*

^e *Università di Cagliari, Cagliari, Italy*

- ^f *Università di Ferrara, Ferrara, Italy*
^g *Università di Firenze, Firenze, Italy*
^h *Università di Urbino, Urbino, Italy*
ⁱ *Università di Modena e Reggio Emilia, Modena, Italy*
^j *Università di Genova, Genova, Italy*
^k *Università di Milano Bicocca, Milano, Italy*
^l *Università di Roma Tor Vergata, Roma, Italy*
^m *Università di Roma La Sapienza, Roma, Italy*
ⁿ *Università della Basilicata, Potenza, Italy*
^o *LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain*
^p *Hanoi University of Science, Hanoi, Viet Nam*
^q *Università di Padova, Padova, Italy*
^r *Università di Pisa, Pisa, Italy*
^s *Scuola Normale Superiore, Pisa, Italy*
^t *Università degli Studi di Milano, Milano, Italy*

The existence of charged charmonium-like states has been a topic of much debate since the Belle collaboration found evidence for a narrow $Z(4430)^-$ peak, with width $\Gamma = 45^{+18+30}_{-13-13}$ MeV, in the $\psi'\pi^-$ mass distribution ($m_{\psi'\pi^-}$) in $B \rightarrow \psi'K\pi^-$ decays ($K = K_s^0$ or K^+) [1].¹ As the minimal quark content of such a state is $c\bar{c}d\bar{u}$, this observation could be interpreted as the first unambiguous evidence for the existence of mesons beyond the traditional $q\bar{q}$ model [2]. This has contributed to a broad theoretical interest in this state [3–19]. Exotic $\chi_{c1,2}\pi^-$ structures were also reported by the Belle collaboration in $B \rightarrow \chi_{c1,2}K\pi^-$ decays [20]. Using the $K^* \rightarrow K\pi^-$ invariant mass ($m_{K\pi^-}$) and helicity angle (θ_{K^*}) [21–23] distributions, the BaBar collaboration was able to describe the observed $m_{\psi'\pi^-}$ and $m_{\chi_{c1,2}\pi^-}$ structures in terms of reflections of any K^* states with spin $J \leq 3$ ($J \leq 1$ for $m_{K\pi^-} < 1.2$ GeV) without invoking exotic resonances [24, 25]. However, the BaBar results did not contradict the Belle evidence for the $Z(4430)^-$ state. The Belle collaboration subsequently updated their $Z(4430)^-$ results with a two-dimensional [26] and later a four-dimensional (4D) amplitude analysis [27] resulting in a $Z(4430)^-$ significance of 5.2σ , a mass of $M_{Z^-} = 4485 \pm 22^{+28}_{-11}$ MeV, a large width of $\Gamma_{Z^-} = 200^{+41+26}_{-46-35}$ MeV, an amplitude fraction (defined further below) of $f_{Z^-} = (10.3^{+3.0+4.3}_{-3.5-2.3})\%$ and spin-parity $J^P = 1^+$ favored over the other assignments by more than 3.4σ . Other candidates for charged four-quark states have been reported in $e^+e^- \rightarrow \pi^+\pi^-\Upsilon(nS)$ [28, 29], $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ [30, 31], $e^+e^- \rightarrow \pi^+\pi^-h_c$ [32] and $e^+e^- \rightarrow (D^*\bar{D}^*)^\pm\pi^\mp$ [33] processes.

In this Letter, we report a 4D model-dependent amplitude fit to a sample of $25\,176 \pm 174$ $B^0 \rightarrow \psi'K^+\pi^-$, $\psi' \rightarrow \mu^+\mu^-$ candidates reconstructed with the LHCb detector in pp collision data corresponding to 3 fb^{-1} collected at $\sqrt{s} = 7$ and 8 TeV. The ten-fold increase in signal yield over the previous measurement [27] improves sensitivity to exotic states and allows their resonant nature to be studied in a novel way. We complement the amplitude fit with a model-independent approach [24].

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, described in detail in Ref. [34]. The B^0 candidate selection follows that in Ref. [35] accounting for the different number of final-state pions. It is based on finding $(\psi' \rightarrow \mu^+\mu^-)K^+\pi^-$ candidates using particle identification information, transverse momentum thresholds and requiring separation of the tracks and of the B^0 vertex from the primary pp interaction points. To improve modeling of the detection efficiency, we exclude regions near the $K^+\pi^-$ vs. $\psi'\pi^-$ Dalitz plot boundary, which reduces the sample size by 12%. The background fraction is determined from the B^0 candidate invariant mass distribution to be $(4.1 \pm 0.1)\%$. The background is dominated by combinations of ψ' mesons from B decays with random kaons and pions.

