Observation of $B_s^0 \rightarrow \chi_{c1}\Phi$ decay and study of $B^0 \rightarrow \chi_{c1,2}K^{*0}$ decays

The LHCb collaboration

Abstract

The first observation of the decay $B_s^0 \rightarrow \chi_{c1}\Phi$ and a study of $B^0 \rightarrow \chi_{c1,2}K^{*0}$ decays are presented. The analysis is performed using a dataset, corresponding to an integrated luminosity of 1.0 fb$^{-1}$, collected by the LHCb experiment in pp collisions at a centre-of-mass energy of 7 TeV. The following ratios of branching fractions are measured:

\[
\frac{\mathcal{B}(B_s^0 \rightarrow \chi_{c1}\Phi)}{\mathcal{B}(B_s^0 \rightarrow J/\psi\Phi)} = (18.9 \pm 1.8 \text{ (stat)} \pm 1.3 \text{ (syst)} \pm 0.8 \text{ (B)}) \times 10^{-2},
\]

\[
\frac{\mathcal{B}(B^0 \rightarrow \chi_{c1}K^{*0})}{\mathcal{B}(B^0 \rightarrow J/\psi K^{*0})} = (19.8 \pm 1.1 \text{ (stat)} \pm 1.2 \text{ (syst)} \pm 0.9 \text{ (B)}) \times 10^{-2},
\]

\[
\frac{\mathcal{B}(B^0 \rightarrow \chi_{c2}K^{*0})}{\mathcal{B}(B^0 \rightarrow \chi_{c1}K^{*0})} = (17.1 \pm 5.0 \text{ (stat)} \pm 1.7 \text{ (syst)} \pm 1.1 \text{ (B)}) \times 10^{-2},
\]

where the third uncertainty is due to the limited knowledge of the branching fractions of $\chi_c \rightarrow J/\psi \gamma$ modes.

