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Observation of Five New Narrow $\Omega_c^0$ States Decaying to $\Xi_c^+K^-$

R. Aaij et al.∗
(LHCb Collaboration)
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The $\Xi_c^+K^-$ mass spectrum is studied with a sample of $pp$ collision data corresponding to an integrated luminosity of 3.3 fb$^{-1}$, collected by the LHCb experiment. The $\Xi_c^+$ is reconstructed in the decay mode $pK^-\pi^+$. Five new, narrow excited $\Omega_c^0$ states are observed: the $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$. Measurements of their masses and widths are reported.

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The spectroscopy of singly charmed baryons is intricate. With three quarks and numerous degrees of freedom, many states are expected. At the same time, the large mass difference between the charm quark and the light quarks provides a natural way to understand the spectrum by using the symmetries provided by the heavy quark effective theory (HQET) [1,2]. In recent years, considerable improvements have been made in the predictions of the properties of these heavy baryons [3–14]. In many of these models, the heavy quark interacts with a $(qq')$ diquark, which is treated as a single object. These models predict seven states in the mass range 2.9–3.2 GeV (natural units are used throughout this Letter), some of them narrow. Other models make use of lattice QCD calculations [15].

The spectroscopy of charmed baryons, particularly the $\Lambda_c^+$, $\Sigma_c^+$, and $\Xi_c^+$ states, has also seen considerable experimental progress, with results obtained at the B factories and in the physics program of the LHCb experiment at CERN [16,17]. Among the expected charmed baryon states, this work addresses the $\Omega_c^0$ baryons, which have quark content $css$ and isospin zero. Their spectrum is largely unknown: Only the $\Omega_c^0$ and $\Omega_c(2770)^0$, presumed to be the $J^P = 1/2^+$ and $3/2^+$ ground states, have been observed [16,18].

To improve the understanding of this little-explored sector of the charmed baryon spectrum, this Letter presents a search for new $\Omega_c^0$ resonances that decay strongly to the final state $\Xi_c^+K^-$, where the $\Xi_c^+$ is a weakly decaying charmed baryon with quark content $css$. (The inclusion of charge-conjugate processes is implied throughout, unless stated otherwise.) The measurement is based on samples of $pp$ collision data corresponding to integrated luminosities of 1.0, 2.0, and 0.3 fb$^{-1}$ at center-of-mass energies of 7, 8, and 13 TeV, respectively, recorded by the LHCb experiment. The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing $b$ or $c$ quarks, and is described in detail in Refs. [19,20]. Hadron identification is provided by two ring-imaging Cherenkov detectors [21], a calorimeter system, and a muon detector. The online event selection is performed by a trigger, which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction [22]. Simulated events are produced with the software packages described in Refs. [23–28].

The reconstruction begins with the $\Xi_c^+$ baryon, via the decay $\Xi_c^+ \rightarrow pK^-\pi^+$. The $\Xi_c^+$ candidates are formed from combinations of three tracks that originate from a common vertex. These are required to pass a cut-based preselection and then a multivariate selection based on likelihood ratios, described below. Candidates fulfilling these requirements are then combined with a fourth track to form $\Omega_c^0 \rightarrow \Xi_c^+K^-$ candidates to which additional selection requirements, also described below, are applied.

The $\Xi_c^+$ preselection requires a positively identified proton and a large $\Xi_c^+$ flight-distance significance (defined as the measured flight distance divided by its uncertainty) from a primary $pp$ interaction vertex (PV). The $\Xi_c^+$ candidates are also constrained to originate from the PV by requiring a small $Z_{\text{IP}}^2$ (defined as the difference between the vertex fit $\chi^2$ of the PV reconstructed with and without the candidate in question). The resulting $pK^-\pi^+$ mass spectrum is fitted with a linear function to describe the background and the sum of two Gaussian functions with a common mean to describe the signal. The fit is used to define signal and sideband regions of the $\Xi_c^+$ invariant mass spectrum: The signal region consists of the range within $\pm 2.0 \sigma$ of the fitted mass, where $\sigma = 6.8$ MeV is the weighted average of the standard deviations of the Gaussian functions, and the sidebands cover the range $3.5 - 5.5 \sigma$ on either side. The fit is also used to determine the $\Xi_c^+$ purity after the preselection, defined as the signal

Full author list given at the end of the article.

