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Search for the decay $D0 \rightarrow + - + -$

LHCb Collaboration ; Aaij, R ; Adeva, B ; Adinolfi, M ; et al ; Bernet, R ; Müller, K ; Steinkamp, O ;
Straumann, U ; Vollhardt, A

Abstract: A search for the $D0 \rightarrow + - + -$ decay, where the muon pair does not originate from a resonance, is performed using proton–proton collision data corresponding to an integrated luminosity of 1.0fb^{-1} recorded by the LHCb experiment at a centre-of-mass energy of 7 TeV. No signal is observed and an upper limit on the relative branching fraction with respect to the resonant decay mode $D0 \rightarrow + - (\rightarrow + -)$, under the assumption of a phase-space model, is found to be $B(D0 \rightarrow + - + -)/B(D0 \rightarrow + - (\rightarrow + -)) < 0.96$ Turn MathJax off at 90% confidence level. The upper limit on the absolute branching fraction is evaluated to be $B(D0 \rightarrow + - + -) < 5.5 \times 10^{-7}$ at 90% confidence level. This is the most stringent to date.

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Search for the decay $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$

The LHCb collaboration[†]

Abstract

A search for the $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ decay, where the muon pair does not originate from a resonance, is performed using proton-proton collision data corresponding to an integrated luminosity of 1.0 fb^{-1} recorded by the LHCb experiment at a centre-of-mass energy of 7 TeV. No signal is observed and an upper limit on the relative branching fraction with respect to the resonant decay mode $D^0 \rightarrow \pi^+ \pi^- \phi (\rightarrow \mu^+ \mu^-)$, under the assumption of a phase-space model, is found to be

$$\mathcal{B}(D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) / \mathcal{B}(D^0 \rightarrow \pi^+ \pi^- \phi (\rightarrow \mu^+ \mu^-)) < 0.96$$

at 90% confidence level. The upper limit on the absolute branching fraction is evaluated to be $\mathcal{B}(D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) < 5.5 \times 10^{-7}$ at 90% confidence level. This is the most stringent to date.

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[†]Authors are listed on the following pages.

LHCb collaboration

R. Aaij⁴⁰, B. Adeva³⁶, M. Adinolfi⁴⁵, C. Adrover⁶, A. Affolder⁵¹, Z. Ajaltouni⁵, J. Albrecht⁹, F. Alessio³⁷, M. Alexander⁵⁰, S. Ali⁴⁰, G. Alkhazov²⁹, P. Alvarez Cartelle³⁶, A.A. Alves Jr²⁴, S. Amato², S. Amerio²¹, Y. Amhis⁷, L. Anderlini^{17,f}, J. Anderson³⁹, R. Andreassen⁵⁶, J.E. Andrews⁵⁷, R.B. Appleby⁵³, O. Aquines Gutierrez¹⁰, F. Archilli¹⁸, A. Artamonov³⁴, M. Artuso⁵⁸, E. Aslanides⁶, G. Auriemma^{24,m}, M. Baalouch⁵, S. Bachmann¹¹, J.J. Back⁴⁷, A. Badalov³⁵, C. Baesso⁵⁹, V. Balagura³⁰, W. Baldini¹⁶, R.J. Barlow⁵³, C. Barschel³⁷, S. Barsuk⁷, W. Barter⁴⁶, Th. Bauer⁴⁰, A. Bay³⁸, J. Beddow⁵⁰, F. Bedeschi²², I. Bediaga¹, S. Belogurov³⁰, K. Belous³⁴, I. Belyaev³⁰, E. Ben-Haim⁸, G. Bencivenni¹⁸, S. Benson⁴⁹, J. Benton⁴⁵, A. Berezhnoy³¹, R. Bernet³⁹, M.-O. Bettler⁴⁶, M. van Beuzekom⁴⁰, A. Bien¹¹, S. Bifani⁴⁴, T. Bird⁵³, A. Bizzeti^{17,h}, P.M. Bjørnstad⁵³, T. Blake³⁷, F. Blanc³⁸, J. Blouw¹⁰, S. Blusk⁵⁸, V. Bocci²⁴, A. Bondar³³, N. Bondar²⁹, W. Bonivento¹⁵, S. Borghi⁵³, A. Borgia⁵⁸, T.J.V. Bowcock⁵¹, E. Bowen³⁹, C. Bozzi¹⁶, T. Brambach⁹, J. van den Brand⁴¹, J. Bressieux³⁸, D. Brett⁵³, M. Britsch¹⁰, T. Britton⁵⁸, N.H. Brook⁴⁵, H. Brown⁵¹, A. Bursche³⁹, G. Busetto^{21,q}, J. Buytaert³⁷, S. Cadeddu¹⁵, O. Callot⁷, M. Calvi^{20,j}, M. Calvo Gomez^{35,n}, A. Camboni³⁵, P. Campana^{18,37}, D. Campora Perez³⁷, A. Carbone^{14,c}, G. Carboni^{23,k}, R. Cardinale^{19,i}, A. Cardini¹⁵, H. Carranza-Mejia⁴⁹, L. Carson⁵², K. Carvalho Akiba², G. Casse⁵¹, L. Castillo Garcia³⁷, M. Cattaneo³⁷, Ch. Cauet⁹, R. Cenci⁵⁷, M. Charles⁵⁴, Ph. Charpentier³⁷, S.-F. Cheung⁵⁴, N. Chiapolini³⁹, M. Chrzaszcz^{39,25}, K. Ciba³⁷, X. Cid Vidal³⁷, G. Ciezarek⁵², P.E.L. Clarke⁴⁹, M. Clemencic³⁷, H.V. Cliff⁴⁶, J. Closier³⁷, C. Coca²⁸, V. Coco⁴⁰, J. Cogan⁶, E. Cogneras⁵, P. Collins³⁷, A. Comerma-Montells³⁵, A. Contu^{15,37}, A. Cook⁴⁵, M. Coombes⁴⁵, S. Coquereau⁸, G. Corti³⁷, B. Couturier³⁷, G.A. Cowan⁴⁹, D.C. Craik⁴⁷, M. Cruz Torres⁵⁹, S. Cunliffe⁵², R. Currie⁴⁹, C. D'Ambrosio³⁷, P. David⁸, P.N.Y. David⁴⁰, A. Davis⁵⁶, I. De Bonis⁴, K. De Bruyn⁴⁰, S. De Capua⁵³, M. De Cian¹¹, J.M. De Miranda¹, L. De Paula², W. De Silva⁵⁶, P. De Simone¹⁸, D. Decamp⁴, M. Deckenhoff⁹, L. Del Buono⁸, N. Déleage⁴, D. Derkach⁵⁴, O. Deschamps⁵, F. Dettori⁴¹, A. Di Canto¹¹, H. Dijkstra³⁷, M. Dogaru²⁸, S. Donleavy⁵¹, F. Dordei¹¹, A. Dosil Suárez³⁶, D. Dossett⁴⁷, A. Dovbnya⁴², F. Dupertuis³⁸, P. Durante³⁷, R. Dzhelyadin³⁴, A. Dziurda²⁵, A. Dzyuba²⁹, S. Easo⁴⁸, U. Egede⁵², V. Egorychev³⁰, S. Eidelman³³, D. van Eijk⁴⁰, S. Eisenhardt⁴⁹, U. Eitschberger⁹, R. Ekelhof⁹, L. Eklund^{50,37}, I. El Rifai⁵, Ch. Elsasser³⁹, A. Falabella^{14,e}, C. Färber¹¹, C. Farinelli⁴⁰, S. Farry⁵¹, D. Ferguson⁴⁹, V. Fernandez Albor³⁶, F. Ferreira Rodrigues¹, M. Ferro-Luzzi³⁷, S. Filippov³², M. Fiore^{16,e}, C. Fitzpatrick³⁷, M. Fontana¹⁰, F. Fontanelli^{19,i}, R. Forty³⁷, O. Francisco², M. Frank³⁷, C. Frei³⁷, M. Frosini^{17,37,f}, E. Furfaro^{23,k}, A. Gallas Torreira³⁶, D. Galli^{14,c}, M. Gandelman², P. Gandini⁵⁸, Y. Gao³, J. Garofoli⁵⁸, P. Garosi⁵³, J. Garra Tico⁴⁶, L. Garrido³⁵, C. Gaspar³⁷, R. Gauld⁵⁴, E. Gersabeck¹¹, M. Gersabeck⁵³, T. Gershon⁴⁷, Ph. Ghez⁴, V. Gibson⁴⁶, L. Giubega²⁸, V.V. Gligorov³⁷, C. Göbel⁵⁹, D. Golubkov³⁰, A. Golutvin^{52,30,37}, A. Gomes², P. Gorbounov^{30,37}, H. Gordon³⁷, M. Grabalosa Gándara⁵, R. Graciani Diaz³⁵, L.A. Granado Cardoso³⁷, E. Graugés³⁵, G. Graziani¹⁷, A. Grecu²⁸, E. Greening⁵⁴, S. Gregson⁴⁶, P. Griffith⁴⁴, L. Grillo¹¹, O. Grünberg⁶⁰, B. Gui⁵⁸, E. Gushchin³², Yu. Guz^{34,37}, T. Gys³⁷, C. Hadjivasiliou⁵⁸, G. Haefeli³⁸, C. Haen³⁷, S.C. Haines⁴⁶, S. Hall⁵², B. Hamilton⁵⁷, T. Hampson⁴⁵, S. Hansmann-Menzemer¹¹, N. Harnew⁵⁴, S.T. Harnew⁴⁵, J. Harrison⁵³, T. Hartmann⁶⁰, J. He³⁷, T. Head³⁷, V. Heijne⁴⁰, K. Hennessy⁵¹, P. Henrard⁵, J.A. Hernando Morata³⁶, E. van Herwijnen³⁷, M. Heß⁶⁰, A. Hicheur¹, E. Hicks⁵¹, D. Hill⁵⁴, M. Hoballah⁵, C. Hombach⁵³, W. Hulsbergen⁴⁰, P. Hunt⁵⁴, T. Huse⁵¹, N. Hussain⁵⁴, D. Hutchcroft⁵¹, D. Hynds⁵⁰, V. Iakovenko⁴³, M. Idzik²⁶, P. Ilten¹², R. Jacobsson³⁷, A. Jaeger¹¹,