Submitted to Nucl. Phys. B

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

†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 Jr24,37, S. Amato2, S. Amoroso21, Y. Amhis7, L. Anderlini17,f, J. Anderson39, R. Andreassen56, J.E. Andrews57, R.B. Appleby53, O. Aquines Gutierrez16, F. Archilli18, A. Artamonov34, M. Artuso38, E. Aslanides6, G. Auriemma24,m, M. Baalouch5, S. Bachmann11, J.J. Baack47, C. Baesso59, V. Balagura30, W. Baldini16, R.J. Barlow53, C. Barschel37, S. Barsuk7, W. Barter46, Th. Bauser40, A. Bay48, J. Beddow50, F. Bedeschi22, I. Bediaga1, S. Belogurov30, K. Belous34, I. Belyaev30, E. Ben-Haim8, G. Bencivenni18, S. Benson49, J. Benton45, A. Berezinoy31, R. Bernet39, M.-O. Bettler49, M. van Beuzekom40, A. Bien11, S. Bifani44, T. Bird33, A. Bizzi17,h, P.M. Bjornstad53, T. Blake37, F. Blan638, J. Blow11, 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, I. Burducea28, A. Bursche39, G. Busetto21,h, J. Buitaert37, S. Cadeddu15, O. Caliot7, M. Calvi40, J. M. Calvo Gomez35,n, A. Camboni36, P. Campana18,37, D. Campora Perez37, A. Carboni14,c, G. Carboni23,k, R. Cardinale19,i, A. Cardini15, H. Carranza-Meija49, L. Carson52, K. Carvalho Akiba2, G. Casse51, L. Castillo Garcia37, M. Cattaneo37, Ch. Cauet9, R. Cenci37, M. Charles54, Ph. Charpentier37, P. Chen3,38, N. Chiapolini39, M. Chrzaszcz25, K. Ciba37, X. Cid Vital37, G. Ciezarek37, P.E.L. Clarke49, M. Clemente37, H.V. Cliff52, J. Closier37, C. Cocc25, V. Coco40, J. Cogan6, E. Comas39, P. Collins37, A. Comerma-Montells35, A. Contu15,37, A. Cook35, M. Coombes45, S. Coquereaux9, G. Corti37, B. Couturier37, G.A. Cowan49, D.C. Craig47, S. Cunliffe32, R. Currie49, C. D’Ambrosio37, P. David8, P.N.Y. David40, A. Davis36, I. De Bonis4, K. De Bruyn40, S. De Capua53, M. De Cian39, J.M. De Miranda1, L. De Paula2, W. De Silva56, P. De Simone18, D. Decamp4, M. Deckenhoff9, L. Del Buono8, N. Deléage5, D. Derkach54, O. Deschamps5, F. Dettori31, A. Di Canto11, F. Di Ruscio23,k, H. Dijkstra37, M. Dogaru28, S. Donleavy51, F. Dordei37, A. Dosil Suarez39, M. D’ Emidio37, A. Dosi Suárez36, D. Dossett47, A. Dovbnya32, F. Dupertuis38, R. Dzhelyadin34, A. Dziurdza29, A. Dzyuba29, S. Easo18,37, U. Egede52, V. Egorychev30, S. Eidelman33, D. van Eijk30, S. Eisenhardt49, U. Eitschberger9, R. Ekelhof9, L. Eklund50,37, I. El Rafai5, Ch. Elsasser29, D. Elsbury44, A. Falabella14,c, C. Färber11, G. Fardell49, C. Farinelli40, S. Farry51, V. Favero38, D. Ferguson51, V. Fernandez Albor36, F. Ferreira Rodrigues4, M. Ferro-Luzzi37, S. Filippov32, M. Fiore16, C. Fitzpatrick37, M. Fontana10, F. Fontanelli19,i, R. Forty37, O. Francisco3, M. Frank37, C. Frei37, M. Frösini17,f, S. Furcas20, E. Furfaro23,k, A. Gallas Torreira36, D. Galli14,c, M. Gandelmann2, P. Gandin58, Y. Gao9, J. Garofoli58, P. Garosi53, J. Garra Tico46, L. Garrido35, C. Gaspar47, R. Gauld54, E. Gersabeck11, M. Gersabeck53, T. Gershon17,37, Ph. Gheza4, V. Gibson46, L. Giubega28, V.V. Gilgorov37, C. Göbel59, D. Golubkov90, A. Golutvin52,30,37, A. Gomes2, H. Gordon54, M. Grabalosa Gándara5, R. Graciani Diaz35, L.A. Granado Cardoso37, E. Graugés35, G. Graziani17, A. Green18, E. Greening54, S. Gregson46, P. Griffith44, O. Grünberg60, B. Gui58, E. Gushchin32, Yu. Guz34,37, T. Gys37, C. Hadjivasiliou58, G. Haefeli38, C. Haen37, S.C. Haines46, S. Hall52, B. Hamilton37, T. Hampson45, S. Hansmann-Menzemer11, N. Harnew54, S.T. Harnew55, J. Harrison53, T. Hartmann40, J. He37, T. Head37, V. Heijne40, K. Hennessy51, P. Henrard5, J.A. Hernando Morata36, E. van Herwijnen37, A. Hicheur1, E. Hicks31, D. Hill54, M. Hoballah8, M. Holtrop40, C. Hombach53, P. Hopchev4, W. Hulsenberg40, P. Hunt54, T. Huse51, N. Hussain54, D. Hutchcroft51, D. Hynds50, V. Iakovenko43, M. Idzik26, P. Ilten12,
F.J.P. Soler50, F. Soomro18, D. Souza45, B. Souza De Paula2, B. Spaan9, A. Sparkes49, P. Spradlin50, F. Stagni37, S. Stahl11, O. Steinkamp39, S. Stoca28, S. Stone38, B. Storaci39, M. Straticiuc28, U. Straumann39, V.K. Subbiah37, L. Sun56, S. Swientek9, V. Syropoulos41, M. Szczekowski27, P. Szczypka38, T. Szumlak26, S. T’Jampens4, M. Teklishyn7, E. Teodoresci28, F. Teubert37, C. Thomas54, E. Thomas37, J. van Tilburg11, V. Tisserand4, M. Tobin38, S. Tolk41, D. Tonelli37, S. Topp-joergensen54, N. Torr54, E. Tournefier4,52, S. Tourneur36, M.T. Tran38, M. Tresch39, A. Tsaregorodtsev6, P. Tsopelas40, N. Tuning40, M. Ubeda Garcia37, A. Ukleja27, D. Urner53, A. Ustyuzhanin52, p, U. Uwer11, V. Vagnoni14, G. Valenti14, A. Vallier7, M. Van Dijk45, R. Vazquez Gomez18, P. Vazquez Regueiro36, C. Vázquez Sierra36, S. Vecchi16, J.J. Velthuis45, M. Veltri17, g, G. Veneziano38, M. Vesterinen37, B. Viaud7, D. Vieira2, X. Vilasis-cardona35, n, A. Vollhardt39, D. Volyanskyy10, D. Voong45, A. Vorobyev29, V. Vorobyev33, C. Vol60, H. Voss10, R. Waldis0, C. Wallace47, R. Wallace12, S. Wandernoth11, J. Wang38, D.R. Ward46, N.K. Watson44, A.D. Webber53, D. Websdale52, M. Whitehead17, J. Wicht37, J. Wiechczynski25, D. Wiedner11, L. Wiggers40, G. Wilkinson54, M.P. Williams47,48, M. Williams55, F.F. Wilson48, J. Wimberley57, J. Wishahi9, M. Witek25, S.A. Wotton46, S. Wright46, S. Wu3, K. Wyllie37, Y. Xie49,37, Z. Xing56, Z. Yang5, R. Young49, X. Yuan3, O. Yushchenko34, M. Zangoli14, M. Zavertyaev9, a, F. Zhang3, L. Zhang58, W.C. Zhang12, Y. Zhang3, A. Zhelezov41, A. Zhokhov4, Z. Xing9, L. Zhang25, A. Zhovtibol30, L. Zhong3, Z. Zhovtibol25, F. Zhang3, Z. Zhovtibol30, 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 Pontificia 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

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 LIFAELS, 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