Amplitude models are fit to the data using the unbinned maximum likelihood method. We follow the formalism and notation of Ref. [27] with the 4D amplitude dependent on $\Phi = (m_{K^+\pi^-}^2, m_{\psi'\pi^-}^2, \cos\theta_{\psi'}, \phi)$, where $\theta_{\psi'}$ is the ψ' helicity angle and ϕ is the angle between the K^* and ψ' decay planes in the B^0 rest frame. The signal probability density function (PDF), $S(\Phi)$, is normalized by summing over simulated events. Since the simulated events are passed through the detector simulation [36], this approach implements 4D efficiency

¹ The inclusion of charge-conjugate states is implied in this Letter. We use units in which $c = 1$.

corrections without use of a parameterization. We use B^0 mass sidebands to obtain a parameterization of the background PDF.

As in Ref. [27], our amplitude model includes all known $K^{*0} \rightarrow K^+\pi^-$ resonances with nominal mass within or slightly above the kinematic limit (1593 MeV) in $B^0 \rightarrow \psi' K^+\pi^-$ decays: $K_0^*(800)$, $K_0^*(1430)$ for $J = 0$; $K^*(892)$, $K^*(1410)$ and $K^*(1680)$ for $J = 1$; $K_2^*(1430)$ for $J = 2$; and $K_3^*(1780)$ for $J = 3$. We also include a non-resonant (NR) $J = 0$ term in the fits. We fix the masses and widths of the resonances to the world average values [37], except for the widths of the two dominant contributions, $K^*(892)$ and $K_2^*(1430)$, and the poorly known $K_0^*(800)$ mass and width, which are allowed to float in the fit with Gaussian constraints. As an alternative $J = 0$ model, we use the LASS parameterization [38, 39], in which the NR and $K_0^*(800)$ components are replaced with an elastic scattering term (two free parameters) interfering with the $K_0^*(1430)$ resonance.

To probe the quality of the likelihood fits, we calculate a binned χ^2 variable using adaptive 4D binning, in which we split the data once in $|\cos\theta_{\psi'}|$, twice in ϕ and then repeatedly in $m_{K^+\pi^-}^2$ and $m_{\psi'\pi^-}^2$ preserving any bin content above 20 events, for a total of $N_{\text{bin}} = 768$ bins. Simulations of many pseudoexperiments, each with the same number of signal and background events as in the data sample, show that the p -value of the χ^2 test (p_{χ^2}) has an approximately uniform distribution assuming that the number of degrees of freedom (ndf) equals $N_{\text{bin}} - N_{\text{par}} - 1$, where N_{par} is the number of unconstrained parameters in the fit. Fits with all K^* components and either of the two different $J = 0$ models do not give a satisfactory description of the data; the p_{χ^2} is below 2×10^{-6} , equivalent to 4.8σ in the Gaussian distribution. If the $K_3^*(1780)$ component is excluded from the amplitude, the discrepancy increases to 6.3σ .

This is supported by an independent study using the model-independent approach developed by the BaBar collaboration [24, 25], which does not constrain the analysis to any combination of known K^* resonances, but merely restricts their maximal spin. We determine the Legendre polynomial moments of $\cos\theta_{K^*}$ as a function of $m_{K^+\pi^-}$ from the sideband-subtracted and efficiency-corrected sample of $B^0 \rightarrow \psi' K^+\pi^-$ candidates. Together with the observed $m_{K^+\pi^-}$ distribution, the moments corresponding to $J \leq 2$ are reflected into the $m_{\psi'\pi^-}$ distribution using simulations as described in Ref. [24]. As shown in Fig. 1, the K^* reflections do not describe the data in the $Z(4430)^-$ region. Since a $Z(4430)^-$ resonance would contribute to the $\cos\theta_{K^*}$ moments, and also interfere with the K^* resonances, it is not possible to determine the $Z(4430)^-$ parameters using this approach. The amplitude fit is used instead.

If a $Z(4430)^-$ component with $J^P = 1^+$ (hereafter Z_1^-) is added to the amplitude, the p_{χ^2} reaches 4% when all the $K^* \rightarrow K^+\pi^-$ resonances with a pole mass below the kinematic limit are included. The p_{χ^2} rises to 12% if the $K^*(1680)$ is added (see Fig. 2), but fails to improve when the $K_3^*(1780)$ is also included. Therefore, as in Ref. [27] we choose to estimate the Z_1^- parameters using the model with the $K^*(1680)$ as the heaviest K^* resonance. In Ref. [27] two independent complex Z_1^- helicity couplings, $H_{\lambda'}^{Z_1^-}$ for $\lambda' = 0, +1$ (parity conservation requires $H_{-1}^{Z_1^-} = H_{+1}^{Z_1^-}$), were allowed to float in the fit. The small energy release in the Z_1^- decay suggests neglecting D -wave decays. A likelihood-ratio test is used to discriminate between any pair of amplitude models based on the log-likelihood