E. Jans⁴⁰, P. Jaton³⁸, A. Jawahery⁵⁷, F. Jing³, M. John⁵⁴, D. Johnson⁵⁴, C.R. Jones⁴⁶,
 C. Joram³⁷, B. Jost³⁷, M. Kaballo⁹, S. Kandybei⁴², W. Kanso⁶, M. Karacson³⁷, T.M. Karbach³⁷,
 I.R. Kenyon⁴⁴, T. Ketel⁴¹, B. Khanji²⁰, O. Kochebina⁷, I. Komarov³⁸, R.F. Koopman⁴¹,
 P. Koppenburg⁴⁰, M. Korolev³¹, A. Kozlinskiy⁴⁰, L. Kravchuk³², K. Kreplin¹¹, M. Kreps⁴⁷,
 G. Krocker¹¹, P. Krokovny³³, F. Kruse⁹, M. Kucharczyk^{20,25,37,j}, V. Kudryavtsev³³, K. Kurek²⁷,
 T. Kvaratskheliya^{30,37}, V.N. La Thi³⁸, D. Lacarrere³⁷, G. Lafferty⁵³, A. Lai¹⁵, D. Lambert⁴⁹,
 R.W. Lambert⁴¹, E. Lanciotti³⁷, G. Lanfranchi¹⁸, C. Langenbruch³⁷, T. Latham⁴⁷,
 C. Lazzeroni⁴⁴, R. Le Gac⁶, J. van Leerdam⁴⁰, J.-P. Lees⁴, R. Lefèvre⁵, A. Leflat³¹,
 J. Lefrançois⁷, S. Leo²², O. Leroy⁶, T. Lesiak²⁵, B. Leverington¹¹, Y. Li³, L. Li Gioi⁵, M. Liles⁵¹,
 R. Lindner³⁷, C. Linn¹¹, B. Liu³, G. Liu³⁷, S. Lohn³⁷, I. Longstaff⁵⁰, J.H. Lopes²,
 N. Lopez-March³⁸, H. Lu³, D. Lucchesi^{21,q}, J. Luisier³⁸, H. Luo⁴⁹, O. Lupton⁵⁴, F. Machefert⁷,
 I.V. Machikhiliyan³⁰, F. Maciuc²⁸, O. Maev^{29,37}, S. Malde⁵⁴, G. Manca^{15,d}, G. Mancinelli⁶,
 J. Maratas⁵, U. Marconi¹⁴, P. Marino^{22,s}, R. Märki³⁸, J. Marks¹¹, G. Martellotti²⁴, A. Martens⁸,
 A. Martín Sánchez⁷, M. Martinelli⁴⁰, D. Martinez Santos^{41,37}, D. Martins Tostes²,
 A. Martynov³¹, A. Massafferri¹, R. Matev³⁷, Z. Mathe³⁷, C. Matteuzzi²⁰, E. Maurice⁶,
 A. Mazurov^{16,37,e}, J. McCarthy⁴⁴, A. McNab⁵³, R. McNulty¹², B. McSkelly⁵¹, B. Meadows^{56,54},
 F. Meier⁹, M. Meissner¹¹, M. Merk⁴⁰, D.A. Milanes⁸, M.-N. Minard⁴, J. Molina Rodriguez⁵⁹,
 S. Monteil⁵, D. Moran⁵³, P. Morawski²⁵, A. Mordà⁶, M.J. Morello^{22,s}, R. Mountain⁵⁸, I. Mous⁴⁰,
 F. Muheim⁴⁹, K. Müller³⁹, R. Muresan²⁸, B. Muryn²⁶, B. Muster³⁸, P. Naik⁴⁵, T. Nakada³⁸,
 R. Nandakumar⁴⁸, I. Nasteva¹, M. Needham⁴⁹, S. Neubert³⁷, N. Neufeld³⁷, A.D. Nguyen³⁸,
 T.D. Nguyen³⁸, C. Nguyen-Mau^{38,o}, M. Nicol⁷, V. Niess⁵, R. Niet⁹, N. Nikitin³¹, T. Nikodem¹¹,
 A. Nomerotski⁵⁴, A. Novoselov³⁴, A. Oblakowska-Mucha²⁶, V. Obraztsov³⁴, S. Oggero⁴⁰,
 S. Ogilvy⁵⁰, O. Okhrimenko⁴³, R. Oldeman^{15,d}, M. Orlandea²⁸, J.M. Otalora Goicochea²,
 P. Owen⁵², A. Oyanguren³⁵, B.K. Pal⁵⁸, A. Palano^{13,b}, M. Palutan¹⁸, J. Panman³⁷,
 A. Papanestis⁴⁸, M. Pappagallo⁵⁰, C. Parkes⁵³, C.J. Parkinson⁵², G. Passaleva¹⁷, G.D. Patel⁵¹,
 M. Patel⁵², G.N. Patrick⁴⁸, C. Patrignani^{19,i}, C. Pavel-Nicorescu²⁸, A. Pazos Alvarez³⁶,
 A. Pearce⁵³, A. Pellegrino⁴⁰, G. Penso^{24,l}, M. Pepe Altarelli³⁷, S. Perazzini^{14,c}, E. Perez Trigo³⁶,
 A. Pérez-Calero Yzquierdo³⁵, P. Perret⁵, M. Perrin-Terrin⁶, L. Pescatore⁴⁴, E. Pesen⁶¹,
 G. Pessina²⁰, K. Petridis⁵², A. Petrolini^{19,i}, A. Phan⁵⁸, E. Picatoste Olloqui³⁵, B. Pietrzyk⁴,
 T. Pilar⁴⁷, D. Pinci²⁴, S. Playfer⁴⁹, M. Plo Casasus³⁶, F. Polci⁸, G. Polok²⁵, A. Poluektov^{47,33},
 E. Polcarpo², A. Popov³⁴, D. Popov¹⁰, B. Popovici²⁸, C. Potterat³⁵, A. Powell⁵⁴,
 J. Prisciandaro³⁸, A. Pritchard⁵¹, C. Prouve⁷, V. Pugatch⁴³, A. Puig Navarro³⁸, G. Punzi^{22,r},
 W. Qian⁴, B. Rachwal²⁵, J.H. Rademacker⁴⁵, B. Rakotomiaramanana³⁸, M.S. Rangel²,
 I. Raniuk⁴², N. Rauschmayr³⁷, G. Raven⁴¹, S. Redford⁵⁴, S. Reichert⁵³, M.M. Reid⁴⁷,
 A.C. dos Reis¹, S. Ricciardi⁴⁸, A. Richards⁵², K. Rinnert⁵¹, V. Rives Molina³⁵,
 D.A. Roa Romero⁵, P. Robbe⁷, D.A. Roberts⁵⁷, A.B. Rodrigues¹, E. Rodrigues⁵³,
 P. Rodriguez Perez³⁶, S. Roiser³⁷, V. Romanovsky³⁴, A. Romero Vidal³⁶, M. Rotondo²¹,
 J. Rouvinet³⁸, T. Ruf³⁷, F. Ruffini²², H. Ruiz³⁵, P. Ruiz Valls³⁵, G. Sabatino^{24,k},
 J.J. Saborido Silva³⁶, N. Sagidova²⁹, P. Sail⁵⁰, B. Saitta^{15,d}, V. Salustino Guimaraes²,
 B. Sanmartin Sedes³⁶, R. Santacesaria²⁴, C. Santamarina Rios³⁶, E. Santovetti^{23,k}, M. Sapunov⁶,
 A. Sarti¹⁸, C. Satriano^{24,m}, A. Satta²³, M. Savrie^{16,e}, D. Savrina^{30,31}, M. Schiller⁴¹,
 H. Schindler³⁷, M. Schlupp⁹, M. Schmelling¹⁰, B. Schmidt³⁷, O. Schneider³⁸, A. Schopper³⁷,
 M.-H. Schune⁷, R. Schwemmer³⁷, B. Sciascia¹⁸, A. Sciubba²⁴, M. Seco³⁶, A. Semennikov³⁰,
 K. Senderowska²⁶, I. Sepp⁵², N. Serra³⁹, J. Serrano⁶, P. Seyfert¹¹, M. Shapkin³⁴,
 I. Shapoval^{16,42,e}, Y. Shcheglov²⁹, T. Shears⁵¹, L. Shekhtman³³, O. Shevchenko⁴²,
 V. Shevchenko³⁰, A. Shires⁹, R. Silva Coutinho⁴⁷, M. Sirendi⁴⁶, N. Skidmore⁴⁵, T. Skwarnicki⁵⁸,