Two-body B-meson decays into a final states containing charmonium meson have played a crucial role in the observation of CP violation in the B-meson system. These decay modes also provide a sensitive laboratory for studying the effects of the strong interaction. Such decays are expected to proceed predominantly via the colour-suppressed tree diagram involving $\bar{b} \to c\bar{s}$ transition shown in Fig. 1. Under the factorization hypothesis the branching ratios of the $B^0(s) \to \chi_{c0,2}X$ decays, where $X$ denotes a $K^{*0}$ or a $\phi$ meson, are expected to be small in comparison to $B^0(s) \to \chi_{c1}X$ decays \cite{1}. However, non-factorizable contributions may be large \cite{1}; the branching fraction for the $B^0 \to \chi_{c0}K^{*0}$ decay was measured by the BaBar collaboration to be $(1.7 \pm 0.3 \pm 0.2) \times 10^{-4}$ \cite{2} while the branching fraction for the $B^0 \to \chi_{c1}K^{*0}$ decay was measured by the BaBar and Belle collaborations to be $(2.5 \pm 0.2 \pm 0.2) \times 10^{-4}$ \cite{3} and $(1.73^{+0.15+0.34}_{-0.12-0.22}) \times 10^{-4}$ \cite{4}, respectively. The branching fraction for the decay $B^0 \to \chi_{c2}K^{*0}$ has been measured by the BaBar collaboration to be $(6.6 \pm 1.8 \pm 0.5) \times 10^{-5}$ \cite{3} and, unlike the branching fraction for the $B^0 \to \chi_{c0}K^{*0}$ decay, can still be explained in the factorization approach \cite{5}. Therefore, future measurements of the branching fractions of both $B^0 \to \chi_{c1}K^{*0}$ and $B^0 \to \chi_{c2}K^{*0}$ decays can provide valuable information for the understanding of the production of $\chi_c$ states in B meson decays, where $\chi_c$ denotes $\chi_{c1}$ and $\chi_{c2}$ states. The decay modes $B^0(s) \to \chi_c\phi$ have not been observed previously.

Figure 1: Leading-order tree level diagram for the $B^0(s) \to \chi_cX$ decays.

In this paper, the first observation of the decay $B^0(s) \to \chi_{c1}\phi$ and a study of the $B^0 \to \chi_{c1,2}K^{*0}$ decays are presented. The analysis is based on a data sample, corresponding to an integrated luminosity of 1.0 fb$^{-1}$, collected with the LHCb detector in pp collisions at a centre-of-mass energy of 7 TeV.

2 LHCb detector

The LHCb detector \cite{6} 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 detector includes a high precision tracking system consisting of a silicon-strip vertex detector surrounding the pp interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip
detectors and straw drift tubes placed downstream. The combined tracking system has
momentum resolution \( \Delta p/p \) that varies from 0.4% at 5 GeV/c to 0.6% at 100 GeV/c, and
impact parameter resolution of 20 \( \mu m \) for tracks with high transverse momentum \( (p_T) \).
Charged hadrons are identified using two ring-imaging Cherenkov detectors [7]. Photon,
electron and hadron candidates are identified by a calorimeter system consisting of
scintillating-pad and preshower detectors, an electromagnetic calorimeter and a hadronic
calorimeter. Muons are identified by a system composed of alternating layers of iron and
multiwire proportional chambers [8].

The trigger [9] consists of a hardware stage, based on information from the calorimeter
and muon systems, followed by a software stage where a full event reconstruction is applied.
Candidate events are first required to pass a hardware trigger which selects muons with
\( p_T > 1.48 \) GeV/c. In the subsequent software trigger, at least one of the muons is required
to have both \( p_T > 0.8 \) GeV/c and impact parameter larger than 100 \( \mu m \) with respect to
all of the primary pp interaction vertices (PVs) in the event. Finally, the two final state
muons are required to form a vertex that is significantly displaced from the PVs.

The analysis technique reported below has been validated using simulated events. The
pp collisions are generated using PYTHIA 6.4 [10] with a specific LHCb configuration [11].
Decays of hadronic particles are described by EVTGEN [12] in which final state radiation
is generated using PHOTOS [13]. The interaction of the generated particles with the
detector and its response are implemented using the GEANT4 toolkit [14,15] as described
in Ref. [16].

3 Event selection

The decays \( B^0 \to \chi_c K^*0 \) and \( B^0_s \to \chi_c \phi \) (the inclusion of charged conjugate processes is
implied throughout) are reconstructed using the \( \chi_c \to J/\psi \gamma \) decay mode. The decays
\( B^0 \to J/\psi K^*0 \) and \( B^0_s \to J/\psi \phi \) are used as normalization channels. The intermediate
resonances are reconstructed in the \( J/\psi \to \mu^+\mu^- \), \( K^*0 \to K^+\pi^- \) and \( \phi \to K^+K^- \) final
states.

As in Refs. [17 –19], pairs of oppositely-charged tracks identified as muons, each having
\( p_T > 0.55 \) GeV/c and originating from a common vertex, are combined to form \( J/\psi \to \mu^+\mu^- \)
candidates. Track quality is ensured by requiring the \( \chi^2 \) per number of degrees of freedom
(\( \chi^2/\text{ndf} \)) provided by the track fit to be less than 5. Well identified muons are selected by
requiring that the difference in logarithms of the likelihood of the muon hypothesis with
respect to the hadron hypothesis is larger than zero [8]. The fit of the common two-prong
vertex is required to satisfy \( \chi^2/\text{ndf} < 20 \). The vertex is required to be well separated
from the reconstructed primary vertex of any of the pp interactions by requiring the decay
length to be at least three times its uncertainty. Finally, the invariant mass of the dimuon
combination is required to be between 3.020 and 3.135 GeV/c^2.

