Study of Beauty Hadron Decays into Pairs of Charm Hadrons

R. Aaij et al. *(LHCb Collaboration)
(Received 17 March 2014; published 21 May 2014)

First observations of the decays $\Lambda_b^0 \to \Lambda_c^+ D_s^-$ and $\Lambda_b^0 \to \Lambda_c^+ D_s^+$ are reported using data corresponding to an integrated luminosity of 3 fb$^{-1}$ collected at 7 and 8 TeV center-of-mass energies in proton-proton collisions with the LHCb detector. In addition, the most precise measurement of the branching fraction $\mathcal{B}(B^0 \to D^+ D^-)$ is made and a search is performed for the decays $B_{(s)}^0 \to \Lambda_c^+ \Lambda_c^-$. The results obtained are

$$
\mathcal{B}(\Lambda^0_b \to \Lambda_c^+ D^-)/\mathcal{B}(\Lambda^0_b \to \Lambda_c^+ D_s^-) = 0.042 \pm 0.003^{\text{stat}} \pm 0.003^{\text{syst}},
$$

$$
\frac{\mathcal{B}(\Lambda^0_b \to \Lambda_c^+ D^-)}{\mathcal{B}(\Lambda^0_b \to \Lambda_c^+ \pi^-)} = 0.96 \pm 0.02^{\text{stat}} \pm 0.06^{\text{syst}},
$$

$$
\mathcal{B}(B^0 \to D^+ D^-)/\mathcal{B}(\bar{B}^0 \to D^+ D^-) = 0.038 \pm 0.004^{\text{stat}} \pm 0.003^{\text{syst}},
$$

$$
\mathcal{B}(B^0 \to \Lambda_c^+ \Lambda_c^-)/\mathcal{B}(\bar{B}^0 \to D^+ D^-) < 0.0022 [95\% \text{ C.L.}],
$$

$$
\mathcal{B}(\bar{B}^0 \to D^+ D^-) / \mathcal{B}(\bar{B}^0 \to D^+ D^-) < 0.30 [95\% \text{ C.L.}].
$$

Measurement of the mass of the $\Lambda^0_b$ baryon relative to the $\bar{B}^0$ meson gives $M(\Lambda^0_b) - M(\bar{B}^0) = 339.72 \pm 0.24^{\text{stat}} \pm 0.18^{\text{syst}}$ MeV/$c^2$. This result provides the most precise measurement of the mass of the $\Lambda^0_b$ baryon to date.

DOI: 10.1103/PhysRevLett.112.202001 PACS numbers: 14.20.Mr, 13.30.–a

Hadrons are systems of quarks bound by the strong interaction, described at the fundamental level by quantum chromodynamics (QCD). Low-energy phenomena, such as the binding of quarks and gluons within hadrons, lie in the nonperturbative regime of QCD and are difficult to calculate. Much progress has been made in recent years in the study of beauty mesons [1]; however, many aspects of beauty baryons are still largely unknown. Many decays of beauty mesons into pairs of charm hadrons have branching fractions at the percent level [2]. Decays of beauty baryons into pairs of charm hadrons are expected to be of comparable size, yet none have been observed to date. If such decays do have sizable branching fractions, they could be used to study beauty-baryon properties. For example, a comparison of beauty meson and baryon branching fractions can be used to test factorization in these decays [3].

Many models and techniques have been developed that attempt to reproduce the spectrum of the measured hadron masses, such as constituent-quark models or lattice QCD calculations [4]. Precise measurements of ground-state beauty-baryon masses are required to permit precision tests of a variety of QCD models [5–11]. The $\Lambda^0_b$ baryon mass is particularly interesting in this context, since several

* Full author list given at the end of the article.

Published by the American Physical Society under the terms of the Creative Commons Attribution 3.0 License. Further distribution of this work must maintain attribution to the author(s) and the published article title, journal citation, and DOI.
which is about $6 - 8$ MeV/c$^2$, is required to be within 25 MeV/c$^2$ of the nominal value [2]. To improve the resolution of the beauty-hadron mass, the decay chain is fit imposing kinematic and vertex constraints [25]; this includes constraining the charm-hadron masses to their nominal values. To suppress contributions from noncharm decays, the reconstructed charm-hadron decay vertex is required to be downstream of, and significantly displaced from, the reconstructed beauty-hadron decay vertex.