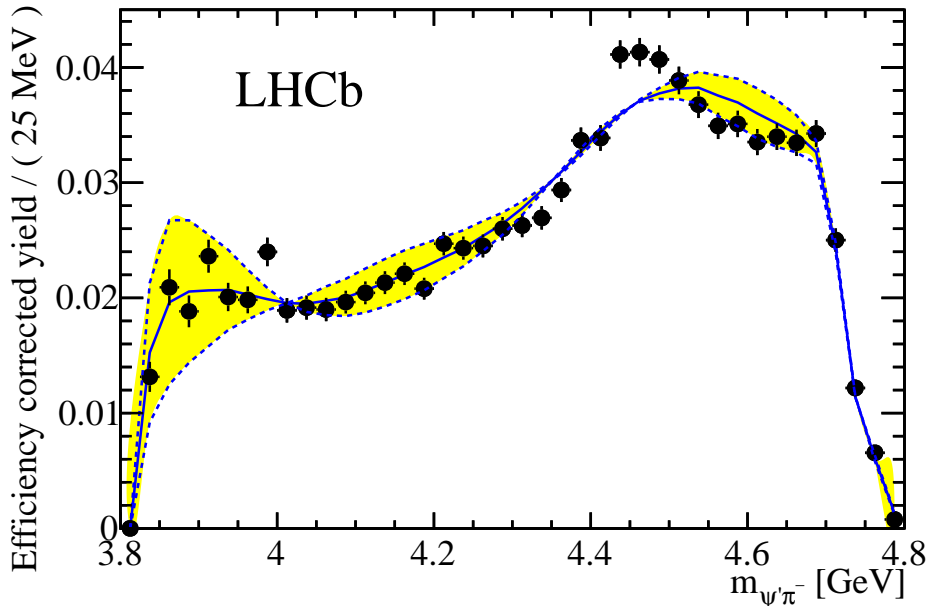


Figure 1: Background-subtracted and efficiency-corrected $m_{\psi'\pi^-}$ distribution (black data points), superimposed with the reflections of $\cos\theta_{K^*}$ moments up to order four allowing for $J(K^*) \leq 2$ (blue line) and their correlated statistical uncertainty (yellow band bounded by blue dashed lines). The distributions have been normalized to unity.

difference $\Delta(-2\ln L)$ [40]. The D -wave contribution is found to be insignificant when allowed in the fit, 1.3σ assuming Wilks' theorem². Thus, we assume a pure S -wave decay, implying $H_{+1}^{Z^-} = H_0^{Z^-}$. The significance of the Z_1^- is evaluated from the likelihood ratio of the fits without and with the Z_1^- component. Since the condition of the likelihood regularity in Z_1^- mass and width is not satisfied when the no- Z_1^- hypothesis is imposed, use of Wilks' theorem is not justified³ [41]. Therefore, pseudoexperiments are used to predict the distribution of $\Delta(-2\ln L)$ under the no- Z_1^- hypothesis, which is found to be well described by a χ^2 PDF with $\text{ndf} = 7.5$. Conservatively, we assume $\text{ndf} = 8$, twice the number of free parameters in the Z_1^- amplitude. This yields a Z_1^- significance for the default K^* model of 18.7σ . The lowest significance among all the systematic variations to the model discussed below is 13.9σ .

The default fit gives $M_{Z_1^-} = 4475 \pm 7$ MeV, $\Gamma_{Z_1^-} = 172 \pm 13$ MeV, $f_{Z_1^-} = (5.9 \pm 0.9)\%$, $f_{\text{NR}} = (0.3 \pm 0.8)\%$, $f_{K_0^*(800)} = (3.2 \pm 2.2)\%$, $f_{K^*(892)} = (59.1 \pm 0.9)\%$, $f_{K^*(1410)} = (1.7 \pm 0.8)\%$, $f_{K_0^*(1430)} = (3.6 \pm 1.1)\%$, $f_{K_2^*(1430)} = (7.0 \pm 0.4)\%$ and $f_{K^*(1680)} = (4.0 \pm 1.5)\%$, which are consistent with the Belle results [27] even without considering systematic uncertainties. Above, the amplitude fraction of any component R is defined as $f_R = \int S_R(\Phi)d\Phi / \int S(\Phi)d\Phi$, where in $S_R(\Phi)$ all except the R amplitude terms are set to zero.

²See e.g. Sec. 10.5.2 of Ref. [40] on asymptotic distribution of $\Delta(-2\ln L)$ for continuous families of hypotheses.

³With the mass and width floated in the fit a look-elsewhere effect must be taken into account.