To create \( \chi_c \) candidates, the selected \( J/\psi \) candidates are combined with a photon
that has been reconstructed using clusters in the electromagnetic calorimeter that have
transverse energy greater than 0.7 GeV. To suppress the large combinatorial background
from $\pi^0 \rightarrow \gamma\gamma$ decays, photons that can form part of a $\pi^0 \rightarrow \gamma\gamma$ candidate with invariant mass within 10 MeV/$c^2$ of the known $\pi^0$ mass [20] are not used for reconstruction of $\chi_c$ candidates. To be considered as a $\chi_c$, the J/$\psi\gamma$ combination needs to have a transverse momentum larger than 3 GeV/$c$ and an invariant mass in the range 3.4 – 3.7 GeV/$c^2$.

The selected $\chi_c$ and J/$\psi$ candidates are then combined with $K^+\pi^-$ or $K^+K^-$ pairs to create $B^0(s)$ meson candidates. To identify kaons (pions), the difference in logarithm of the likelihood of the kaon and pion hypotheses [7] is required to be greater than (less than) zero. The track $\chi^2/ndf$ provided by the track fit is required to be less than 5. The kaons and pions are required to have transverse momentum larger than 0.8 GeV/$c$ and to have an impact parameter $\chi^2$, defined as the difference between the $\chi^2$ of the reconstructed pp collision vertex formed with and without the considered track, larger than 4. The invariant mass of the kaon and pion system, $M_{K^+\pi^-}$, is required to be 0.675 < $M_{K^+\pi^-}$ < 1.215 GeV/$c^2$ and the invariant mass of the kaon pair, $M_{K^+K^-}$, is required to be 0.999 < $M_{K^+K^-}$ < 1.051 GeV/$c^2$.

In the reconstruction of $K^{*0}$ candidates, a possible background arises from $\phi \rightarrow K^+K^-$ decays when a kaon is misidentified as a pion. To suppress this contribution, the invariant mass of the kaon and pion system, calculated under the kaon mass hypothesis for the pion track, is required to be outside the range from 1.01 to 1.03 GeV/$c^2$.

In addition, the decay time of B candidates is required to be larger than 150 $\mu$m/$c$ to reduce the large combinatorial background from particles produced in the primary pp interaction. To improve the invariant mass resolution of the $B^0(s)$ meson candidate a kinematic fit [21] is performed. In this fit, constraints are applied to the masses of the intermediate $J/\psi$ and $\chi_c$ resonances [20] and it is also required that the $B^0(s)$ meson candidate momentum vector points to the primary vertex. The $\chi^2/ndf$ for this fit is required to be less than 5.

4 $B^0 \rightarrow \chi_c K^{*0}$ and $B^0_s \rightarrow \chi_{c1} \phi$ decays

The invariant mass distributions after selecting $B^0 \rightarrow \chi_c K^{*0}$ and $B^0_s \rightarrow \chi_{c1} \phi$ candidates, separately with a $\chi_{c1}$ and $\chi_{c2}$ mass constraints, are shown in Fig. 2. The signal is modelled by a single Gaussian function and the combinatorial background is modelled by an exponential function. In the $B^0$ channel (Figs. 2(a) and (c)), the right peak in the mass distributions corresponds to the $\chi_{c1}$ mode and the left one to the $\chi_{c2}$ mode. Owing to the small $\chi_{c0} \rightarrow J/\psi\gamma$ branching fraction [20] the contribution from the $\chi_{c0}$ mode is negligible. As the $B^0$ candidate mass is calculated with the J/$\psi\gamma$ invariant mass constrained to the $\chi_{c1}$ ($\chi_{c2}$) known mass, the signal peak corresponding to the $\chi_{c2}$ ($\chi_{c1}$) mode is shifted to a lower (higher) value with respect to the $B^0$ mass. The same effect is observed in simulation. The ratio of the mass resolutions of these two signal peaks is fixed to the value obtained from simulation. In the $B^0_s$ channel no significant contribution from the $\chi_{c2}$ decay mode is expected and therefore it is not considered in the fit. The statistical significance for the observed signal is determined as $S = \sqrt{-2 \ln \frac{L_B}{L_{S+B}}}$, where $L_{S+B}$ and $L_B$ denote the likelihood of the signal plus background hypothesis and the background only hypothesis, respectively. The statistical significance of the $B^0_s \rightarrow \chi_{c1} \phi$ signal is found to be larger than
Figure 2: Invariant mass distributions for: (a) $B^0 \rightarrow \chi_c K^{*0}$ and (b) $B^0_s \rightarrow \chi_{c1} \phi$ candidates with $\chi_{c1}$ mass constraint; (c) $B^0 \rightarrow \chi_c K^{*0}$ and (d) $B^0 \rightarrow \chi_{c1} \phi$ candidates with $\chi_{c2}$ mass constraint. The total fitted function (thick solid blue), signal for the $\chi_{c1}$ and $\chi_{c2}$ modes (thin green solid and dotted, respectively) and the combinatorial background (dashed blue) are shown.

9 standard deviations.