N.A. Smith⁵¹, E. Smith^{54,48}, E. Smith⁵², J. Smith⁴⁶, M. Smith⁵³, M.D. Sokoloff⁵⁶, F.J.P. Soler⁵⁰, F. Soomro³⁸, D. Souza⁴⁵, B. Souza De Paula², B. Spaan⁹, A. Sparkes⁴⁹, P. Spradlin⁵⁰, F. Stagni³⁷, S. Stahl¹¹, O. Steinkamp³⁹, S. Stevenson⁵⁴, S. Stoica²⁸, S. Stone⁵⁸, B. Storaci³⁹, M. Straticiu²⁸, U. Straumann³⁹, V.K. Subbiah³⁷, L. Sun⁵⁶, W. Sutcliffe⁵², S. Swientek⁹, V. Syropoulos⁴¹, M. Szczekowski²⁷, P. Szczypka^{38,37}, D. Szilard², T. Szumlak²⁶, S. T’Jampens⁴, M. Teklishyn⁷, E. Teodorescu²⁸, F. Teubert³⁷, C. Thomas⁵⁴, E. Thomas³⁷, J. van Tilburg¹¹, V. Tisserand⁴, M. Tobin³⁸, S. Tolk⁴¹, D. Tonelli³⁷, S. Topp-Joergensen⁵⁴, N. Torr⁵⁴, E. Tournefier^{4,52}, S. Tourneur³⁸, M.T. Tran³⁸, M. Tresch³⁹, A. Tsaregorodtsev⁶, P. Tsopelas⁴⁰, N. Tuning^{40,37}, M. Ubeda Garcia³⁷, A. Ukleja²⁷, A. Ustyuzhanin^{52,p}, U. Uwer¹¹, V. Vagnoni¹⁴, G. Valenti¹⁴, A. Vallier⁷, R. Vazquez Gomez¹⁸, P. Vazquez Regueiro³⁶, C. Vázquez Sierra³⁶, S. Vecchi¹⁶, J.J. Velthuis⁴⁵, M. Veltri^{17,g}, G. Veneziano³⁸, M. Vesterinen³⁷, B. Viaud⁷, D. Vieira², X. Vilasis-Cardona^{35,n}, A. Vollhardt³⁹, D. Volyanskyy¹⁰, D. Voong⁴⁵, A. Vorobyev²⁹, V. Vorobyev³³, C. Voß⁶⁰, H. Voss¹⁰, R. Waldi⁶⁰, C. Wallace⁴⁷, R. Wallace¹², S. Wandernoth¹¹, J. Wang⁵⁸, D.R. Ward⁴⁶, N.K. Watson⁴⁴, A.D. Webber⁵³, D. Websdale⁵², M. Whitehead⁴⁷, J. Wicht³⁷, J. Wiechczynski²⁵, D. Wiedner¹¹, L. Wiggers⁴⁰, G. Wilkinson⁵⁴, M.P. Williams^{47,48}, M. Williams⁵⁵, F.F. Wilson⁴⁸, J. Wimberley⁵⁷, J. Wishahi⁹, W. Wislicki²⁷, M. Witek²⁵, G. Wormser⁷, S.A. Wotton⁴⁶, S. Wright⁴⁶, S. Wu³, K. Wyllie³⁷, Y. Xie^{49,37}, Z. Xing⁵⁸, Z. Yang³, X. Yuan³, O. Yushchenko³⁴, M. Zangoli¹⁴, M. Zavertyaev^{10,a}, F. Zhang³, L. Zhang⁵⁸, W.C. Zhang¹², Y. Zhang³, A. Zhelezov¹¹, A. Zhokhov³⁰, L. Zhong³, A. Zvyagin³⁷.