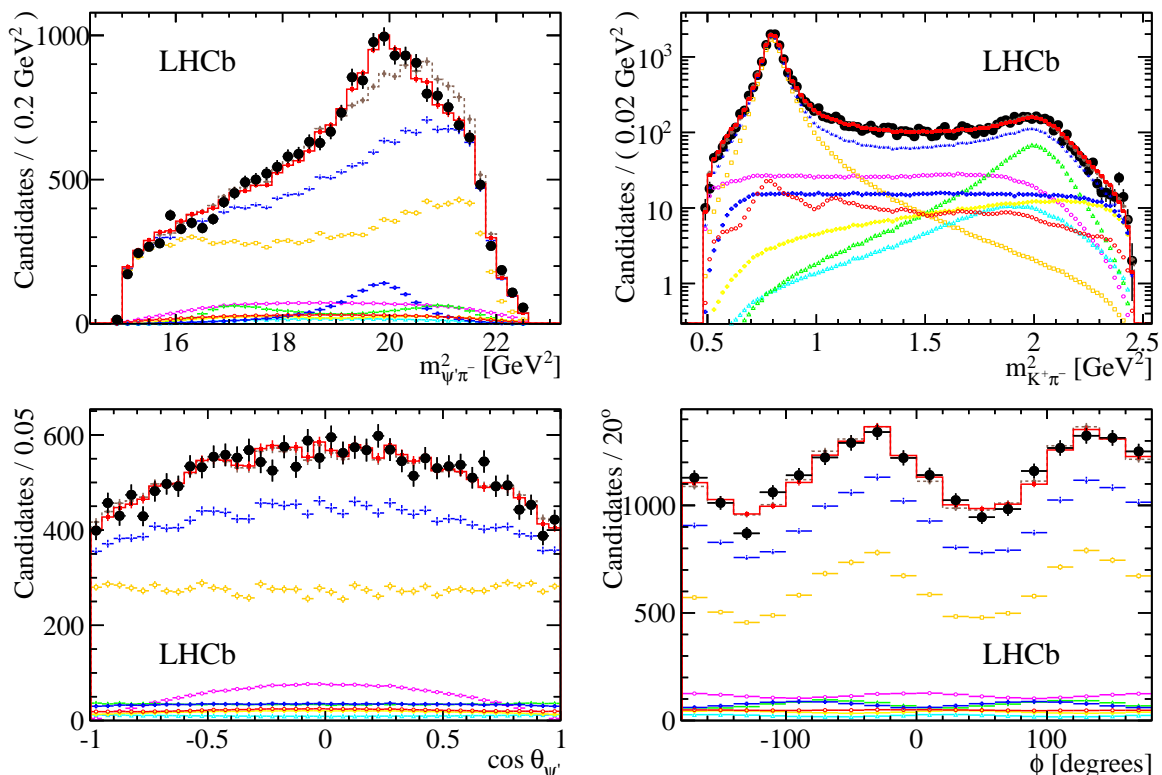


Figure 2: Distributions of the fit variables (black data points) together with the projections of the 4D fit. The red solid (brown dashed) histogram represents the total amplitude with (without) the Z_1^- . The other points illustrate various subcomponents of the fit that includes the Z_1^- : the upper (lower) blue points represent the Z_1^- component removed (taken alone). The orange, magenta, cyan, yellow, green, and red points represent the $K^*(892)$, total S -wave, $K^*(1410)$, $K^*(1680)$, $K_2^*(1430)$ and background terms, respectively.

The sum of all amplitude fractions is not 100% because of interference effects. To assign systematic errors, we: vary the K^* models by removing the $K^*(1680)$ or adding the $K_3^*(1780)$ in the amplitude ($f_{K_3^*(1780)} = (0.5 \pm 0.2)\%$); use the LASS function as an alternative K^* S -wave representation; float all K^* masses and widths while constraining them to the known values [37]; allow a second Z^- component; increase the orbital angular momentum assumed in the B^0 decay; allow a D -wave component in the Z_1^- decay; change the effective hadron size in the Blatt-Weisskopf form factors from the default 1.6 GeV^{-1} [27] to 3.0 GeV^{-1} ; let the background fraction float in the fit or neglect the background altogether; tighten the selection criteria probing the efficiency simulation; and use alternative efficiency and background implementations in the fit. We also evaluate the systematic uncertainty from the formulation of the resonant amplitude. In the default fit, we follow the approach of Eq. (2) in Ref. [27] that uses a running mass M_R in the $(p_R/M_R)^{L_R}$ term, where M_R is the invariant mass of two daughters of the R resonance; p_R is the daughter's momentum in the rest frame of R and L_R is the orbital angular momentum of the decay. The more conventional formulation [37,42] is to use $p_R^{L_R}$ (equivalent to a fixed

M_R mass). This changes the Z_1^- parameters via the K^* terms in the amplitude model: $M_{Z_1^-}$ varies by -22 MeV, $\Gamma_{Z_1^-}$ by $+29$ MeV and $f_{Z_1^-}$ by $+1.7\%$ (the p_{χ^2} drops to 7%). Adding all systematic errors in quadrature we obtain $M_{Z_1^-} = 4475 \pm 7_{-25}^{+15}$ MeV, $\Gamma_{Z_1^-} = 172 \pm 13_{-34}^{+37}$ MeV and $f_{Z_1^-} = (5.9 \pm 0.9_{-3.3}^{+1.5})\%$. We also calculate a fraction of Z_1^- that includes its interferences with the K^* resonances as $f_{Z_1^-}^I = 1 - \int S_{\text{no-}Z_1^-}(\Phi)d\Phi / \int S(\Phi)d\Phi$, where the Z_1^- term in $S_{\text{no-}Z_1^-}(\Phi)$ is set to zero. This fraction, $(16.7 \pm 1.6_{-5.2}^{+4.5})\%$, is much larger than $f_{Z_1^-}$ implying large constructive interference.