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yield in the signal region divided by the total yield in the same region. A purity of 41% is obtained, which is not sufficient for the spectroscopy study but allows the extraction of background-subtracted probability density functions (PDFs) of the kinematic and geometric properties of the signal. These distributions are taken from the data rather than the simulation, given the limited understanding of heavy baryon production dynamics and the difficulty of modeling them correctly for different center-of-mass energies.

For each variable of interest, the background PDF is obtained from the corresponding distribution in the mass sideband regions and is also used for the background subtraction. The signal PDF is obtained from the normalized, background-subtracted distribution in the signal mass region. Variables found to have a good discrimination between the signal and background are the vertex fit $\chi^2$, the $\Xi^+_c$ flight-distance significance and $\chi^2_{IP}$, the particle identification probability for the proton and the kaon from the $\Xi^+_c$ decay, the $\chi^2_{IP}$ of the three individual tracks, the $\Xi^+_c$ transverse momentum $p_T$ with respect to the beam axis, the pseudorapidity $\eta$, and the angle between the $\Xi^+_c$ momentum and the vector joining the PV and the $\Xi^+_c$ decay vertex.

The PDFs of the 11 variables ($x$) above are used to form a likelihood ratio, whose logarithm is defined as

$$\mathcal{L}(x) = \sum_{i=1}^{11} \ln PDF_{sig}(x_i) - \ln PDF_{back}(x_i),$$

where PDF$_{sig}$ and PDF$_{back}$ are the PDF distributions for the signal and background, respectively. Correlations between the variables are neglected in the likelihood.

The likelihood ratios and their PDFs are defined separately for the three samples and lead to $\Xi^+_c$ purities of approximately 83% in the inclusive $\Xi^+_c$ sample.

Figure 1 shows the $pK^-\pi^+$ mass spectrum of $\Xi^+_c$ candidates passing the likelihood ratio selection for all three data sets combined, along with the result of a fit with the functional form described above. The $\Xi^+_c$ signal region contains $1.05 \times 10^6$ events. Note that this inclusive $\Xi^+_c$ sample contains not only those produced in the decays of charmed baryon resonances but also from other sources, including decays of $b$ hadrons and direct production at the PV.

Each $\Xi^+_c$ candidate passing the likelihood ratio selection and lying within the $\Xi^+_c$ signal mass region is then combined in turn with each $K^-$ candidate in the event. A vertex fit is used to reconstruct each $\Xi^+_c K^-$ combination, with the constraint that it originates from the PV. The $\Xi^+_c K^-$ candidate must have a small vertex fit $\chi^2$, a high kaon identification probability, and transverse momentum $p_T(\Xi^+_c K^-) > 4.5$ GeV.

The $\Xi^+_c K^-$ invariant mass is computed as

$$m(\Xi^+_c K^-) = m([pK^-\pi^+]_{\Xi^+_c} K^-) - m([pK^-\pi^+]_{\Xi^+_c}) + m_{\Xi^+_c},$$

where $m_{\Xi^+_c} = 2467.89^{+0.34}_{-0.50}$ MeV is the world-average $\Xi^+_c$ mass [16] and $[pK^-\pi^+]_{\Xi^+_c}$ is the reconstructed $\Xi^+_c \to pK^-\pi^+$ candidate.

In this analysis, the distribution of the invariant mass $m(\Xi^+_c K^-)$ is studied from the threshold up to 3450 MeV.