A boosted decision tree (BDT) [26] is used to select each type of charm-hadron candidate. These BDTs use five variables for the charm hadron and 23 for each of its decay products. The variables include kinematic quantities, track and vertex qualities, and particle identification (PID) information. The signal samples used to train the BDTs are obtained from large data sets of heavy quarkonia. The signal samples used to train the BDTs are taken from charm-hadron and high-mass beauty-hadron sidebands in the same data sets. To obtain the BDT efficiency in a given signal decay mode, the kinematical properties and correlations between the two charm hadrons are taken from simulation. The BDT response distributions are obtained from independent data samples of the decays used in the BDT training, weighted to match the kinematics of the signal.

Because of the kinematic similarity of the decays $D^+ \to K^+\pi^+\pi^+$, $D^+ \to K^-K^+\pi^+$, and $\Lambda^+_c \to pK^-\pi^+$, cross feed may occur among beauty-hadron decays into pairs of charm hadrons. For example, cross feed between $D^+$ and $D_s^+$ mesons occurs when a $K^-h^+\pi^+$ candidate is reconstructed in the $D^+$ mass region under the $h^+ = \pi^+$ hypothesis and in the $D_s^+$ mass region under the $h^+ = K^+$ hypothesis. In such situations, an arbitration is performed: if the ambiguous track ($h^+$) can be associated to an oppositely charged track to form a $\phi(1020) \to K^+K^-$ candidate, the kaon hypothesis is taken, resulting in a $D_s^+$ assignment to the charm-hadron candidate; otherwise, stringent PID requirements are applied to $h^+$ to choose which hypothesis to take. The efficiency of these arbitrations, which is found to be about 90% per charm hadron, is obtained using simulated signal decays to model the kinematical properties and $D^{++} \to D^0\pi^+$ calibration data for the PID efficiencies. The misidentification probability is roughly 1% per charm hadron.

Signal yields are determined by performing unbinned extended likelihood fits to the beauty-hadron invariant-mass spectra observed in the data. The signal distributions are modeled using a so-called Apollonios function, which is the exponential of a hyperbola combined with a power-law low-mass tail [28]. The peak position and resolution parameters are allowed to vary while fitting the data, while the low-mass tail parameters are taken from simulation and fixed in the fits.

Four categories of background contributions are considered: partially reconstructed decays of beauty hadrons where at least one final-state particle is not reconstructed; decays into a single charm hadron and three light hadrons; reflections, defined as cases where the cross-feed arbitration fails to remove a misidentified particle; and combinatorial background. The only partially reconstructed decays that contribute in the mass region studied are those where a single pion or photon is not reconstructed; thus, only final states comprised of $D_{s1}^{(*)+}$ or $\Sigma^+_c$ and another charm hadron are considered (e.g., $\Lambda^0_b \to \Lambda^+_cD_s^{(*)-}$). These background contributions are modeled using exponential probability density functions (PDFs) [29] obtained from simulation; their yields are free to vary in the fits. Single-charm backgrounds are studied using data that are reconstructed outside of a given charm-hadron mass region. These backgrounds are found to be $\mathcal{O}(1\%)$ of the size of the signal yield for signal decays containing a $D_s^+$ (e.g., $\bar{B}^0 \to D^0K^-K^+\pi^-$) and are negligible otherwise. The only non-negligible reflection is found to be $\Lambda^0_b \to \Lambda^+_cD^-\pi^+$ decays misidentified as $\Lambda^+_cD^-\pi^+$ candidates. The invariant-mass distribution for this reflection is obtained from simulation, while the normalization is fixed using simulation and the aforementioned PID calibration sample to determine the fraction of $\Lambda^0_b \to \Lambda^+_cD^-\pi^+$ decays that are not removed by the cross-feed criteria. Reflections of $\bar{B}^0 \to D^+D_s^-\pi^+$ decays misidentified as final states containing $\Lambda^+_c$ particles do not have a peaking structure in the beauty-hadron invariant mass and, therefore, are absorbed into the combinatorial backgrounds, which are modeled using exponential distributions.