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 Padova, Padova, Italy*

²² *Sezione INFN di Pisa, Pisa, Italy*

²³ *Sezione INFN di Roma Tor Vergata, Roma, Italy*

²⁴ *Sezione INFN di Roma La Sapienza, Roma, Italy*

²⁵ *Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland*

²⁶ *AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland*

²⁷ *National Center for Nuclear Research (NCBJ), Warsaw, Poland*

²⁸ *Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania*

²⁹ *Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia*

- ³⁰*Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia*
- ³¹*Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia*
- ³²*Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia*
- ³³*Budker Institute of Nuclear Physics (SB RAS) and Novosibirsk State University, Novosibirsk, Russia*
- ³⁴*Institute for High Energy Physics (IHEP), Protvino, Russia*
- ³⁵*Universitat de Barcelona, Barcelona, Spain*
- ³⁶*Universidad de Santiago de Compostela, Santiago de Compostela, Spain*
- ³⁷*European Organization for Nuclear Research (CERN), Geneva, Switzerland*
- ³⁸*Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
- ³⁹*Physik-Institut, Universität Zürich, Zürich, Switzerland*
- ⁴⁰*Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands*
- ⁴¹*Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, The Netherlands*
- ⁴²*NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine*
- ⁴³*Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine*
- ⁴⁴*University of Birmingham, Birmingham, United Kingdom*
- ⁴⁵*H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
- ⁴⁶*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- ⁴⁷*Department of Physics, University of Warwick, Coventry, United Kingdom*
- ⁴⁸*STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ⁴⁹*School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- ⁵⁰*School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- ⁵¹*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- ⁵²*Imperial College London, London, United Kingdom*
- ⁵³*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- ⁵⁴*Department of Physics, University of Oxford, Oxford, United Kingdom*
- ⁵⁵*Massachusetts Institute of Technology, Cambridge, MA, United States*
- ⁵⁶*University of Cincinnati, Cincinnati, OH, United States*
- ⁵⁷*University of Maryland, College Park, MD, United States*
- ⁵⁸*Syracuse University, Syracuse, NY, United States*
- ⁵⁹*Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to ²*
- ⁶⁰*Institut für Physik, Universität Rostock, Rostock, Germany, associated to ¹¹*
- ⁶¹*Celal Bayar University, Manisa, Turkey, associated to ³⁷*
- ^a*P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia*
- ^b*Università di Bari, Bari, Italy*
- ^c*Università di Bologna, Bologna, Italy*
- ^d*Università di Cagliari, Cagliari, Italy*
- ^e*Università di Ferrara, Ferrara, Italy*
- ^f*Università di Firenze, Firenze, Italy*
- ^g*Università di Urbino, Urbino, Italy*
- ^h*Università di Modena e Reggio Emilia, Modena, Italy*
- ⁱ*Università di Genova, Genova, Italy*
- ^j*Università di Milano Bicocca, Milano, Italy*
- ^k*Università di Roma Tor Vergata, Roma, Italy*
- ^l*Università di Roma La Sapienza, Roma, Italy*
- ^m*Università della Basilicata, Potenza, Italy*
- ⁿ*LIFAEELS, La Salle, Universitat Ramon Llull, Barcelona, Spain*
- ^o*Hanoi University of Science, Hanoi, Viet Nam*
- ^p*Institute of Physics and Technology, Moscow, Russia*
- ^q*Università di Padova, Padova, Italy*
- ^r*Università di Pisa, Pisa, Italy*
- ^s*Scuola Normale Superiore, Pisa, Italy*

1 Introduction

Flavour-changing neutral current (FCNC) processes are rare within the Standard Model (SM) as they cannot occur at tree level and are suppressed by the Glashow-Iliopoulos-Maiani (GIM) mechanism at loop level. In contrast to the B meson system, where the high mass of the top quark in the loop weakens the suppression, the GIM cancellation is almost exact [1] in D meson decays, leading to expected branching fractions for $c \rightarrow u\mu^+\mu^-$ processes in the range $(1-3) \times 10^{-9}$ [2–4]. This suppression allows for sub-leading processes with potential for physics beyond the SM, such as FCNC decays of D mesons, and the coupling of up-type quarks in electroweak processes illustrated in Fig. 1, to be probed more precisely.

The total branching fraction for these decays is expected to be dominated by long-distance contributions involving resonances, such as $D^0 \rightarrow \pi^+\pi^-V(\rightarrow \mu^+\mu^-)$, where V can be any of the light vector mesons ϕ , ρ^0 or ω . The corresponding branching fractions can reach $\mathcal{O}(10^{-6})$ [2–4]. The angular structure of these four-body semileptonic D^0 decays provides access to a variety of differential distributions. Of particular interest are angular asymmetries that allow for a theoretically robust separation of long- and short-distance effects, the latter being more sensitive to physics beyond the SM [4]. No such decays have been observed to date and the most stringent limit reported is $\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-) < 3.0 \times 10^{-5}$ at 90% confidence level (CL) by the E791 collaboration [5]. The same processes can be probed using $D_{(s)}^+ \rightarrow \pi^+\mu^+\mu^-$ decays. Upper limits on their branching fractions have been recently set to $\mathcal{B}(D^+ \rightarrow \pi^+\mu^+\mu^-) < 7.3 \times 10^{-8}$ and $\mathcal{B}(D_s^+ \rightarrow \pi^+\mu^+\mu^-) < 4.1 \times 10^{-7}$ at 90% CL by the LHCb collaboration [6].

This Letter presents the result of a search for the $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ decay, in which the muons do not originate from a resonance, performed using $D^{*+} \rightarrow D^0\pi^+$ decays, with the D^{*+} meson produced directly at the pp collision primary vertex. The reduction in background yield associated with this selection vastly compensates for the loss of signal yield. No attempt is made to distinguish contributions from intermediate resonances in the dipion invariant mass such as the ρ^0 . Throughout this Letter, the inclusion of charge conjugate processes is implied. The data samples used in this analysis correspond to an integrated luminosity of 1.0 fb^{-1} at $\sqrt{s} = 7 \text{ TeV}$ recorded by the LHCb experiment.

The analysis is performed in four dimuon mass ranges to exclude decays dominated by the contributions of resonant dimuon final states. The regions at low and high dimuon masses, away from the η , ρ^0 and ϕ resonant regions, are the most sensitive to non-SM physics and are defined as the signal regions. The signal yield is normalised to the yield of resonant $D^0 \rightarrow \pi^+\pi^-\phi(\rightarrow \mu^+\mu^-)$ decays, isolated in an appropriate dimuon range centred around the ϕ pole.

2 The LHCb detector and trigger

The LHCb detector [7] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The

40 detector includes a high-precision tracking system consisting of a silicon-strip vertex
 41 detector surrounding the pp interaction region, a large-area silicon-strip detector located
 42 upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of
 43 silicon-strip detectors and straw drift tubes placed downstream. The combined tracking
 44 system provides a momentum measurement with relative uncertainty that varies from 0.4%
 45 at 5 GeV/ c to 0.6% at 100 GeV/ c , and impact parameter resolution of 20 μm for tracks
 46 with large transverse momentum. Different types of charged hadrons are distinguished
 47 by information from two ring-imaging Cherenkov detectors [8]. Photon, electron and
 48 hadron candidates are identified by a calorimeter system consisting of scintillating-pad and
 49 preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons
 50 are identified by a system composed of alternating layers of iron and multiwire proportional
 51 chambers [9].

52 The trigger [10] consists of a hardware stage, based on information from the calorimeter
 53 and muon systems, followed by a software stage, which applies a full event reconstruction.
 54 The hardware trigger selects muons with transverse momentum, p_T , exceeding 1.48 GeV/ c ,
 55 and dimuons whose product of p_T values exceeds $(1.3 \text{ GeV}/c)^2$. In the software trigger,
 56 at least one of the final state muons is required to have momentum larger than 8 GeV/ c ,
 57 and to have an impact parameter, IP, defined as the minimum distance of the particle
 58 trajectory from the associated primary vertex (PV) in three dimensions, greater than
 59 100 μm . Alternatively, a dimuon trigger accepts events with oppositely charged muon
 60 candidates having good track quality, p_T exceeding 0.5 GeV/ c , and momentum exceeding
 61 6 GeV/ c . In a second stage of the software trigger, two algorithms select $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$
 62 candidates. The first algorithm, used to increase the efficiency in the highest dimuon mass
 63 region, requires oppositely charged muons with scalar sum of p_T greater than 1.5 GeV/ c
 64 and dimuon mass greater than 1 GeV/ c^2 . A second algorithm selects events with two
 65 oppositely charged muons and two oppositely charged hadrons with no invariant mass
 66 requirement on the dimuon.

67 Simulated events for the signal, using a phase-space model, and the normalisation

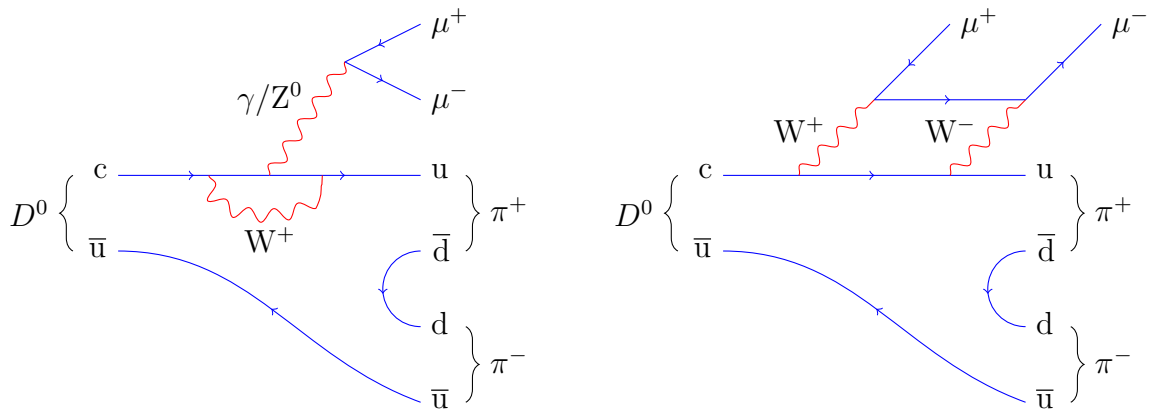


Figure 1: Leading Feynman diagrams for the FCNC decay $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ in the SM.