The $\Xi^+_c K^-$ mass distribution for the combined data sets is shown in Fig. 2, where five narrow structures are observed. To investigate the origin of these structures,

![Figure 1: Distribution of the reconstructed invariant mass $m(pK^-\pi^+)$ for all candidates in the inclusive $\Xi^+_c$ sample passing the likelihood ratio selection described in the text. The solid (red) curve shows the result of the fit, and the dashed (blue) line indicates the fitted background.](image1)

![Figure 2: Distribution of the reconstructed invariant mass $m(\Xi^+_c K^-)$ for all candidates passing the likelihood ratio selection; the solid (red) curve shows the result of the fit, and the dashed (blue) line indicates the fitted background. The shaded (red) histogram shows the corresponding mass spectrum from the $\Xi^+_c$ sidebands, and the shaded (light gray) distributions indicate the feed-down from partially reconstructed $\Omega_c(X)^0$ resonances.](image2)
one of the structures being resonant states, henceforth denoted features in the control samples is consistent with the five wrong-sign mass spectrum. The absence of corresponding spectra in Fig. 3 exhibit different behavior close to the in which the potential misreconstruction consists of combinations are processed in the same way as the right-hand sample. In addition, wrong-sign sidebands as a shaded (red) histogram; no structure is seen in this background sample. The simulation samples are also used to obtain the reconstruction efficiency, which is consistent with being constant as a function of m(Ξ^+_c K^-).

Another possible decay mode for Ω_c(X)^0 resonances is

$$Ω_c(X)^0 \rightarrow K^- Ξ^+_c \quad \text{with} \quad Ξ^+_c \rightarrow Ξ^+_c γ \quad (4)$$

or, in general, to a final state that includes Ξ^+_c K^- but also contains one or more additional particles that are not included in the reconstruction. For the case of a narrow Ω_c(X)^0 resonance decaying via Ξ^+_c, the resulting distribution in m(Ξ^+_c K^-) is a relatively narrow structure that is shifted down in mass (feed-down) that needs to be taken into account in the description of the data. Simulation studies of the decay chain shown in Eq. (4) have been performed with resonance masses of 3066, 3090, and 3119 MeV. It is found that the feed-down shapes deviate from Breit-Wigner distributions and are therefore parameterized by B splines [30].

A binned χ^2 fit to the m(Ξ^+_c K^-) spectrum is performed in the range from the threshold to 3450 MeV. In this fit, the background is modeled by Eq. (3), while the resonances are described by spin-zero relativistic Breit-Wigner functions convolved with the experimental resolution. In addition, three feed-down contributions arising from the partially reconstructed decays of Ω_c(3066)^0, Ω_c(3090)^0, and Ω_c(3119)^0 resonances are included with fixed shapes but free yields. It is found that the fit improves if an additional broad Breit-Wigner function is included in the 3188 MeV mass region. This broad structure may be due to a single resonance, to the superposition of several resonances, to feed-down from higher states, or to some

\[ B(m) = \begin{cases} P(m) e^{a_1 m + a_2 m^2} & \text{for } m < m_0, \\ P(m) e^{b_0 + b_1 m + b_2 m^2} & \text{for } m > m_0, \end{cases} \]

where \( P(m) \) is a two-body phase-space factor and \( m_0, a_i, \) and \( b_i \) are free parameters. Both \( B(m) \) and its first derivative must be continuous at \( m = m_0 \); these constraints reduce the number of free parameters to four. This model gives a good description of the wrong-sign mass spectrum up to a mass of 3450 MeV with a \( p \) value of 18% for a binned \( \chi^2 \) fit.