Figure 1 shows the invariant mass spectra for the $\Lambda^0_b \to \Lambda^+_cD^-\pi^+$ and $\Lambda^0_b \to \Lambda^+_cD^-\pi^+$ candidates. The signal yields obtained are $4633 \pm 69$ and $262 \pm 19$ for $\Lambda^0_b \to \Lambda^+_cD^-\pi^+$ and $\Lambda^0_b \to \Lambda^+_cD^-\pi^+$, respectively. This is the first observation of each of these decays. The ratio of branching fractions determined using the nominal $D^-_s$ [2] and $D^-$ [30] meson branching fractions and the ratio of efficiencies is

$$\frac{\mathcal{B}(\Lambda^0_b \to \Lambda^+_cD^-)}{\mathcal{B}(\Lambda^0_b \to \Lambda^+_cD^-)} = 0.042 \pm 0.003(\text{stat}) \pm 0.003(\text{syst}).$$

The similarity of the final states and the shared parent particle result in many cancellations of uncertainties in the determination of the ratio of branching fractions. The remaining uncertainties include roughly equivalent contributions from determining the efficiency-corrected yields and from the ratio of charm-hadron branching fractions (see Table I). The dominant contribution to the uncertainty of the fit PDF is due to the low-mass background contributions, which are varied in size and shape to determine the effect on the signal yield. The uncertainty due to signal model is found to be negligible. The efficiencies of the cross feed and BDT criteria are determined in a data-driven manner that produces small uncertainties. The observed ratio is approximately the ratio of the relevant quark-mixing...
factors and meson decay constants, $|V_{cd}/V_{cs}|^2 \times (f_D/f_{D^*})^2 \approx 0.034$, as expected assuming nonfactorizable effects are small.

The branching fraction of the decay $\Lambda_b^0 \rightarrow \Lambda_c^+ D^-$ is determined relative to that of the $B^0 \rightarrow D^+ D^-$ decay. Using $D^+ D^-$ BDT criteria optimized to maximize the expected $B^0$ significance, 19,395 $B^0 \rightarrow D^+ D^-$ decays are observed (see Fig. 2). The measurement of $B(\Lambda_b^0 \rightarrow \Lambda_c^+ D^-)/B(\bar{B}^0 \rightarrow D^+ D^-)$ is complicated by the fact that the ratio of the $\Lambda_b^0$ and $\bar{B}^0$ production cross sections, $\sigma(\Lambda_b^0)/\sigma(\bar{B}^0)$, depends on the $p_T$ of the beauty hadrons [32]. Figure 3 shows the ratio of efficiency-corrected yields, $N(\Lambda_b^0 \rightarrow \Lambda_c^+ D^-)/N(\bar{B}^0 \rightarrow D^+ D^-)$, as a function of beauty-hadron $p_T$.

The ratio of branching-fraction ratios is obtained using a fit with the shape of the $p_T$ dependence measured in $B(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)/B(\bar{B}^0 \rightarrow D^+ \pi^-)$ [33] and found to be

$$\frac{B(\Lambda_b^0 \rightarrow \Lambda_c^+ D^-)}{B(\bar{B}^0 \rightarrow D^+ D^-)} \times \frac{B(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)}{B(\bar{B}^0 \rightarrow D^+ \pi^-)} = 0.96 \pm 0.02\text{ (stat)} \pm 0.06\text{ (syst)}.$$

This result does not depend on the absolute ratio of production cross sections or on any charm-hadron branching fractions. The systematic uncertainties on this result are listed in Table I. The uncertainty in the fit model is due largely to the sizable single-charm background contributions to these modes and to contributions from the fits described in Ref. [33]. The $B(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)/B(\bar{B}^0 \rightarrow D^+ \pi^-)$ result was obtained only using data collected at $\sqrt{s} = 7$ TeV. The ratio $N(\Lambda_b^0 \rightarrow \Lambda_c^+ D^-)/N(\bar{B}^0 \rightarrow D^+ D^-)$ is observed to be consistent in data collected at $\sqrt{s} = 7$ and 8 TeV. The statistical uncertainty on this comparison is assigned as the systematic uncertainty on the energy dependence of the $\Lambda_b^0$ and $\bar{B}^0$ production fractions. The ratio of branching ratios is consistent with unity, as expected assuming small nonfactorizable effects.

