Original citation:

Permanent WRAP url:
http://wrap.warwick.ac.uk/59623

Copyright and reuse:
The Warwick Research Archive Portal (WRAP) makes this work of researchers of the University of Warwick available open access under the following conditions.

This article is made available under the Creative Commons Attribution- 3.0 Unported (CC BY 3.0) license and may be reused according to the conditions of the license. For more details see http://creativecommons.org/licenses/by/3.0/

A note on versions:
The version presented in WRAP is the published version, or, version of record, and may be cited as it appears here.

For more information, please contact the WRAP Team at: publications@warwick.ac.uk
Measurement of the $CP$ Asymmetry in $B^+ \rightarrow K^+ \mu^+ \mu^-$ Decays

R. Aaij et al.*

(LHCb Collaboration)

(Received 7 August 2013; published 7 October 2013)

A measurement of the $CP$ asymmetry in $B^+ \rightarrow K^+ \mu^+ \mu^-$ decays is presented using $pp$ collision data, corresponding to an integrated luminosity of 1.0 fb$^{-1}$, recorded by the LHCb experiment during 2011 at a center-of-mass energy of 7 TeV. The measurement is performed in seven bins of $\mu^+ \mu^-$ invariant mass squared in the range $0.05 < q^2 < 22.00$ GeV$^2$/c$^4$, excluding the $J/\psi$ and $\psi(2S)$ resonance regions. Production and detection asymmetries are corrected for using the $B^+ \rightarrow J/\psi K^+$ decay as a control mode. Averaged over all the bins, the $CP$ asymmetry is found to be $A_{CP} = 0.000 \pm 0.033$ (stat) $\pm 0.005$ (syst) $\pm 0.007$ ($J/\psi K$), where the third uncertainty is due to the $CP$ asymmetry of the control mode. This is consistent with the standard model prediction.

DOI: 10.1103/PhysRevLett.111.151801

PACS numbers: 13.20.He, 11.30.Er, 12.15.Mm, 12.60.Jv

The rare decay $B^+ \rightarrow K^+ \mu^+ \mu^-$ is a flavor-changing neutral current process mediated by electroweak loop (penguin) and box diagrams. The absence of tree-level diagrams for the decay results in a small value of the standard model (SM) prediction for the branching fraction, which is supported by a measurement of $(4.36 \pm 0.23) \times 10^{-7}$ [1]. Physics processes beyond the SM that may enter via the loop and box diagrams could have large effects on observables of the decay. Examples include the decay rate, the $\mu^+ \mu^-$ forward-backward asymmetry [1–3], and the $CP$ asymmetry [2,4], as functions of the $\mu^+ \mu^-$ invariant mass squared ($q^2$).

The $CP$ asymmetry is defined as

$$A_{CP} = \frac{\Gamma(B^+ \rightarrow K^- \mu^+ \mu^-) - \Gamma(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\Gamma(B^+ \rightarrow K^- \mu^+ \mu^-) + \Gamma(B^+ \rightarrow K^+ \mu^+ \mu^-)},$$

where $\Gamma$ is the decay rate of the mode. This asymmetry is predicted to be of order $10^{-4}$ in the SM [5] but can be significantly enhanced in models beyond the SM [6]. Current measurements including the dielectron mode $A_{CP}(B \rightarrow K^{*} \ell^+ \ell^-)$ from BABAR and Belle give $-0.03 \pm 0.14$ and $0.04 \pm 0.10$, respectively [2,4], and are consistent with the SM. The $CP$ asymmetry has already been measured at LHCb in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays [7], $A_{CP} = -0.072 \pm 0.040$. Assuming that contributions beyond the SM are independent of the flavor of the spectator quark, $A_{CP}$ should be similar for both $B^+ \rightarrow K^+ \mu^+ \mu^-$ and $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays.

In this Letter, a measurement of $A_{CP}$ in $B^+ \rightarrow K^+ \mu^+ \mu^-$ decays is presented using $pp$ collision data, corresponding to an integrated luminosity of 1.0 fb$^{-1}$, recorded at a center-of-mass energy of 7 TeV at LHCb in 2011. The inclusion of charge conjugate modes is implied throughout unless explicitly stated.

The LHCb detector [8] 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 provides a momentum measurement with relative uncertainty that varies from 0.4% at 5 GeV/c to 0.6% at 100 GeV/c, and impact parameter (IP) resolution of 20 $\mu$m for tracks with high transverse momentum ($p_T$).

Charged hadrons are identified using two ring-imaging Cherenkov detectors [9]. Muons are identified by a system composed of alternating layers of iron and multihire proportional chambers [10].