To study the reconstruction efficiency and the mass resolution of each of the structures, samples of simulated events are generated in which Ω_c(X)^0 resonances decay to Ξ^+_c K^-, with the masses and natural widths of the Ω_c(X)^0 chosen to approximately match those seen in the data. The mass residuals, defined as the difference between the generated Ω_c(X)^0 mass and the reconstructed value of m(Ξ^+_c K^-), are well described by the sum of two Gaussian functions with a common mean. The parameters of these fits are used to determine the mass-dependent experimental resolution, which runs from 0.75 MeV at 3000 MeV to 1.74 MeV at 3119 MeV, and is found to be well described by a linear function. The simulation samples are also used to study the reconstruction efficiency, which is consistent with the shape of m(Ξ^+_c K^-) spectrum

Fig. 2 also shows the distribution of m(Ξ^+_c K^-) in the Ξ^+_c sidebands as a shaded (red) histogram; no structure is seen in this background sample. In addition, wrong-sign Ξ^+_c K^+ combinations are processed in the same way as the right-sign combinations. The resulting wrong-sign Ξ^+_c K^+ mass spectrum is shown in Fig. 3, scaled by a factor of 0.95 so that the two spectra approximately match at a large invariant mass, along with the right-sign m(Ξ^+_c K^-) spectrum for comparison. No structure is observed in the wrong-sign mass spectrum. The absence of corresponding features in the control samples is consistent with the five structures being resonant states, henceforth denoted Ω_c(X)^0 for mass X. It can also be seen that the two mass spectra in Fig. 3 exhibit different behavior close to the Ξ^+_c K^- threshold (2960–2970 MeV). The right-sign distribution has a much steeper rise compared to the wrong-sign spectrum, suggesting the presence of additional components in the Ξ^+_c K^- mass spectrum as discussed below.

Further tests are performed by studying combinations of one of the Ξ^+_c → pK^-π^+ decay products with the other kaon used to form the Ω_c(X)^0 candidate (i.e., pK^-, K^- K^- , and π^- K^-). The resulting two-body invariant mass spectra do not show any structure except for a small K^0 signal in the π^- K^- mass, also visible in the Ξ^+_c sidebands, which is attributed to background contributions. Another class of potential misreconstruction consists of Ξ^+_c π^- combinations in which the π^- is misidentified as a kaon. To test for this, the selected Ξ^+_c K^- sample is investigated with the pion mass assigned to the kaon candidate. No narrow peaks are observed in this pseudo-Ξ^+_c π^- spectrum, indicating that peaks in the Ξ^+_c K^- spectrum do not arise from misidentified Ξ^+_c π^- resonances.

The wrong-sign Ξ^+_c K^+ sample is used to study the combinatorial background. The parameterization used is [29]...
combination of the above. Under the simplest hypothesis, namely, that it is due to a single state, its parameters are given in Table I.

This configuration is denoted the reference fit and is shown in Fig. 2. No significant structure is seen above 3300 MeV. Table I gives the fitted parameters and yields of the resonances, along with the yields for the feed-down contributions indicated with the subscript “fd”. The statistical significance of each resonance is computed as $N_{\sigma} = \sqrt{\Delta\chi^2}$, where $\Delta\chi^2$ is the increase in $\chi^2$ when the resonance is excluded in the fit. Very high significances are obtained for all the narrow resonances observed in the mass spectrum. The threshold enhancement below 2970 MeV is fully explained by feed-down from the $\Omega_c(3066)^0$ resonance.

Several additional checks are performed to verify the presence of the signals and the stability of the fitted parameters. The likelihood ratio requirements are varied, testing both looser and tighter selections. As another test, the data are divided into subsamples according to the data-taking conditions, and each subsample is analyzed and fitted separately. The charge combinations $\Xi^+_c K^-$ and $\Xi^+_c K^-$ are also studied separately. In all cases, the fitted resonance parameters are consistent among the subsamples and with the results from the reference fit.

Systematic uncertainties on the $\Omega_c^0$ resonance parameters are evaluated as follows. The fit bias is evaluated by generating and fitting an ensemble of 500 random mass spectra that are generated according to the reference fit. For each parameter, the absolute value of the difference between the input value and the mean fitted value of the ensemble is taken as the systematic uncertainty.