The positions and resolutions of the signal peaks are consistent with the expectations from simulation. To investigate the different signal yields obtained with the $\chi_{c1}$ and $\chi_{c2}$ mass constraints, a simplified simulation study was performed, which accounts for correlations, differences in selection efficiencies and background fluctuations. This study demonstrates that the yields are in agreement within the statistical uncertainty.

To examine the resonance structure of the $B^0 \rightarrow \chi_c K^{*0}$ and $B^0_s \rightarrow \chi_{c1} \phi$ decays, the $sPlot$ technique [22] was used with weights determined from the $B^0_s$ candidate invariant mass fits described above. The invariant mass distributions for each signal component are obtained. For the $J/\psi \gamma$ invariant mass distributions the requirement on the invariant mass of the $K^+ \pi^-$ ($K^+ K^-$) system is tightened to be within 50(10) MeV/$c^2$ around the known $K^{*0}(\phi)$ mass to reduce background.

The resulting invariant mass distributions for $J/\psi \gamma$, $K^+ \pi^-$ and $K^+ K^-$ from $B^0 \rightarrow \chi_c K^{*0}$ and $B^0_s \rightarrow \chi_{c1} \phi$ candidates are shown in Fig. 3. The $J/\psi \gamma$ invariant mass distributions are modelled with the sum of a constant and a Crystal Ball function [23] with tail parameters fixed to simulation. In the $\chi_{c2}$ mode the signal peak position is fixed to the sum of the $\chi_{c1}$ peak position and the known difference between $\chi_{c1}$ and $\chi_{c2}$ masses [20]. The $\chi_{c2}$ mass resolution is fixed to the $\chi_{c1}$ mass resolution multiplied by a scale factor determined using simulation. The $K^+ \pi^-$ and $K^+ K^-$ invariant mass distributions are modelled with the sum of a relativistic P-wave Breit-Wigner function with the natural width fixed to the known value [20] and a non-resonant component modelled with the LASS parametrization [24].
Figure 3: Background-subtracted invariant mass distributions for: (a) J/ψγ and (b) K⁺π⁻ final states from B⁰ → χc1K⁺⁰⁰ decays obtained with the χc1 mass constraint applied to the B⁰(s) candidate invariant mass; (c) J/ψγ and (d) K⁺π⁻ final states from B⁰ → χc2K⁺⁰⁰ decays obtained with the χc2 mass constraint applied to the B⁰(s) candidate invariant mass; (e) J/ψγ and (f) K⁺K⁻ final states from B⁰(s) → χc1Φ decays obtained with the χc1 mass constraint applied to the B⁰(s) candidate invariant mass. The total fitted function (solid) and the non-resonant contribution (dotted) are shown.

For the K⁺K⁻ case the relativistic P-wave Breit-Wigner function is convolved with a Gaussian function for the detector resolution.

The signal peak positions are consistent with the known masses of the mesons while the invariant mass resolutions are consistent with the expectation from simulation. In the J/ψγ invariant mass distributions, the non-resonant contribution is consistent with zero.
The resonant contributions for the $B^0 \rightarrow \chi_{c1} K^{*0}$ and $B^0_s \rightarrow \chi_{c1} \phi$ decays are determined with the $\chi_{c1}$ mass constraint while the resonant contribution for the $B^0 \rightarrow \chi_{c2} K^{*0}$ decay is determined with the $\chi_{c2}$ mass constraint. The resulting resonant yields, obtained from the fits to the background-subtracted $K^+ \pi^-$ and $K^+ K^-$ distributions, are shown in Table 1.

### Table 1: Signal yields for the B decays.

| Decay               | Yield            |
|---------------------|------------------|
| $B^0 \rightarrow \chi_{c1} K^{*0}$ | $566 \pm 31$    |
| $B^0 \rightarrow \chi_{c2} K^{*0}$ | $66 \pm 19$     |
| $B^0_s \rightarrow \chi_{c1} \phi$ | $146 \pm 14$    |
| $B^0 \rightarrow J/\psi K^{*0}$   | $56,707 \pm 279$|
| $B^0_s \rightarrow J/\psi \phi$  | $15,027 \pm 139$|
The resonant contributions in the $B^0 \rightarrow J/\psi K^{*0}$ and $B^0_s \rightarrow J/\psi \phi$ decays are determined using the sPlot technique with the same method as that used for the $B^0 \rightarrow \chi_c K^{*0}$ and $B^0_s \rightarrow \chi_c \phi$ decays. The resulting $K^+\pi^-$ and $K^+K^-$ invariant mass distributions from $B^0 \rightarrow J/\psi K^{*0}$ and $B^0_s \rightarrow J/\psi \phi$ candidates are shown in Fig. 5. The resulting resonant yields are summarized in Table 1. The S-wave contributions are consistent with those considered in other analyses [17,25,26].