The kinematic similarity of the decay modes $\Lambda_b^0 \rightarrow \Lambda_c^+ D^- \bar{B}^0$ and $B^0 \rightarrow D^+ D^-$ permits a precision measurement of the mass difference of the $\Lambda_b^0$ and $\bar{B}^0$ hadrons. The relatively small value of $[M(\Lambda_b^0) - M(\Lambda_c^+) - M(D^-)] - [M(\bar{B}^0) - M(D^+) - M(D^+)]$ means that the uncertainty due to momentum scale, the dominant uncertainty in absolute-mass measurements, mostly cancels; however, it is still important to determine accurately the momenta of the final-state particles. The momentum-scale calibration of the spectrometer, which accounts for imperfect knowledge of the magnetic field and alignment, is discussed in detail in Refs. [12,34]. The uncertainty on the calibrated momentum scale is estimated to be 0.03% by comparing various particle masses measured at LHCb to their nominal values [34].

The kinematic and vertex constraints used in the fits described previously reduce the statistical uncertainty on $M(\Lambda_b^0) - M(\bar{B}^0)$ by improving the resolution. These

---

**TABLE I.** Relative systematic uncertainties on branching fraction measurements (%). The production ratio $\sigma(B_s^0)/\sigma(\bar{B}^0)$ is taken from Ref. [31]. The numbers in parentheses in the last column are for the $B_s^0$ decay mode.

<table>
<thead>
<tr>
<th>Source</th>
<th>$B(\Lambda_b^0 \rightarrow \Lambda_c^+ D^-)/B(\bar{B}^0 \rightarrow D^+ D^-)$</th>
<th>$[B(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)/B(\bar{B}^0 \rightarrow D^+ \pi^-)]$</th>
<th>$B(\bar{B}^0 \rightarrow D^+ D^-)/B(\bar{B}^0 \rightarrow D^+ D^-)$</th>
<th>$B(\Lambda_b^0 \rightarrow \Lambda_c^+ D^-)/B(\bar{B}^0 \rightarrow D^+ D^-)$</th>
<th>$[B(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)/B(\bar{B}^0 \rightarrow D^+ \pi^-)]$</th>
<th>$B(\bar{B}^0 \rightarrow D^+ D^-)/B(\bar{B}^0 \rightarrow D^+ D^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>3.5</td>
<td>5.2</td>
<td>1.0</td>
<td>3.9 (5.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fit model</td>
<td>3.0</td>
<td>2.6</td>
<td>3.0</td>
<td>8.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B(D_{s0}^0, \Lambda_c^+)$</td>
<td>5.2</td>
<td>...</td>
<td>...</td>
<td>5.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma(B_s^0)/\sigma(\bar{B}^0)$</td>
<td>...</td>
<td>2.0</td>
<td>...</td>
<td>...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>6.9</td>
<td>6.1</td>
<td>6.6</td>
<td>9.6 (10.1)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
constraints also increase the systematic uncertainty by introducing a dependence on the precision of the nominal charm-hadron masses. These constraints are not imposed in the mass measurement, as it is found that this approach produces a smaller total uncertainty. The mass difference obtained is

\[
M(\Lambda^0_b) - M(\bar{B}^0) = 339.72 \pm 0.24\text{(stat)} \\
\quad \pm 0.18\text{(syst)} \text{ MeV/c}^2.
\]

The dominant systematic uncertainty (see Table II) arises due to a correlation between the reconstructed beauty-hadron mass and reconstructed charm-hadron flight distance. The large difference in the \(\Lambda^+\) and \(D^+\) hadron lifetimes [2] could lead to only a partial cancellation of the biases induced by the charm-lifetime selection criteria. This effect is studied in simulation and a 0.16 MeV/c² uncertainty is assigned. The 0.03% uncertainty in the momentum scale results in an uncertainty on the mass difference of 0.08 MeV/c². Many variations in the fit model are considered, and none produce a significant shift in the mass difference. The systematic uncertainty in the mass difference due to the uncertainty in the amount of detector material in which charged particles lose energy is negligible [34]. Furthermore, the uncertainty on \(M(\Lambda^0_b) - M(\bar{B}^0)\) due to differences in beauty-hadron production kinematics, as seen in Fig. 3, is also found to be negligible.