To discriminate between various J^P assignments we determine the $\Delta(-2 \ln L)$ between the different spin hypotheses. Following the method of Ref. [27], we exclude the 0^- hypothesis in favor of the 1^+ assignment at 25.7σ in the fits with the default K^* model. Such a large rejection level is expected according to the $\Delta(-2 \ln L)$ distribution of the pseudoexperiments generated under the 1^+ hypothesis. For large data samples, assuming a $\chi^2(\text{ndf} = 1)$ distribution for $\Delta(-2 \ln L)$ under the disfavored J^P hypothesis gives a lower limit on the significance of its rejection⁴. This method gives more than 17.8σ rejection. Since the latter method is conservative and provides sufficient rejection, we employ it while studying systematic effects. Among all systematic variations described above, allowing the $K_3^*(1780)$ in the fit produces the weakest rejection. Relative to 1^+ , we rule out the 0^- , 1^- , 2^+ and 2^- hypotheses by at least 9.7σ , 15.8σ , 16.1σ and 14.6σ , respectively. This reinforces the 5.1σ (4.7σ) rejection of the 2^+ (2^-) hypotheses previously reported by the Belle collaboration [27], and confirms the 3.4σ (3.7σ) indications from Belle that 1^+ is favored over 0^- (1^-).

In the amplitude fit, the Z_1^- is represented by a Breit-Wigner amplitude, where the magnitude and phase vary with $m_{\psi'\pi^-}^2$ according to an approximately circular trajectory in the $(\text{Re } A^{Z^-}, \text{Im } A^{Z^-})$ plane (Argand diagram [37]), where A^{Z^-} is the $m_{\psi'\pi^-}^2$ dependent part of the Z_1^- amplitude. We perform an additional fit to the data, in which we represent the Z_1^- amplitude as the combination of independent complex amplitudes at six equidistant points in the $m_{\psi'\pi^-}^2$ range covering the Z_1^- peak, $18.0 - 21.5$ GeV². Thus, the K^* and the Z_1^- components are no longer influenced in the fit by the assumption of a Breit-Wigner amplitude for the Z_1^- . The resulting Argand diagram, shown in Fig. 3, is consistent with a rapid change of the Z_1^- phase when its magnitude reaches the maximum, a behavior characteristic of a resonance.

If a second Z^- resonance is allowed in the amplitude with $J^P = 0^-$ (Z_0^-) the p_{χ^2} of the fit improves to 26% . The Z_0^- significance from the $\Delta(-2 \ln L)$ is 6σ including the systematic variations. It peaks at a lower mass, $4239 \pm 18_{-10}^{+45}$ MeV, and has a larger width, $220 \pm 47_{-74}^{+108}$ MeV, with a much smaller fraction, $f_{Z_0^-} = (1.6 \pm 0.5_{-0.4}^{+1.9})\%$ ($f_{Z_0^-}^I = (2.4 \pm 1.1_{-0.2}^{+1.7})\%$) than the Z_1^- . With the default K^* model, 0^- is preferred over 1^- , 2^- and 2^+ by 8σ . The preference over 1^+ is only 1σ . However, the width in the 1^+ fit becomes implausibly large, 660 ± 150 MeV. The Z_0^- has the same mass and width as one of the $\chi_{c1}\pi^-$ states reported previously [20] but a 0^- state cannot decay strongly to $\chi_{c1}\pi^-$. Figure 4 compares the $m_{\psi'\pi^-}^2$ projections of the fits with both Z_0^- and Z_1^- , or Z_1^-

⁴See Sec. 10.5.7 of Ref. [40] on testing separate hypotheses.