68 mode, are used to define selection criteria and to evaluate efficiencies. The pp collisions
 69 are generated using PYTHIA 6.4 [11] with a specific LHCb configuration [12]. Decays
 70 of hadronic particles are described by EVTGEN [13]. The interaction of the generated
 71 particles with the detector and its response are implemented using the GEANT4 toolkit [14]
 72 as described in Ref. [15].

73 3 Candidate selection

74 Candidate $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ decays are required to originate from $D^{*+} \rightarrow D^0\pi^+$ decays.
 75 The D^0 candidate is formed by combining two pion and two muon candidates where both
 76 pairs consist of oppositely charged particles. An additional pion track is combined with the
 77 D^0 candidate to build the D^{*+} candidate. The χ^2 per degree of freedom of the vertex fit is
 78 required to be less than 5 for both the D^{*+} and the D^0 candidates. The angle between the
 79 D^0 momentum vector and the direction from the associated PV to the decay vertex, θ_{D^0} ,
 80 is required to be less than 0.8° . Each of the four particles forming the D^0 meson must have
 81 momentum exceeding 3 GeV/ c and p_T exceeding 0.4 GeV/ c . The tracks must be displaced
 82 with respect to any PV and have χ_{IP}^2 larger than 4. Here χ_{IP}^2 is defined as the difference
 83 between the χ^2 of the PV fit done with and without the track under consideration.

84 Further discrimination is achieved using a boosted decision tree (BDT) [16,17], which
 85 distinguishes between signal and combinatorial background candidates. This multivariate
 86 analysis algorithm is trained using simulated $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ signal events and a
 87 background sample taken from data mass sidebands around the $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ signal
 88 mass region. Only 1% of the candidates in the sidebands are used in the training. The
 89 BDT uses the following variables: θ_{D^0} , χ^2 of the decay vertex and flight distance of the
 90 D^0 candidate, p and p_T of the D^0 candidate and of each of the four final state tracks, χ^2
 91 of the vertex and p_T of the D^{*+} candidate, χ_{IP}^2 of the D^0 candidate and of the final state
 92 particles, the maximum distance of closest approach between all pairs of tracks forming the
 93 D^0 and D^{*+} candidates, and the p_T and χ_{IP}^2 of the bachelor pion from the D^{*+} candidate.

94 The BDT discriminant is used to classify each candidate. Assuming a signal branching
 95 fraction of 10^{-9} , an optimisation study is performed to choose the combined BDT and
 96 muon particle identification (PID) selection criteria that maximise the expected statistical
 97 significance of the signal. This significance is defined as $S/\sqrt{S+B}$, where S and B
 98 are the signal and background yields respectively. The PID information is quantified as
 99 the difference in the log-likelihood of the detector response under different particle mass
 100 hypotheses (DLL) [8,18]. The optimisation procedure yields an optimal threshold for the
 101 BDT discriminant and a minimum value for $DLL_{\mu\pi}$ (the difference between the muon and
 102 pion hypotheses) of 1.5 for both μ candidates. In addition, the pion candidate is required
 103 to have $DLL_{K\pi}$ less than 3.0 and $DLL_{p\pi}$ less than 2.0, and each muon candidate must not
 104 share hits in the muon stations with any other muon candidate. In the 2% of events in
 105 which multiple candidates are reconstructed, the candidate with the smallest D^0 vertex χ^2
 106 is chosen.

107 The bachelor π^+ of the $D^{*+} \rightarrow D^0\pi^+$ decay is constrained to the PV using a Kalman

108 filter [19]. This constraint improves the resolution for the mass difference between the D^{*+}
 109 and the D^0 candidates, $\Delta m \equiv m(\pi^+\pi^-\mu^+\mu^-\pi^+) - m(\pi^+\pi^-\mu^+\mu^-)$, by a factor of two, down
 110 to $0.3 \text{ MeV}/c^2$. Candidates are selected with a Δm value in the range $140.0 - 151.4 \text{ MeV}/c^2$.

111 Candidates from the kinematically similar decay $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ form an important
 112 peaking background due to the possible misidentification of two oppositely charged pions as
 113 muons. A sample of this hadronic background is retained with a selection that is identical to
 114 that applied to the signal except that no muon identification is required. These candidates
 115 are then reconstructed under the $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ hypothesis and a subsample of the
 116 candidates, in which at least one such pion satisfies the muon identification requirements,
 117 is used to determine the shape of this peaking background in each region of dimuon mass,
 118 $m(\mu^+\mu^-)$. Under the correct mass hypotheses the $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ candidates are also
 119 used as a control sample to check differences between data and simulation that may affect
 120 the event selection performance. Moreover, they are used to determine the expected signal
 121 shape in each $m(\mu^+\mu^-)$ region by subdividing the $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ sample in the same
 122 regions of $m(\pi^+\pi^-)$.

123 Another potential source of peaking background is due to $\Lambda_c(2595)^+ \rightarrow \Sigma_c(2455)^0\pi^+$
 124 decays, followed by the $\Sigma_c(2455)^0 \rightarrow \Lambda_c^+\pi^-$ and then $\Lambda_c^+ \rightarrow pK^-\pi^+$ decays, with the two
 125 pions in the decay chain misidentified as muons and the proton and the kaon misidentified
 126 as pions. Therefore, the $\text{DLL}_{K\pi}$ and $\text{DLL}_{p\pi}$ requirements are tightened to be less than zero
 127 for the low- $m(\mu^+\mu^-)$ region, where the baryonic background is concentrated, suppressing
 128 this background to a negligible level.

129 Another potentially large background from the $D^0 \rightarrow \pi^+\pi^-\eta$ decay, followed by
 130 the decay $\eta \rightarrow \mu^+\mu^-\gamma$, does not peak at the D^0 mass since candidates in which the
 131 $m(\mu^+\mu^-)$ is within $\pm 20 \text{ MeV}/c^2$ of the nominal η mass are removed from the final fit. The
 132 remaining contribution to low values of the $m(\pi^+\pi^-\mu^+\mu^-)$ invariant mass is included in
 133 the combinatorial background.

134 4 Mass fit

135 The shapes and yields of the signal and background contributions are determined using
 136 an unbinned maximum likelihood fit to the two-dimensional $[m(\pi^+\pi^-\mu^+\mu^-\pi^+), \Delta m]$
 137 distributions in the ranges $1810 - 1920$ and $140 - 151.4 \text{ MeV}/c^2$, respectively. This range
 138 is chosen to contain all reconstructed $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ candidates.

139 The $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ data are split into four regions of $m(\mu^+\mu^-)$: two regions
 140 containing the ρ/ω and ϕ resonances and two signal regions, referred to as low- $m(\mu^+\mu^-)$
 141 and high- $m(\mu^+\mu^-)$, respectively. The definitions of these regions are provided in Table 1.

142 The D^0 mass and Δm shapes for $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ candidates are described by a
 143 double Crystal Ball function [20], which consists of a Gaussian core and independent left
 144 and right power-law tails, on either sides of the core. The parameters of these shapes are
 145 determined from the $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ control sample independently for each of the four
 146 $m(\mu^+\mu^-)$ regions.

147 The $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ peaking background is also split into the predefined dimuon

Table 1: $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ fitted yields in the four $m(\mu^+\mu^-)$ regions. The corresponding signal fractions under the assumption of a phase-space model, as described in Section 7, are listed in the last column.