The background model uncertainty is estimated by exchanging it for the alternative function $B'(m) = (m - m_{th})^{\alpha e^{\beta + \gamma m + \delta m^2}}$, where $m_{th}$ is the threshold mass and $\alpha$, $\beta$, $\gamma$, and $\delta$ are free parameters. The uncertainty associated with the choice of the Breit-Wigner model is estimated by fitting the data with relativistic $L = 1, 2$ Breit-Wigner functions with varying Blatt-Weisskopf factors [31] and is found to be negligible.

Resonances can interfere if they are close in mass and have the same spin parity. The effect is studied by introducing interference terms between each resonance and its neighboring resonances, one pair of resonances at a time. This is implemented with an amplitude of the form $A = |c_i BW_i + c_j BW_j e^{i\phi}|^2$ for the interference between resonances $i$ and $j$, where $BW_i$ and $BW_j$ are complex Breit-Wigner functions and $c_i$ and $\phi$ are free parameters. For the central three resonances, where interference could occur with the state to the left or to the right, the absolute values of the deviations are added in quadrature. No evidence for interference effects is observed.

Recently, the Belle Collaboration has reported a measurement of the $\Xi^+_c$ mass [32] that is significantly more precise than the previous value and which differs from it by about 2.8 MeV. The effect of this is tested by shifting the $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$ feed-down shapes accordingly, and it is included as a systematic uncertainty.

The mass scale uncertainty is studied with a series of control samples and is found to be 0.03% of the mass difference from the threshold $(m - m_{th})$. A comparison between the fitted $\Xi^+_c$ mass resolution in the data and simulation shows a 1.7% discrepancy, which is assigned as a systematic uncertainty on the width of the resonances. The description of the broad, high-mass structure labeled $\Omega_c(3188)^0$ is changed to the sum of four incoherent Breit-Wigner functions, and the effect on the other five resonances is included in the list of the systematic uncertainties. The largest contribution is found to be from possible interference, while the feed-down shift has a sizable effect only on the $\Omega_c(3090)^0$ parameters. For the

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**Table I.** Results of the fit to $m(\Xi^+_c K^-)$ for the mass, width, yield, and significance for each resonance. The subscript fd indicates the feed-down contributions described in the text. For each fitted parameter, the first uncertainty is statistical and the second systematic. The asymmetric uncertainty on the $\Omega_c^0$ mass is given separately. Upper limits are also given for the resonances $\Omega_c(3050)^0$ and $\Omega_c(3119)^0$ for which the width is not significant.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>Yield</th>
<th>$N_{\sigma}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_c(3000)^0$</td>
<td>3000.4 ± 0.2 ± 0.1$^{+0.3}_{-0.5}$</td>
<td>4.5 ± 0.6 ± 0.3</td>
<td>1300 ± 100 ± 80</td>
<td>20.4</td>
</tr>
<tr>
<td>$\Omega_c(3050)^0$</td>
<td>3050.2 ± 0.1 ± 0.1$^{+0.3}_{-0.5}$</td>
<td>0.8 ± 0.2 ± 0.1</td>
<td>970 ± 60 ± 20</td>
<td>20.4</td>
</tr>
<tr>
<td>$\Omega_c(3066)^0$</td>
<td>3065.6 ± 0.1 ± 0.3$^{+0.3}_{-0.5}$</td>
<td>3.5 ± 0.4 ± 0.2</td>
<td>1740 ± 100 ± 50</td>
<td>23.9</td>
</tr>
<tr>
<td>$\Omega_c(3090)^0$</td>
<td>3090.2 ± 0.3 ± 0.5$^{+0.3}_{-0.5}$</td>
<td>8.7 ± 1.0 ± 0.8</td>
<td>2000 ± 140 ± 130</td>
<td>21.1</td>
</tr>
<tr>
<td>$\Omega_c(3119)^0$</td>
<td>3119.1 ± 0.3 ± 0.9$^{+0.3}_{-0.5}$</td>
<td>1.1 ± 0.8 ± 0.4</td>
<td>480 ± 70 ± 30</td>
<td>10.4</td>
</tr>
<tr>
<td>$\Omega_c(3188)^0$</td>
<td>3188 ± 5 ± 13</td>
<td>60 ± 15 ± 11</td>
<td>1670 ± 450 ± 360</td>
<td></td>
</tr>
<tr>
<td>$\Omega_c(3066)^0_{fd}$</td>
<td></td>
<td></td>
<td>700 ± 40 ± 140</td>
<td></td>
</tr>
<tr>
<td>$\Omega_c(3090)^0_{fd}$</td>
<td></td>
<td></td>
<td>220 ± 60 ± 90</td>
<td></td>
</tr>
<tr>
<td>$\Omega_c(3119)^0_{fd}$</td>
<td></td>
<td></td>
<td>190 ± 70 ± 20</td>
<td></td>
</tr>
</tbody>
</table>
total systematic uncertainty, the individual contributions are added in quadrature. Finally, an uncertainty arises from the uncertainty on the $\Xi^0$ mass, whose world-average value is $m(\Xi^0) = 2467.89^{+0.34}_{-0.50}$ MeV [16]. It is quoted separately from the other uncertainties on the resonance masses and is the dominant uncertainty on several of them.