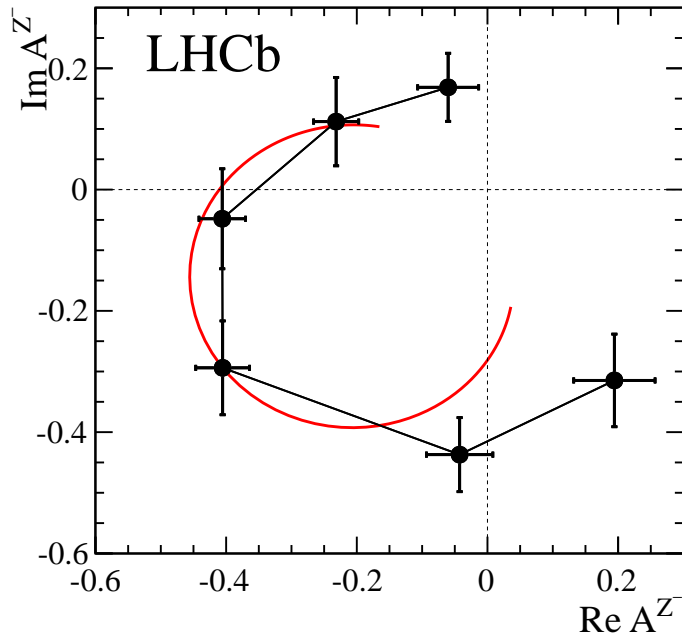


Figure 3: Fitted values of the Z_1^- amplitude in six $m_{\psi'\pi^-}^2$ bins, shown in an Argand diagram (connected points with the error bars, $m_{\psi'\pi^-}^2$ increases counterclockwise). The red curve is the prediction from the Breit-Wigner formula with a resonance mass (width) of 4475 (172) MeV and magnitude scaled to intersect the bin with the largest magnitude centered at $(4477 \text{ MeV})^2$. Units are arbitrary. The phase convention assumes the helicity-zero $K^*(892)$ amplitude to be real.

component only. The model-independent analysis has a large statistical uncertainty in the Z_0^- region and shows no deviations of the data from the reflections of the K^* degrees of freedom (Fig. 1). Argand diagram studies for the Z_0^- are inconclusive. Therefore, its characterization as a resonance will need confirmation when larger samples become available.

In summary, an amplitude fit to a large sample of $B^0 \rightarrow \psi' K^+ \pi^-$ decays provides the first independent confirmation of the existence of the $Z(4430)^-$ resonance and establishes its spin-parity to be 1^+ , both with very high significance. The measured mass, $4475 \pm 7_{-25}^{+15}$ MeV, width, $172 \pm 13_{-34}^{+37}$ MeV, and amplitude fraction, $(5.9 \pm 0.9_{-3.3}^{+1.5})\%$, are consistent with, but more precise than, the Belle results [27]. An analysis of the data using the model-independent approach developed by the BaBar collaboration [24] confirms the inconsistencies in the $Z(4430)^-$ region between the data and $K^+ \pi^-$ states with $J \leq 2$. The D -wave contribution is found to be insignificant in $Z(4430)^-$ decays, as expected for a true state at such mass. The Argand diagram obtained for the $Z(4430)^-$ amplitude is consistent with the resonant behavior. For the first time the resonant character is demonstrated in this way among all known candidates for charged four-quark states.

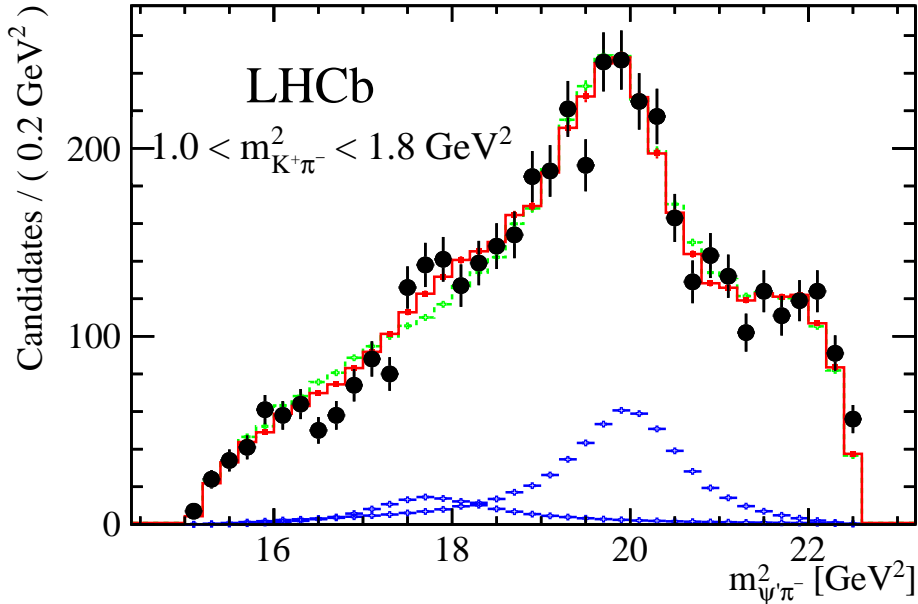


Figure 4: Distribution of $m_{\psi'\pi^-}^2$ in the data (black points) for $1.0 < m_{K^+\pi^-}^2 < 1.8 \text{ GeV}^2$ ($K^*(892)$, $K_2^*(1430)$ veto region) compared with the fit with two, 0^- and 1^+ (solid-line red histogram) and only one 1^+ (dashed-line green histogram) Z^- resonances. Individual Z^- terms (blue points) are shown for the fit with two Z^- resonances.