Range description	$m(\mu^+\mu^-)$ [MeV/ c^2]	$D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ yield	Fraction
low- $m(\mu^+\mu^-)$	250 – 525	2 ± 2	30.6%
ρ/ω	565 – 950	23 ± 6	43.4%
ϕ	950 – 1100	63 ± 10	10.1%
high- $m(\mu^+\mu^-)$	> 1100	3 ± 2	8.9%

148 mass regions and is fitted with a double Crystal Ball function. This provides a well-defined
149 shape for this prominent background, which is included in the fit to the signal sample.
150 The yield of the misidentified component is allowed to vary and fitted in each region of
151 the analysis. The combinatorial background is described by an exponential function in
152 the D^0 candidate mass, while the shape in Δm is described by the empirical function
153 $f_{\Delta}(\Delta m, a) = 1 - e^{-(\Delta m - \Delta m_0)/a}$, where the parameter Δm_0 is fixed to 139.6 MeV/ c^2 . The
154 two-dimensional shape used in the fit implicitly assumes that $m(\pi^+\pi^-\mu^+\mu^-\pi^+)$ and Δm
155 are not correlated.

156 All the floating coefficients are allowed to vary independently in each of the $m(\mu^+\mu^-)$
157 regions. Migration between the regions is found to be negligible from simulation studies.
158 The yield observed in the ϕ region is used to normalise the yields in the signal regions.

159 One-dimensional projections for the D^0 candidate invariant mass and Δm spectra,
160 together with the result of the fits, are shown in Figs. 2 and 3, respectively. The signal
161 yields, which include contributions from the tails of the $m(\mu^+\mu^-)$ resonances leaking
162 into the low- and high- $m(\mu^+\mu^-)$ ranges, are shown in Table 1. No significant excess of
163 candidates is seen in either of the two signal regions.

164 The yields in the signal regions are compatible with the expectations from leakage from
165 the $m(\mu^+\mu^-)$ resonant regions. The number of expected events from leakage is calculated
166 assuming the $m(\mu^+\mu^-)$ spectrum given by a sum of relativistic Breit-Wigner functions,
167 describing the η , ρ/ω and ϕ resonances. The contribution from each resonance is scaled
168 according to the branching fractions as determined from resonant $D^0 \rightarrow K^+K^-\pi^+\pi^-$
169 and $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ decays [21]. The resulting shape is used to extrapolate the yields
170 fitted in the ϕ and ρ regions into the $m(\mu^+\mu^-)$ signal regions. An additional extrapolation
171 is performed using the signal yield in the $m(\mu^+\mu^-)$ range 773 – 793 MeV/ c^2 , where the
172 contribution from the ω resonance is enhanced. In this approach the interference among
173 different resonances is not accounted for and a systematic uncertainty to the extrapolated
174 yield is assigned according to the spread in their extrapolations. The expected number of
175 leakage events is estimated to be 1 ± 1 in both the low- and high- $m(\mu^+\mu^-)$ regions. This
176 precision of this estimate is dominated by the systematic uncertainty.

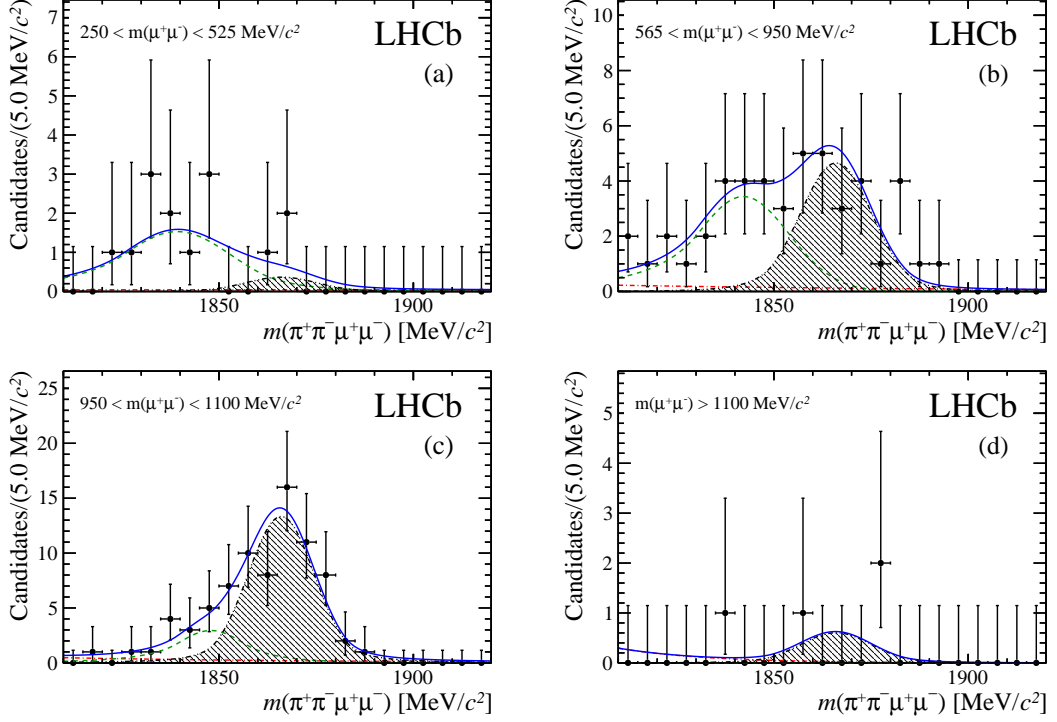


Figure 2: Distributions of $m(\pi^+\pi^-\mu^+\mu^-)$ for $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ candidates in the (a) low- $m(\mu^+\mu^-)$, (b) ρ/ω , (c) ϕ , and (d) high- $m(\mu^+\mu^-)$ regions, with Δm in the range 144.4 – 146.6 MeV/c^2 . The data are shown as points (black) and the fit result (dark blue line) is overlaid. The components of the fit are also shown: the signal (filled area), the $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ background (green dashed line) and the non-peaking background (red dashed-dotted line).

5 Branching fraction determination

177

178 The $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ branching fraction ratio for each $m(\mu^+\mu^-)$ signal region i is
 179 calculated using

$$\frac{\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-)^i}{\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\phi(\rightarrow \mu^+\mu^-))} = \frac{N_{D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-}^i}{N_{D^0 \rightarrow \pi^+\pi^-\phi(\rightarrow \mu^+\mu^-)}} \times \frac{\epsilon_{D^0 \rightarrow \pi^+\pi^-\phi(\rightarrow \mu^+\mu^-)}}{\epsilon_{D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-}^i}. \quad (1)$$

180 The yield and efficiency are given by $N_{D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-}$ and $\epsilon_{D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-}$, respectively, for the
 181 signal channel, and by $N_{D^0 \rightarrow \pi^+\pi^-\phi(\rightarrow \mu^+\mu^-)}$ and $\epsilon_{D^0 \rightarrow \pi^+\pi^-\phi(\rightarrow \mu^+\mu^-)}$ for the reference channel.
 182 The values for the efficiency ratio $\epsilon_{D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-}/\epsilon_{D^0 \rightarrow \pi^+\pi^-\phi(\rightarrow \mu^+\mu^-)}$ in the low- $m(\mu^+\mu^-)$
 183 and high- $m(\mu^+\mu^-)$ regions, as estimated from simulations, are 0.24 ± 0.03 and 0.69 ± 0.11 ,
 184 respectively, where the uncertainty reflects the limited statistics of the simulated samples.
 185 The efficiencies for reconstructing the signal decay mode and the reference mode include
 186 the geometric acceptance of the detector, the efficiencies for track reconstruction, particle
 187 identification, selection and trigger. Both efficiency ratios deviate from unity due to
 188 differences in the kinematic distributions of the final state particles in the two decays.