6 Efficiencies and systematic uncertainties

The branching fraction ratios are calculated using the formulas

$$\frac{\mathcal{B}(B \rightarrow \chi_{c1} X)}{\mathcal{B}(B \rightarrow J/\psi X)} = \frac{N_{B \rightarrow \chi_{c1} X}}{N_{B \rightarrow J/\psi X}} \times \frac{\varepsilon_{B \rightarrow J/\psi X}}{\varepsilon_{B \rightarrow \chi_{c1} X}} \times \frac{1}{\mathcal{B}(\chi_{c1} \rightarrow J/\psi \gamma)} ,$$

$$\frac{\mathcal{B}(B \rightarrow \chi_{c2} X)}{\mathcal{B}(B \rightarrow \chi_{c1} X)} = \frac{N_{B \rightarrow \chi_{c2} X}}{N_{B \rightarrow \chi_{c1} X}} \times \frac{\varepsilon_{B \rightarrow \chi_{c1} X}}{\varepsilon_{B \rightarrow \chi_{c2} X}} \times \frac{\mathcal{B}(\chi_{c1} \rightarrow J/\psi \gamma)}{\mathcal{B}(\chi_{c2} \rightarrow J/\psi \gamma)} ,$$

where $N$ represents the measured yield and $\varepsilon$ represents the total efficiency. The total efficiency is the product of the geometrical acceptance, the detection, reconstruction, selection and trigger efficiencies. The efficiencies are derived using simulation and are presented in Table 2.

Most potential sources of systematic uncertainty cancel in the ratio, in particular, those related to the muon and $J/\psi$ reconstruction and identification. The remaining systematic uncertainties are summarized in Table 3 and each is now discussed in turn.

Systematic uncertainties related to the signal determination procedure are estimated using a number of alternative options. For each of the alternatives the ratio of event yields is calculated and the systematic uncertainty is then determined as the maximum deviation of this ratio from the ratio obtained with the baseline model. For the $B^0_s$ meson decays a fit with a second-order polynomial for the combinatorial background description, a fit with
a Crystal Ball \cite{23} function for the signal peaks and fit over different ranges of invariant mass are used. In the B_{0}^{s} channel a fit including the χ_{c2} decay mode is also performed. For the K^{+}\pi^{-} and K^{+}K^{-} combinations the fits are repeated, modelling the background with an S-wave two-body phase-space function or an S-wave two-body phase-space function multiplied by a linear function. The K^{+}\pi^{-} and K^{+}K^{-} invariant mass ranges and the bin size are also varied. The resulting uncertainties are 3\% on \frac{B(B_{0}^{0} \rightarrow χ_{c1}K^{*0})}{B(B_{0}^{0} \rightarrow J/ψK^{*0})}, 5\% on \frac{B(B_{0}^{s} \rightarrow χ_{c1}\phi)}{B(B_{0}^{0} \rightarrow J/ψ\phi)}, and 9\% on \frac{B(B_{0}^{0} \rightarrow χ_{c2}K^{*0})}{B(B_{0}^{0} \rightarrow χ_{c1}K^{*0})}.

Another important source of systematic uncertainty arises from the potential disagreement between data and simulation in the estimation of efficiencies. To study this source of uncertainty, the selection criteria are varied in ranges corresponding to as much as 30\% change in the signal yields and the ratios of the selection and reconstruction efficiencies are compared between data and simulation. The largest difference (3\%) is assigned as a systematic uncertainty in each mode.

A further source of possible disagreement between data and simulation is the photon reconstruction efficiency. As in Ref. \cite{18}, the photon reconstruction efficiency has been studied using B^{+} \rightarrow J/ψK^{+}, followed by K^{*+} \rightarrow K^{+}\pi^{0} and π^{0} \rightarrow γγ decays. For photons with transverse momentum greater than 0.7 GeV/c the agreement between data and simulation is at the level of 4\%, which is assigned as a systematic uncertainty to the ratios \frac{B(B^{0} \rightarrow χ_{c1}K^{*0})}{B(B^{0} \rightarrow J/ψK^{*0})} and \frac{B(B_{0}^{s} \rightarrow χ_{c1}\phi)}{B(B_{0}^{0} \rightarrow J/ψ\phi)}. As the transverse momentum spectra of photons are similar in B^{0} \rightarrow χ_{c1}K^{*0} and B^{0} \rightarrow χ_{c2}K^{*0} decays, this systematic uncertainty cancels in the ratio \frac{B(B^{0} \rightarrow χ_{c2}K^{*0})}{B(B^{0} \rightarrow χ_{c1}K^{*0})}.

The systematic uncertainty related to the trigger efficiency has been obtained by comparing the trigger efficiency ratios in data and simulation for the high yield decay modes B^{+} \rightarrow J/ψK^{+} and B^{+} \rightarrow ψ(2S)K^{+} which have similar kinematics and the same trigger requirements as the channels under study in this analysis \cite{17}. An agreement within 1\% is found, which is assigned as systematic uncertainty.

The uncertainty due to the finite simulation sample size is included in the statistical uncertainty of the result by adding it in quadrature to the statistical uncertainty on the ratio of yields.