Acknowledgements

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); NSFC (China); CNRS/IN2P3 and Region Auvergne (France); BMBF, DFG, HGF and MPG (Germany); SFI (Ireland); INFN (Italy); FOM and NWO (The Netherlands); SCSR (Poland); MEN/IFA (Romania); MinES, Rosatom, RFBR and NRC “Kurchatov Institute” (Russia); MinCo, XuntaGal and GENCAT (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC and the Royal Society (United Kingdom); NSF (USA). We also acknowledge the support received from EPLANET, Marie Curie Actions and the ERC under FP7. The Tier1 computing centres are supported by IN2P3 (France), KIT and BMBF (Germany), INFN (Italy), NWO and SURF (The Netherlands), PIC (Spain), GridPP (United Kingdom). We are indebted to the communities behind the multiple open source software packages on which we depend. We are also thankful for the computing resources and the access to software R&D tools provided by Yandex LLC (Russia).

References

- [1] Belle collaboration, S. Choi *et al.*, *Observation of a resonance-like structure in the $\pi^\pm\psi'$ mass distribution in exclusive $B \rightarrow K\pi^\pm\psi'$ decays*, Phys. Rev. Lett. **100** (2008) 142001, [arXiv:0708.1790](#).
- [2] M. Gell-Mann, *A schematic model of baryons and mesons*, Phys. Lett. **8** (1964) 214.
- [3] J. L. Rosner, *Threshold effect and $\pi^\pm\psi(2S)$ peak*, Phys. Rev. **D76** (2007) 114002, [arXiv:0708.3496](#).
- [4] E. Braaten and M. Lu, *Line shapes of the $Z(4430)$* , Phys. Rev. **D79** (2009) 051503, [arXiv:0712.3885](#).
- [5] K. Cheung, W.-Y. Keung, and T.-C. Yuan, *Bottomed analog of $Z^+(4433)$* , Phys. Rev. **D76** (2007) 117501, [arXiv:0709.1312](#).
- [6] C. Meng and K.-T. Chao, *$Z^+(4430)$ as a resonance in the $D_1(D'_1)D^*$ channel*, [arXiv:0708.4222](#).
- [7] G.-J. Ding, *Understanding the charged meson $Z(4430)$* , [arXiv:0711.1485](#).
- [8] Y. Li, C.-D. Lu, and W. Wang, *Partners of $Z(4430)$ and productions in B decays*, Phys. Rev. **D77** (2008) 054001, [arXiv:0711.0497](#).
- [9] L. Maiani, A. Polosa, and V. Riquer, *The charged $Z(4433)$: towards a new spectroscopy*, [arXiv:0708.3997](#).
- [10] C.-F. Qiao, *A uniform description of the states recently observed at B -factories*, J. Phys. **G35** (2008) 075008, [arXiv:0709.4066](#).
- [11] X.-H. Liu, Q. Zhao, and F. E. Close, *Search for tetraquark candidate $Z(4430)$ in meson photoproduction*, Phys. Rev. **D77** (2008) 094005, [arXiv:0802.2648](#).
- [12] L. Maiani, A. Polosa, and V. Riquer, *The charged $Z(4430)$ in the diquark-antidiquark picture*, New J. Phys. **10** (2008) 073004.
- [13] D. Bugg, *How resonances can synchronise with thresholds*, J. Phys. **G35** (2008) 075005, [arXiv:0802.0934](#).
- [14] T. Matsuki, T. Morii, and K. Sudoh, *Is the $Z^+(4430)$ a radially excited state of D_s ?*, Phys. Lett. **B669** (2008) 156, [arXiv:0805.2442](#).
- [15] M. Cardoso and P. Bicudo, *Microscopic calculation of the decay of Jaffe-Wilczek tetraquarks, and the $Z(4433)$* , [arXiv:0805.2260](#).
- [16] Y.-R. Liu and Z.-Y. Zhang, *A chiral quark model study of $Z^+(4430)$ in the molecular picture*, [arXiv:0908.1734](#).