The $\Omega_c(3050)^0$ and $\Omega_c(3119)^0$ resonances have very narrow widths. For these states, Table I also includes Bayesian 95% confidence level (C.L.) upper limits assuming Gaussian PDFs.

The observation of these $\Omega_c$ states in an inclusive process through a two-body decay does not allow the determination of their quantum numbers, and therefore no attempt is made to compare the measured masses with HQET expectations. More information can be obtained from the study of possible three-body decays or when reconstructing these states in decays of heavy baryons.

In conclusion, the $\Xi^+ K^-$ mass spectrum is investigated using a data set corresponding to an integrated luminosity of 3.3 fb$^{-1}$ collected by the LHCB experiment. A large and high-purity sample of $\Xi_c^0$ baryons is reconstructed in the Cabibbo-suppressed decay mode $p K^- \pi^+$. Five new, narrow excited $\Omega_c^0$ states are observed: the $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$, and measurements of their masses and widths are reported. The data indicate also the presence of a broad structure around 3188 MeV that is fitted as a single resonance but could be added in quadrature. Finally, an uncertainty arises from the other uncertainties on the resonance masses and is the dominant uncertainty on several of them.

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(LHCb Collaboration)

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 Savoie Mont-Blanc, CNRS/IN2P3, Annecy-Le-Vieux, France
5 Clermont Université, Université Blaise Pascal, CNRS/IN2P3, 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 I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany
10 Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
11 Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany
12 Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
13 School of Physics, University College Dublin, Dublin, Ireland
14 Sezione INFN di Bari, Bari, Italy
15 Sezione INFN di Bologna, Bologna, Italy
16 Sezione INFN di Cagliari, Cagliari, Italy
17 Sezione INFN di Ferrara, Ferrara, Italy
18 Sezione INFN di Firenze, Firenze, Italy
19 Laboratori Nazionali dell’INFN di Frascati, Frascati, Italy
20 Sezione INFN di Genova, Genova, Italy
21 Sezione INFN di Milano Bicocca, Milano, Italy
22 Sezione INFN di Milano, Milano, Italy
23 Sezione INFN di Padova, Padova, Italy
24 Sezione INFN di Pisa, Pisa, Italy
25 Sezione INFN di Roma Tor Vergata, Roma, Italy
26 Sezione INFN di Roma La Sapienza, Roma, Italy
27 Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
28 AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland
29 National Center for Nuclear Research (NCBJ), Warsaw, Poland
30 Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
31 Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia
32 Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia
33 Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia
Yandex School of Data Analysis, Moscow, Russia
Budker Institute of Nuclear Physics (SB RAS), Novosibirsk, Russia
Institute for High Energy Physics (IHEP), Protvino, Russia
ICCUB, Universitat de Barcelona, Barcelona, Spain
Universidad de Santiago de Compostela, Santiago de Compostela, Spain
European Organization for Nuclear Research (CERN), Geneva, Switzerland
Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
Physik-Institut, Universität Zürich, Zürich, Switzerland
Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands
NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
University of Birmingham, Birmingham, United Kingdom
H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom
Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
Department of Physics, University of Warwick, Coventry, United Kingdom
STFC Rutherford Appleton Laboratory, Didcot, United Kingdom
School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Imperial College London, London, United Kingdom
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