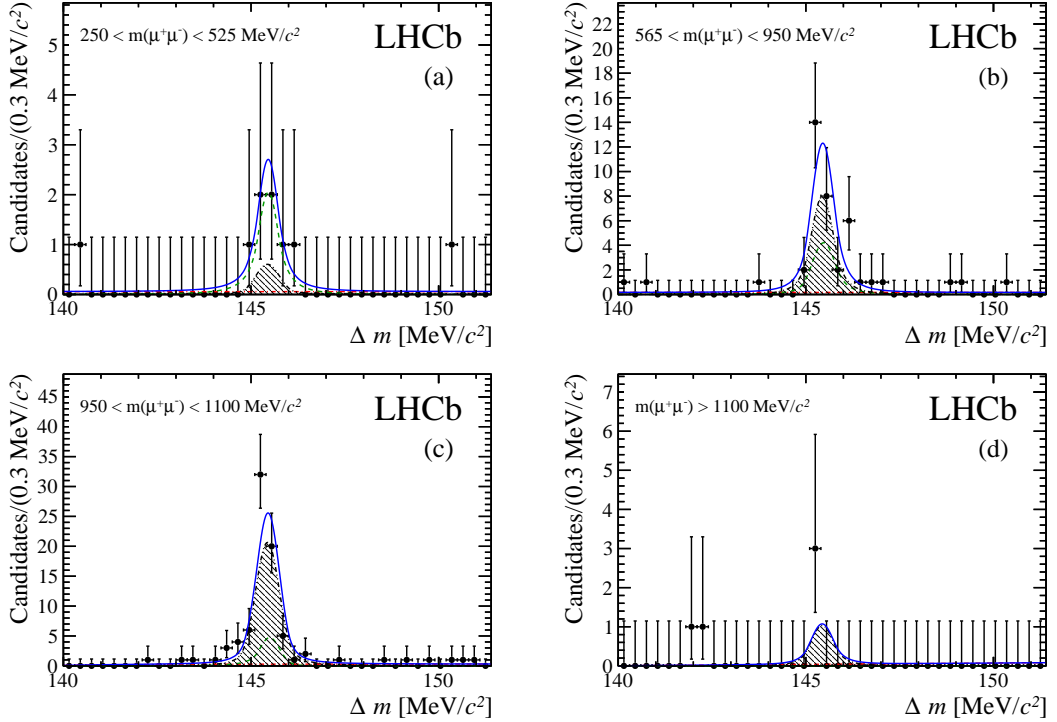


Figure 3: Distributions of Δm for $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ candidates in the (a) low- $m(\mu^+\mu^-)$, (b) ρ/ω , (c) ϕ , and (d) high- $m(\mu^+\mu^-)$ regions, with the D^0 invariant mass in the range 1840 – 1888 MeV/c^2 . The data are shown as points (black) and the fit result (dark blue line) is overlaid. The components of the fit are also shown: the signal (filled area), the $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ background (green dashed line) and the non-peaking background (red dashed-dotted line).

189 Moreover, tighter particle identification requirements are responsible for a lower efficiency
 190 ratio in the low- $m(\mu^+\mu^-)$ region. The accuracy with which the simulation reproduces the
 191 track reconstruction and particle identification is limited. Therefore, the corresponding
 192 efficiencies are also studied in data and systematic uncertainties are assigned.

193 An upper limit on the absolute branching fraction is given using an estimate of the
 194 branching fraction of the normalisation mode. The $D^0 \rightarrow \pi^+\pi^-\phi(\rightarrow \mu^+\mu^-)$ branching
 195 fraction is estimated using the results of the amplitude analysis of the $D^0 \rightarrow K^+K^-\pi^+\pi^-$
 196 decay performed at CLEO [22]. Only the fit fraction of the decay modes in which the
 197 two kaons originate from an intermediate ϕ resonance are considered and the $D^0 \rightarrow$
 198 $\pi^+\pi^-\phi(\rightarrow \mu^+\mu^-)$ branching fraction is calculated by multiplying this fraction by the total
 199 $D^0 \rightarrow K^+K^-\pi^+\pi^-$ branching fraction and using the known value of $\mathcal{B}(\phi \rightarrow \mu^+\mu^-)/\mathcal{B}(\phi \rightarrow$
 200 $K^+K^-)$ [21]. There are several interfering contributions to the $D^0 \rightarrow \pi^+\pi^-\phi(\rightarrow K^+K^-)$
 201 amplitude. Considering the interference fractions provided in Ref. [22], the following
 202 estimate for the branching fraction is obtained, $\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\phi(\rightarrow \mu^+\mu^-)) = (5.2 \pm 0.6) \times$
 203 10^{-7} . This estimate includes only the statistical uncertainty and refers to the baseline fit
 204 model used for the CLEO measurement. Similar estimates for $\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\phi(\rightarrow \mu^+\mu^-))$

205 are performed using all the alternative models considered in Ref. [22] assuming the
 206 interference fractions to be the same as for the baseline model. The spread among the
 207 estimates is used to assign a systematic uncertainty of 17% on $\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\phi(\rightarrow \mu^+\mu^-))$.
 208 The above procedure to estimate $\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\phi(\rightarrow \mu^+\mu^-))$ is supported by the narrow
 209 width of the ϕ resonance resulting in interference effects with other channels [22] that are
 210 negligible compared to the statistical uncertainty. The estimate for $\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\phi(\rightarrow$
 211 $\mu^+\mu^-))$ is $(5.2 \pm 1.1) \times 10^{-7}$, including both statistical and systematic uncertainties, and
 212 is used to set an upper limit on the absolute $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ branching fraction.

213 A possible alternative normalisation, with respect to the ρ/ω dimuon mass region, would
 214 be heavily limited by the low statistics available and the relatively high contamination
 215 from $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$, as can be seen in Figure 2b.

216 6 Systematic uncertainties

217 Several systematic uncertainties affect the efficiency ratio. Differences in the particle
 218 identification between the signal and the normalisation regions are investigated in data. A
 219 tag-and-probe technique applied to $b \rightarrow J/\psi X$ decays provides a large sample of muon
 220 candidates to determine the muon identification efficiencies [18]. General agreement
 221 between simulation and data is found to a level of 1%, which is assigned as a systematic
 222 uncertainty.

223 The particle identification performance for hadrons is investigated by comparing the
 224 efficiency in $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ candidates in data and simulation as a function of the
 225 $DLL_{K\pi}$ requirement. The largest discrepancy between data and simulation on the efficiency
 226 ratio is found to be 4% and is taken as a systematic uncertainty.

227 Several quantities, particularly the impact parameter, are known to be imperfectly
 228 reproduced in the simulation. Since this may affect the reconstruction and selection
 229 efficiency, a systematic uncertainty is estimated by smearing track properties to reproduce
 230 the distributions observed in data. The corresponding variation in the efficiency ratio yields
 231 an uncertainty of 5%. The BDT description in simulation is checked using background-
 232 subtracted $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ candidates where no significant difference is seen. Therefore,
 233 no extra systematic uncertainty is assigned.

234 The systematic uncertainty due to possible mismodelling of the trigger efficiency in
 235 the simulation is assigned as follows. The trigger requirements in simulations are varied
 236 reproducing the typical changes of trigger configurations that occurred during data taking
 237 and an alternate efficiency ratio is calculated in both the $m(\mu^+\mu^-)$ signal regions. The
 238 largest difference between the alternate and the baseline efficiency ratio, 5%, is found in
 239 the low- $m(\mu^+\mu^-)$ region. This difference is assumed as the overall systematic uncertainty
 240 on the trigger efficiency.

241 The uncertainties on the efficiency ratio due to the finite size of the simulated samples
 242 in the low- and high- $m(\mu^+\mu^-)$ regions are 12% and 16% respectively. The production of
 243 significantly larger sample of simulated events is impractical due to the low reconstruction
 244 and selection efficiencies, particularly in the signal regions. In addition, the statistical

245 uncertainties of the fitted yields in data, listed in Table 1, dominate the total uncertainty.
 246 The sources of uncertainty are summarised in Table 2.

247 According to simulations, biases in the efficiency ratio introduced by varying the relative
 248 contribution of $D^0 \rightarrow \rho^0(\rightarrow \pi\pi)\phi(\rightarrow \mu\mu)$ and three-body $D^0 \rightarrow \pi^+\pi^-\phi(\rightarrow \mu^+\mu^-)$ decays
 249 are well within the assigned uncertainty. Varying the value of $\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\phi(\rightarrow \mu^+\mu^-))$
 250 has a negligible effect on the number of leakage events, and no additional systematic
 251 uncertainty is assigned.