Table 2: Total efficiencies for all decay modes. Uncertainties are statistical only and reflect the size of the simulation sample.

| Decay                  | Efficiency [10^{-4}] |
|------------------------|-----------------------|
| B^{0} \rightarrow χ_{c1}K^{*0} | 7.89 ± 0.12          |
| B^{0} \rightarrow χ_{c2}K^{*0} | 9.45 ± 0.13          |
| B^{0} \rightarrow χ_{c1}\phi    | 12.7 ± 0.2           |
| B^{0} \rightarrow J/ψK^{*0}     | 53.9 ± 0.3           |
| B_{0}^{s} \rightarrow J/ψ\phi   | 85.1 ± 0.4           |
where the third uncertainty corresponds to the uncertainty on the branching fraction of the $B^0 \rightarrow J/\psi \phi$ decay and using the known value $\mathcal{B}(X_{c1} \rightarrow J/\psi \gamma) = (34.4 \pm 1.5\% \, [20]$), is measured to be

$$\frac{\mathcal{B}(B^0 \rightarrow X_{c1}\phi)}{\mathcal{B}(B^0 \rightarrow J/\psi \phi)} = (6.51 \pm 0.64 \, \text{(stat)} \pm 0.46 \, \text{(syst)}) \times 10^{-2} \times \frac{1}{\mathcal{B}(X_{c1} \rightarrow J/\psi \gamma)} = (18.9 \pm 1.8 \, \text{(stat)} \pm 1.3 \, \text{(syst)} \pm 0.8 \, \text{(B)}) \times 10^{-2},$$

where the third uncertainty corresponds to the uncertainty on the branching fraction of the $X_{c1} \rightarrow J/\psi \gamma$ decay. Using the same dataset, the ratio of the branching fractions of the $B^0 \rightarrow X_{c1}K^{*0}$ and $B^0 \rightarrow J/\psi K^{*0}$ modes and the ratio of the branching fractions of the $B^0 \rightarrow X_{c2}K^{*0}$ and $B^0 \rightarrow X_{c1}K^{*0}$ modes have been measured. The ratios are determined using Eq. 1 and the known value $\frac{\mathcal{B}(X_{c1} \rightarrow J/\psi \gamma)}{\mathcal{B}(X_{c2} \rightarrow J/\psi \gamma)} = (34.4\pm1.5\%) \, (19.5\pm0.8\%) = 1.76 \pm 0.11 \, [20]$ and are

$$\frac{\mathcal{B}(B^0 \rightarrow X_{c1}K^{*0})}{\mathcal{B}(B^0 \rightarrow J/\psi K^{*0})} = (6.82 \pm 0.39 \, \text{(stat)} \pm 0.41 \, \text{(syst)}) \times 10^{-2} \times \frac{1}{\mathcal{B}(X_{c1} \rightarrow J/\psi \gamma)} = (19.8 \pm 1.1 \, \text{(stat)} \pm 1.2 \, \text{(syst)} \pm 0.9 \, \text{(B)}) \times 10^{-2},$$

$$\frac{\mathcal{B}(B^0 \rightarrow X_{c2}K^{*0})}{\mathcal{B}(B^0 \rightarrow X_{c1}K^{*0})} = (9.74 \pm 2.86 \, \text{(stat)} \pm 0.97 \, \text{(syst)}) \times 10^{-2} \times \frac{\mathcal{B}(X_{c1} \rightarrow J/\psi \gamma)}{\mathcal{B}(X_{c2} \rightarrow J/\psi \gamma)} = (17.1 \pm 5.0 \, \text{(stat)} \pm 1.7 \, \text{(syst)} \pm 1.1 \, \text{(B)}) \times 10^{-2},$$

where the third uncertainty is due to the uncertainty on the branching fractions of the $X_{c} \rightarrow J/\psi \gamma$ modes.

The ratio $\mathcal{B}(B^0 \rightarrow X_{c1}K^{*0})/\mathcal{B}(B^0 \rightarrow J/\psi K^{*0})$ obtained in this paper is compatible with, but more precise than, the previous best value of $(17.2^{+3.6}_{-3.0}) \times 10^{-2}$ determined from the world average value $\mathcal{B}(B^0 \rightarrow X_{c1}K^{*0}) = (2.22^{+0.40}_{-0.31}) \times 10^{-4}$ [20] and the branching fraction $\mathcal{B}(B^0 \rightarrow J/\psi K^{*0}) = (1.29 \pm 0.05 \pm 0.13) \times 10^{-3}$ measured by the Belle collaboration [27].
Other measurements of $B(B^0 \to J/\psi K^{*0})$ are not considered as they do not take into account the $K^+\pi^-$ S-wave component. The ratio $B(B^0 \to \chi_{c2} K^{*0})/B(B^0 \to \chi_{c1} K^{*0})$ obtained in this paper is compatible with the value derived from BaBar measurements, $(26 \pm 7\,\text{stat}) \times 10^{-2}$ [3], taking only the statistical uncertainties into account.

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); ANCS/IFA (Romania); MinES, Rosatom, RFBR and NRC “Kurchatov Institute” (Russia); MinECo, XuntaGal and GENCAT (Spain); SNSF and SER (Switzerland); NAS Ukraine (Ukraine); STFC (United Kingdom); NSF (USA). We also acknowledge the support received from 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 thankful for the computing resources put at our disposal by Yandex LLC (Russia), as well as to the communities behind the multiple open source software packages that we depend on.

References

[1] C. Meng, Y.-J. Gao, and K.-T. Chao, Puzzles in $B \to h_c(\chi_{c2})K$ decays and QCD factorization, arXiv:hep-ph/0607221.

[2] BaBar collaboration, B. Aubert et al., Observation of $B^0 \to \chi_{c0} K^{*0}$ and evidence for $B^+ \to \chi_{c0} K^{*+}$, Phys. Rev. D78 (2008) 091101, arXiv:0808.1487.