Using the nominal value for \(M(\bar{B}^0)[2]\) gives \(M(\Lambda^0_b) = 5619.30 \pm 0.34\text{ MeV/c}^2\), where the uncertainty includes both statistical and systematic contributions. This is the most precise result to date. The total uncertainty is dominated by statistics and charm-hadron lifetime effects; thus, this result can be treated as being uncorrelated with the previous LHCb result obtained using the \(\Lambda^0_b \rightarrow J/\psi \Lambda^0\) decay [35]. A weighted average of the LHCb results gives \(M(\Lambda^0_b) = 5619.36 \pm 0.26\text{ MeV/c}^2\). This value may then be used to improve the precision of the \(\Xi^-\) and \(\Omega^-\) baryon masses using their mass differences with respect to the \(\Lambda^0_b\) baryon, as reported in Ref. [35].

Using BDT criteria optimized for maximizing the expected significance of \(\bar{B}^0 \rightarrow D^+ D^-\), 14 608 ± 121 \(\bar{B}^0\) and 143 ± 14 \(B^0\) decays are observed (see Fig. 2), from which the ratio extracted is

\[
\frac{\mathcal{B}(\bar{B}^0 \rightarrow D^+ D^-)}{\mathcal{B}(B^0 \rightarrow D^+ D^-)} = 0.038 \pm 0.004\text{(stat)} \pm 0.003\text{(syst)}.
\]

This is the most precise measurement to date of \(\mathcal{B}(\bar{B}^0 \rightarrow D^+ D^-)\) and supersedes Ref. [36]. Since the two decay modes share the same final state, many systematic uncertainties cancel. The dominant contribution to the uncertainty comes from the beauty-hadron production fractions.

### Table II. Systematic uncertainties for \(M(\Lambda^0_b) - M(\bar{B}^0)\).

<table>
<thead>
<tr>
<th>Description</th>
<th>Value (MeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Lambda^+ - D^+) lifetime difference</td>
<td>0.16</td>
</tr>
<tr>
<td>Momentum scale</td>
<td>0.08</td>
</tr>
<tr>
<td>Fit model</td>
<td>0.02</td>
</tr>
<tr>
<td>Total</td>
<td>0.18</td>
</tr>
</tbody>
</table>
fraction measurements have been made for the decays \( B_s^0 \rightarrow \Lambda_c^+ \Lambda_c^- \). Regions centered around the nominal \( B_s^0 \) meson masses with boundaries defined such that each region contains 95% of the corresponding signal are determined using simulation. The expected background contribution in each of these regions is obtained from the charm-hadron mass sidebands. Applying this technique to \( B_s^0 \rightarrow D^+ D_s^- \) and \( \Lambda_b^0 \rightarrow \Lambda_c^+ D_s^- \) decays produces background estimates consistent with those obtained by fitting the invariant mass spectra for those modes. The number of observed candidates in each signal region is then compared to the expected background contribution; no significant excess is observed in either \( \Lambda_c^+ \Lambda_c^- \) signal region. The limits obtained using the method of Ref. [37] and the known \( D_s^- \) [2], \( D^- \) [30], and \( \Lambda_c^+ \) [38] hadron branching fractions are

\[
\frac{B(\bar{B}^0 \rightarrow \Lambda_c^+ \Lambda_c^-)}{B(\bar{B}^0 \rightarrow D^+ D^-)} < 0.0022 [95\% \, C.L.],
\]

\[
\frac{B(B_s^0 \rightarrow \Lambda_c^+ \Lambda_c^-)}{B(B_s^0 \rightarrow D^+ D^-)} < 0.30 [95\% \, C.L.].
\]

For these results the lifetime of the light-mass \( B_s^0 \) eigenstate is assumed, as this produces the most conservative limits [1]. This is the best limit to date for the \( \bar{B}^0 \) decay mode and the first limit for the \( B_s^0 \) decay mode.