252 The systematic uncertainties affecting the yield ratio are taken into account when
 253 the branching fraction limits are calculated. The shapes of the signal peaks are taken
 254 from the $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ samples separately for each $m(\mu^+\mu^-)$ region to account for
 255 variations of the shape as a function of $m(\mu^+\mu^-)$. The impact of alternative shapes for the
 256 signal and misidentified $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ decays on the fitted yields and the final limit
 257 are investigated. The signal and misidentification background shapes in the signal regions
 258 are fitted using the shapes obtained in the ϕ region, and from $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ events
 259 reconstructed as $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$, but without any muon identification requirements.
 260 The change in the result is negligible.

261 The absolute branching fraction limit includes an extra uncertainty of 21% from the
 262 estimate of the branching fraction of the normalisation mode.

263 7 Results

264 The compatibility of the observed distribution of candidates with a signal plus background
 265 or background-only hypothesis is evaluated using the CL_s method [23, 24], which includes
 266 the treatment of systematic uncertainties. Upper limits on the non-resonant $D^0 \rightarrow$
 267 $\pi^+\pi^-\mu^+\mu^-$ to $D^0 \rightarrow \pi^+\pi^-\phi(\rightarrow \mu^+\mu^-)$ branching fraction ratio and on the absolute
 268 $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ branching fraction are determined using the observed distribution
 269 of CL_s as a function of the branching fraction in each $m(\mu^+\mu^-)$ search region. The
 270 extrapolation to the full $m(\mu^+\mu^-)$ phase space is performed assuming a four-body phase
 271 space model for $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ for which fractions in each $m(\mu^+\mu^-)$ region are quoted
 272 in Table 1. The observed distribution of CL_s as a function of the total branching fraction
 273 ratio for $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ is shown in Fig. 4. A similar distribution for the absolute

Table 2: Relative systematic uncertainties averaged over all the $m(\mu^+\mu^-)$ regions for the efficiency ratio.

Source	Uncertainty (%)
Trigger efficiency	5
Hadron identification	4
Reconstruction and selection efficiency	5
Muon identification	1
Finite simulation sample size	12–16
Total	15–18

274 branching fraction is shown in Fig. 5. The upper limits on the branching fraction ratio
 275 and absolute branching fraction at 90% and 95% CL and the p-values ($1 - \text{CL}_b$) for
 276 the background-only hypothesis are given in Table 3 and in Table 4. The p-values are
 277 computed for the branching fraction value at which $\text{CL}_{\text{s+b}}$ equals 0.5. Despite the smaller
 278 event yield for $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ relative to $D^0 \rightarrow \pi^+\pi^-\phi(\rightarrow \mu^+\mu^-)$, the upper limit on
 279 the total relative branching fraction is of order unity due to several factors. These are the
 280 low reconstruction and selection efficiency ratio in the signal region, the systematic and
 281 statistical uncertainties, and the extrapolation to the full $m(\mu^+\mu^-)$ range according to
 282 a phase-space model. It is noted that, while the results in individual $m(\mu^+\mu^-)$ regions
 283 naturally include possible contributions from $D^0 \rightarrow \rho(\rightarrow \pi^+\pi^-)\mu^+\mu^-$ since differences in
 284 the reconstruction and selection efficiency with respect to the four-body $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$
 285 are negligible, the extrapolation to the full $m(\mu^+\mu^-)$ phase-space depends on the four-
 286 body assumption. Distinguishing a ρ component in the dipion mass spectrum requires an
 287 amplitude analysis which would be hardly informative given the small sample size and
 288 beyond the scope of this first search.

289 Contributions for non-resonant $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ events in the normalisation mode

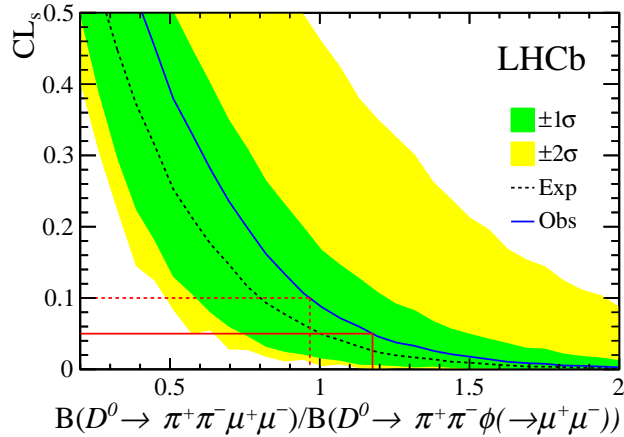


Figure 4: Observed (solid curve) and expected (dashed curve) CL_s values as a function of $\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-)/\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\phi(\rightarrow \mu^+\mu^-))$. The green (yellow) shaded area contains 68.3% and 95.5% of the results of the analysis on experiments simulated with no signal. The upper limits at the 90(95)% CL are indicated by the dashed (solid) line.

Table 3: Upper limits on $\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-)/\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\phi(\rightarrow \mu^+\mu^-))$ at 90 and 95% CL, and p-values for the background-only hypothesis in each $m(\mu^+\mu^-)$ region and in the full $m(\mu^+\mu^-)$ range (assuming a phase-space model).

Region	90%	95%	p-value
low- $m(\mu^+\mu^-)$	0.41	0.51	0.32
high- $m(\mu^+\mu^-)$	0.17	0.21	0.12
Total	0.96	1.19	0.25

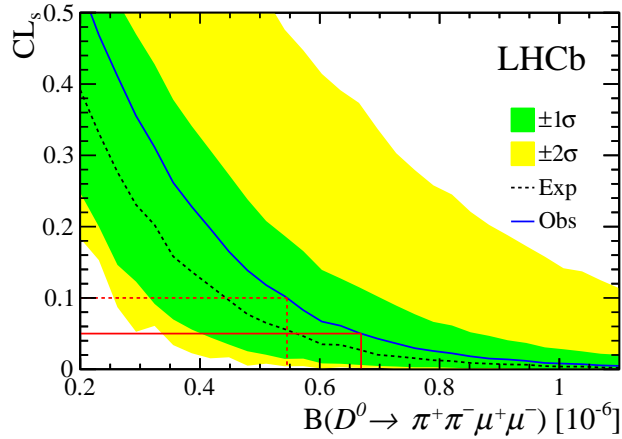


Figure 5: Observed (solid curve) and expected (dashed curve) CL_s values as a function of $\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-)$. The green (yellow) shaded area contains 68.3% and 95.5% of the results of the analysis on experiments simulated with no signal. The upper limits at the 90(95)% CL are indicated by the dashed (solid) line.

Table 4: Upper limits on $\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-)$ at 90 and 95% CL in each $m(\mu^+\mu^-)$ region and in the full $m(\mu^+\mu^-)$ range (assuming a phase-space model).

Region	90% [$\times 10^{-7}$]	95% [$\times 10^{-7}$]
low- $m(\mu^+\mu^-)$	2.3	2.9
high- $m(\mu^+\mu^-)$	1.0	1.2
Total	5.5	6.7

290 $m(\mu^+\mu^-)$ window are neglected in the upper limit calculations. Assuming a branching
 291 fraction equal to the 90% CL upper limit set in the highest $m(\mu^+\mu^-)$ region, the relative
 292 contribution of the non-resonant mode is estimated to be less than 3%, which is small
 293 compared with other uncertainties.

294 8 Conclusions

295 A search for the $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ decay is conducted using pp collision data, corresponding
 296 to an integrated luminosity of 1.0 fb^{-1} at $\sqrt{s} = 7 \text{ TeV}$ recorded by the LHCb experiment.
 297 The numbers of events in the non-resonant $m(\mu^+\mu^-)$ regions are compatible with the
 298 background-only hypothesis. The limits set on branching fractions in two $m(\mu^+\mu^-)$ bins
 299 and on the total branching fraction, excluding the resonant contributions and assuming a
 300 phase-space model, are

$$\frac{\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-)}{\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\phi(\rightarrow \mu^+\mu^-))} < 0.96 (1.19), \text{ at the 90 (95)\% CL,}$$

$$\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-) < 5.5 (6.7) \times 10^{-7}, \text{ at the 90 (95)\% CL.}$$

301 The upper limit on the absolute branching fraction is improved by a factor of 50 with
 302 respect to the previous search [5], yielding the most stringent result to date.

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