[3] BaBar collaboration, B. Aubert et al., Evidence for $X(3872) \to \psi(2S)\gamma$ in $B^\pm \to X(3872)K^\mp$ decays, and a study of $B \to c\bar{c}\gamma K$, Phys. Rev. Lett. 102 (2009) 132001, arXiv:0809.0042.

[4] Belle collaboration, R. Mizuk et al., Observation of two resonance-like structures in the $\pi^+ \chi_{c1}$ mass distribution in exclusive $B^0 \to K^- \pi^+ \chi_{c1}$ decays, Phys. Rev. D78 (2008) 072004, arXiv:0806.4098.

[5] M. Beneke and L. Vernazza, $B \to \chi_{c3} K$ decays revisited, Nucl. Phys. B811 (2009) 155, arXiv:0810.3575.

[6] LHCb collaboration, A. A. Alves et al., The LHCb detector at the LHC, JINST 3 (2008) S08005.
[7] M. Adinolfi et al., *Performance of the LHCb RICH detector at the LHC*, Eur. Phys. J. C73 (2013) 2431, arXiv:1211.6759.

[8] A. A. Alves et al., *Performance of the LHCb muon system*, JINST 8 (2013) P02022, arXiv:1211.1346.

[9] R. Aaij et al., *The LHCb trigger and its performance in 2011*, JINST 8 (2013) P04022, arXiv:1211.3055.

[10] T. Sjöstrand, S. Mrenna, and P. Skands, *PYTHIA 6.4 physics and manual*, JHEP 05 (2006) 026, arXiv:hep-ph/0603175.

[11] I. Belyaev et al., *Handling of the generation of primary events in GAUSS, the LHCb simulation framework*, Nuclear Science Symposium Conference Record (NSS/MIC) IEEE (2010) 1155.

[12] D. J. Lange, *The EvtGen particle decay simulation package*, Nucl. Instrum. Meth. A462 (2001) 152.

[13] P. Golonka and Z. Was, *PHOTOS Monte Carlo: a precision tool for QED corrections in Z and W decays*, Eur. Phys. J. C45 (2006) 97, arXiv:hep-ph/0506026.

[14] GEANT4 collaboration, S. Agostinelli et al., *GEANT4: A simulation toolkit*, Nucl. Instrum. Meth. A506 (2003) 250.

[15] GEANT4 collaboration, J. Allison et al., *GEANT4 developments and applications*, IEEE Trans. Nucl. Sci. 53 (2006) 270.

[16] M. Clemencic et al., *The LHCb simulation application, GAUSS: design, evolution and experience*, J. Phys.: Conf. Ser. 331 (2011) 032023.

[17] LHCb collaboration, R. Aaij et al., *Measurement of relative branching fractions of B decays to ψ(2S) and J/ψ mesons*, Eur. Phys. J C72 (2012) 2118, arXiv:1205.0918.

[18] LHCb collaboration, R. Aaij et al., *Evidence for the decay B^0_s → J/ψω and measurement of the relative branching fractions of B^0_s meson decays to J/ψη and J/ψη'*, Nucl. Phys. B867 (2013) 547, arXiv:1210.2631.

[19] LHCb collaboration, R. Aaij et al., *Observation of the B^0_s → ψ(2S)η and B^0_s → ψ(2S)π^+π^- decays*, Nucl. Phys. B871 (2013) 403, arXiv:1302.6354.

[20] Particle Data Group, J. Beringer et al., *Review of particle physics*, Phys. Rev. D86 (2012) 010001.

[21] W. D. Hulsbergen, *Decay chain fitting with a Kalman filter*, Nucl. Instrum. Meth. A552 (2005) 566, arXiv:physics/0503191.
[22] M. Pivk and F. R. Le Diberder, *sPlot: a statistical tool to unfold data distributions*, Nucl. Instrum. Meth. **A555** (2005) 356, [arXiv:physics/0402083](http://arxiv.org/abs/physics/0402083).

[23] T. Skwarnicki, *A study of the radiative cascade transitions between the Upsilon-prime and Upsilon resonances*, PhD thesis, Institute of Nuclear Physics, Krakow, 1986, [DESY-F31-86-02](http://www.desy.de/)

[24] D. Aston *et al.*, *A study of K−π+ scattering in the reaction K−π+ → K−π+n at 11 GeV/c*, Nucl. Phys. **B296** (1988) 493.

[25] LHCb collaboration, R. Aaij *et al.*, *Measurement of the B0s → J/ψK∗0 branching fraction and angular amplitudes*, Phys. Rev. **D86** (2012) 071102, [arXiv:1208.0738](http://arxiv.org/abs/1208.0738).

[26] LHCb collaboration, R. Aaij *et al.*, *Measurement of CP violation and the B0s-meson decay width difference with B0s → J/ψK+K− and B0s → J/ψπ+π− decays*, to appear in Phys. Rev. D (2013) [arXiv:1304.2600](http://arxiv.org/abs/1304.2600).

[27] Belle collaboration, K. Abe *et al.*, *Measurements of branching fractions and decay amplitudes in B → J/ψK+ decays*, Phys. Lett. **B538** (2002) 11, [arXiv:hep-ex/0205021](http://arxiv.org/abs/hep-ex/0205021).