In summary, first observations and relative branching-fraction measurements have been made for the decays \( \Lambda_b^0 \rightarrow \Lambda_c^+ D_s^- \). The most precise measurements of the \( \Lambda_b^0 \) baryon mass and of \( B(B_s^0 \rightarrow D^+ D^-) \) have been presented and the most stringent upper limits have been placed on \( B(B_s^0 \rightarrow \Lambda_c^+ \Lambda_c^-) \). Using \( B(\bar{B}^0 \rightarrow D^+ D^-) = (7.2 \pm 0.8) \times 10^{-3} \) [2] and \( B(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-) = B(\bar{B}^0 \rightarrow D^+ \pi^-) \) from Ref. [33], the absolute branching fractions obtained are

\[
B(\Lambda_b^0 \rightarrow \Lambda_c^+ D^-) = (1.1 \pm 0.1) \times 10^{-2},
\]

\[
B(\Lambda_b^0 \rightarrow \Lambda_c^+ D^-) = (4.7 \pm 0.6) \times 10^{-4},
\]

\[
B(B_s^0 \rightarrow D^+ D^-) = (2.7 \pm 0.5) \times 10^{-4},
\]

\[
B(B_s^0 \rightarrow \Lambda_c^+ \Lambda_c^-) < 1.6 \times 10^{-5} [95\% \, C.L.],
\]

\[
B(B_s^0 \rightarrow \Lambda_c^+ \Lambda_c^-) < 8.0 \times 10^{-5} [95\% \, C.L.].
\]

These results are all consistent with expectations that assume small nonfactorizable effects.

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

1Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil
2Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil
3Center for High Energy Physics, Tsinghua University, Beijing, China
4LAPP, Université de Savoie, CNRS/IN2P3, Annecy-Le-Vieux, France
5Clermont Université, Université Blaise Pascal, CNRS/IN2P3, LPC, Clermont-Ferrand, France
6CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
7LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
8LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France
9Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
10Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany
11Physikaaliskes Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
12School of Physics, University College Dublin, Dublin, Ireland
13Sezione INFN di Bari, Bari, Italy
14Sezione INFN di Bologna, Bologna, Italy
15Sezione INFN di Catania, Catania, Italy
16SEzione INFN di Ferrara, Ferrara, Italy
17Sezione INFN di Firenze, Firenze, Italy
18Laboratori Nazionali dell’INFN di Frascati, Frascati, Italy
19Sezione INFN di Genova, Genova, Italy
20Sezione INFN di Milano Bicocca, Milano, Italy
21Sezione INFN di Milano, Milano, Italy
22Sezione INFN di Padova, Padova, Italy
23Sezione INFN di Pisa, Pisa, Italy
24Sezione INFN di Roma Tor Vergata, Roma, Italy
25Sezione INFN di Roma La Sapienza, Roma, Italy
26Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
27AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland
28National Center for Nuclear Research (NCBJ), Warsaw, Poland
29Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
30Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia
31Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia
32Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
33Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia
34Budker Institute of Nuclear Physics (SB RAS) and Novosibirsk State University, Novosibirsk, Russia
35Institute for High Energy Physics (IHEP), Protvino, Russia
36Universitat de Barcelona, Barcelona, Spain
37Universidad de Santiago de Compostela, Santiago de Compostela, Spain
38European Organization for Nuclear Research (CERN), Geneva, Switzerland
39Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
40Physik-Institut, Universität Zürich, Zürich, Switzerland
41Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands
42Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, The Netherlands
43NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
44Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
45University of Birmingham, Birmingham, United Kingdom
46H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom
47Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
48Department of Physics, University of Warwick, Coventry, United Kingdom
49STFC Rutherford Appleton Laboratory, Didcot, United Kingdom