- [17] T. Branz, T. Gutsche, and V. E. Lyubovitskij, *Hidden-charm and radiative decays of the $Z(4430)$ as a hadronic $D_1\bar{D}^*$ bound state*, Phys. Rev. **D82** (2010) 054025, arXiv:1005.3168.
- [18] G. Galata, *Photoproduction of $Z(4430)$ through mesonic Regge trajectories exchange*, Phys. Rev. **C83** (2011) 065203, arXiv:1102.2070.
- [19] M. Nielsen and F. S. Navarra, *Charged exotic charmonium states*, Mod. Phys. Lett. **A29** (2014), no. 5 1430005, arXiv:1401.2913.
- [20] Belle collaboration, R. Mizuk *et al.*, *Observation of two resonance-like structures in the $\pi^+\chi_{c1}$ mass distribution in exclusive $\bar{B}^0 \rightarrow K^-\pi^+\chi_{c1}$ decays*, Phys. Rev. **D78** (2008) 072004, arXiv:0806.4098.
- [21] M. Jacob and G. Wick, *On the general theory of collisions for particles with spin*, Annals Phys. **7** (1959) 404.
- [22] J. D. Richman, *An experimenter's guide to the helicity formalism*, 1984, CALT-68-1148.
- [23] S. U. Chung, *General formulation of covariant helicity-coupling amplitudes*, Phys. Rev. **D57** (1998) 431.
- [24] BaBar collaboration, B. Aubert *et al.*, *Search for the $Z(4430)^-$ at BaBar*, Phys. Rev. **D79** (2009) 112001, arXiv:0811.0564.
- [25] BaBar collaboration, J. P. Lees *et al.*, *Search for the $Z_1(4050)^+$ and $Z_2(4250)^+$ states in $\bar{B}^0 \rightarrow \chi_{c1}K^-\pi^+$ and $B^+ \rightarrow \chi_{c1}K_S^0\pi^+$* , Phys. Rev. **D85** (2012) 052003, arXiv:1111.5919.
- [26] Belle collaboration, R. Mizuk *et al.*, *Dalitz analysis of $B \rightarrow K\pi^+\psi'$ decays and the $Z(4430)^+$* , Phys. Rev. **D80** (2009) 031104, arXiv:0905.2869.
- [27] Belle collaboration, K. Chilikin *et al.*, *Experimental constraints on the spin and parity of the $Z(4430)^+$* , Phys. Rev. **D88** (2013) 074026, arXiv:1306.4894.
- [28] Belle collaboration, A. Bondar *et al.*, *Observation of two charged bottomonium-like resonances in $\Upsilon(5S)$ decays*, Phys. Rev. Lett. **108** (2012) 122001, arXiv:1110.2251.
- [29] Belle collaboration, A. Garmash *et al.*, *Amplitude analysis of $e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-$ at $\sqrt{s} = 10.865$ GeV*, arXiv:1403.0992.
- [30] Belle collaboration, Z. Q. Liu *et al.*, *Study of $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ and observation of a charged charmonium-like state at Belle*, Phys. Rev. Lett. **110** (2013) 252002, arXiv:1304.0121.

- [31] BESIII collaboration, M. Ablikim *et al.*, *Observation of a charged charmonium-like structure in e^+e^- to $\pi^+\pi^-J/\psi$ at $\sqrt{s} = 4.26$ GeV*, Phys. Rev. Lett. **110** (2013) 252001, arXiv:1303.5949.
- [32] BESIII collaboration, M. Ablikim *et al.*, *Observation of a charged charmoniumlike structure $Z_c(4020)$ and search for the $Z_c(3900)$ in $e^+e^- \rightarrow \pi^+\pi^-h_c$* , Phys. Rev. Lett. **111** (2013) 242001, arXiv:1309.1896.
- [33] BESIII collaboration, M. Ablikim *et al.*, *Observation of a charged charmoniumlike structure in $e^+e^- \rightarrow (D^*\bar{D}^*)^\pm\pi^\mp$ at $\sqrt{s} = 4.26$ GeV*, arXiv:1308.2760.
- [34] LHCb collaboration, A. A. Alves Jr. *et al.*, *The LHCb detector at the LHC*, JINST **3** (2008) S08005.
- [35] LHCb collaboration, R. Aaij *et al.*, *Determination of the $X(3872)$ meson quantum numbers*, Phys. Rev. Lett. **110** (2013) 222001, arXiv:1302.6269.
- [36] M. Clemencic *et al.*, *The LHCb simulation application, GAUSS: design, evolution and experience*, J. Phys. Conf. Ser. **331** (2011) 032023.
- [37] Particle Data Group, J. Beringer *et al.*, *Review of particle physics*, Phys. Rev. **D86** (2012) 010001.
- [38] P. Estabrooks, *Where and what are the scalar mesons?*, Phys. Rev. **D19** (1979) 2678.
- [39] LASS collaboration, D. Aston *et al.*, *A Study of $K^-\pi^+$ scattering in the reaction $K^-p \rightarrow K^-\pi^+n$ at 11 GeV/c*, Nucl. Phys. **B296** (1988) 493.
- [40] F. James, *Statistical methods in experimental physics*, World Scientific Publishing, 2006.
- [41] E. Gross and O. Vitells, *Trial factors or the look elsewhere effect in high energy physics*, Eur. Phys. J. **C70** (2010) 525, arXiv:1005.1891.
- [42] D. J. Lange, *The EvtGen particle decay simulation package*, Nucl. Instrum. Meth. **A462** (2001) 152.