Department of Physics, University of Oxford, Oxford, United Kingdom
Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
University of Cincinnati, Cincinnati, Ohio, USA
University of Maryland, College Park, Maryland, USA
University of Maryand, College Park, Maryland, USA
Syracuse University, Syracuse, New York, USA
Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil (associated with Institution Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil)
University of Chinese Academy of Sciences, Beijing, China (associated with Institution Center for High Energy Physics, Tsinghua University, Beijing, China)
School of Physics and Technology, Wuhan University, Wuhan, China (associated with Institution Center for High Energy Physics, Tsinghua University, Beijing, China)
Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China (associated with Institution Center for High Energy Physics, Tsinghua University, Beijing, China)
Departamento de Fisica, Universidad Nacional de Colombia, Bogota, Colombia (associated with Institution LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France)
Institut für Physik, Universität Rostock, Rostock, Germany (associated with Institution Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany)
National Research Centre Kurchatov Institute, Moscow, Russia (associated with Institution Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia)
Instituto de Fisica Corpuscular, Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain (associated with Institution ICCUB, Universitat de Barcelona, Barcelona, Spain)
Van Swinderen Institute, University of Groningen, Groningen, The Netherlands (associated with Institution Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands)

Also at University of Chinese Academy of Sciences, Beijing, China (associated with Institution Center for High Energy Physics, Tsinghua University, Beijing, China)
Also at School of Physics and Technology, Wuhan University, Wuhan, China (associated with Institution Center for High Energy Physics, Tsinghua University, Beijing, China)
Also at Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China (associated with Institution Center for High Energy Physics, Tsinghua University, Beijing, China)
Also at Departamento de Fisica, Universidad Nacional de Colombia, Bogota, Colombia (associated with Institution LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France)
Also at Institut für Physik, Universität Rostock, Rostock, Germany (associated with Institution Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany)
Also at National Research Centre Kurchatov Institute, Moscow, Russia (associated with Institution Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia)
Also at Instituto de Fisica Corpuscular, Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain (associated with Institution ICCUB, Universitat de Barcelona, Barcelona, Spain)

Also at Università di Ferrara, Ferrara, Italy.
Also at Università di Milano Bicocca, Milan, Italy.
Also at Università di Modena e Reggio Emilia, Modena, Italy.
Also at Novosibirsk State University, Novosibirsk, Russia.
Also at LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain.
Also at Università di Bologna, Bologna, Italy.
Also at Università di Roma Tor Vergata, Rome, Italy.
Also at Università di Genova, Genova, Italy.
Also at Scuola Normale Superiore, Pisa, Italy.
Also at Università di Cagliari, Cagliari, Italy.
Also at Università di Bari, Bari, Italy.
Also at Laboratoire Leprince-Ringuet, Palaiseau, France.
Also at Università degli Studi di Milano, Milano, Italy.
Also at Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil.
Also at Università di Padova, Padova, Italy.
Also at Iligan Institute of Technology (IIT), Iligan, Philippines.
Also at Hanoi University of Science, Hanoi, Viet Nam.
Also at Università di Pisa, Pisa, Italy.
Also at Università di Roma La Sapienza, Roma, Italy.
Also at Università della Basilicata, Potenza, Italy.
Also at Università di Urbino, Urbino, Italy.