Samples of simulated events are used to determine the efficiency of selecting $B^+ \rightarrow K^+ \mu^+ \mu^-$ signal events and to study certain backgrounds. In the simulation, $pp$ collisions are generated using PYTHIA 6.4 [11] with a specific LHCb configuration [12]. Decays of hadronic particles are described by EVTGEN [13], in which final-state radiation is generated using PHOTOS [14]. The interaction of the generated particles with the detector and its response are implemented using the GEANT4 toolkit [15] as described in Ref. [16]. The simulated samples are corrected to reproduce the data distributions of the $B^+$ meson $p_T$ and vertex $\chi^2$, the track $\chi^2$ of the kaon, as well as the detector IP resolution, particle identification, and momentum resolution.

Candidate events are first required to pass a hardware trigger, which selects muons with $p_T > 1.48$ GeV/c [17]. In the subsequent software trigger, at least one of the final-state particles is required to have $p_T > 1.0$ GeV/c and IP $> 100$ $\mu$m with respect to all primary $pp$ interaction events.

*Full author list given at 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’s title, journal citation, and DOI.
vertices (PVs) in the event. Finally, the tracks of two or more of the final-state particles are required to form a vertex that is displaced from the PVs.

An initial selection is applied to the \( B^+ \rightarrow K^+ \mu^+ \mu^- \) candidates to enhance signal decays and suppress combinatorial background. Candidate \( B^+ \) mesons must satisfy requirements on their direction and flight distance, to ensure consistency with originating from the PV. The decay products must pass criteria regarding the \( \chi^2 \) of a given PV reconstructed with and without the considered particle. There is also a requirement on the vertex \( \chi^2 \) of the \( \mu^+ \mu^- \) pair. All the tracks are required to have \( p_T > 250 \) MeV/c.

Additional background rejection is achieved by using a boosted decision tree [18] that implements the AdaBoost algorithm [19]. The boosted decision tree uses the \( p_T \) and \( \chi^2 \) of the muons and the \( B^+ \) meson candidate, as well as the decay time, vertex \( \chi^2 \), and flight direction of the \( B^+ \) candidate and the \( \chi^2 \) of the kaon. Data, corresponding to an integrated luminosity of 0.1 fb\(^{-1}\), are used to optimize this selection, leaving 0.9 fb\(^{-1}\) for the determination of \( \mathcal{A}_{CP} \).

Following the multivariate selection, candidate events pass several requirements to remove specific sources of background. Particle identification criteria are applied to kaon candidates to reduce the number of pions incorrectly identified as kaons. Candidates with \( \mu^+ \mu^- \) invariant mass in the ranges 2.95 < \( m_{\mu\mu} \) < 3.18 GeV/c\(^2\) and 3.59 < \( m_{\mu\mu} \) < 3.77 GeV/c\(^2\) are removed to reject backgrounds from tree level \( B^+ \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) K^+ \) and \( B^+ \rightarrow \psi (2S)(\rightarrow \mu^+ \mu^-) K^+ \) decays. Those in the first range are selected as \( B^+ \rightarrow J/\psi K^+ \) decays, which are used as a control sample. If \( m_{\mu\mu} < 5.22 \) GeV/c\(^2\), the vetoes are extended downwards by 0.25 and 0.19 GeV/c\(^2\), respectively, to remove the radiative tails of the resonant decays. If 5.35 < \( m_{\mu\mu} \) < 5.50 GeV/c\(^2\), the vetoes are extended upwards by 0.05 GeV/c\(^2\) to remove misconstructed resonant candidates that appear at large \( m_{\mu\mu} \) and \( m_{\mu\mu} \). Further vetoes are applied to remove \( B^+ \rightarrow J/\psi K^+ \) events in which the kaon and a muon have been swapped and contributions from decays involving charm mesons such as \( B^+ \rightarrow D^0 (\rightarrow K^+ \pi^-) \pi^+ \) where both pions are misidentified as muons. After these selection requirements have been applied, there are two sources of background that are difficult to distinguish from the signal. These are \( B^+ \rightarrow K^+ \pi^+ \pi^- \) and \( B^+ \rightarrow \pi^+ \mu^+ \mu^- \) decays, which both contribute at the level of 1% of the signal yield. These peaking backgrounds are accounted for during the analysis.

In order to perform a measurement of \( \mathcal{A}_{CP} \), the production and detection asymmetries associated with the measurement must be considered. The raw measured asymmetry is, to first order,

\[
\mathcal{A}_{RAW} = \mathcal{A}_{CP} + \mathcal{A}_P + \mathcal{A}_D, \tag{2}
\]

where the production and detection asymmetries are defined as

\[
\mathcal{A}_P \equiv \frac{[R(B^+) - R(B^+)]/[R(B^+) + R(B^+)],[3]}
\]

\[
\mathcal{A}_D \equiv \frac{[\epsilon(K^-) - \epsilon(K^+)]/[\epsilon(K^-) + \epsilon(K^+)],[4]}
\]

where \( R \) and \( \epsilon \) represent the \( B \) meson production rate and kaon detection efficiency, respectively. The detection asymmetry has two components: one due to the different interactions of positive and negative kaons with the detector material, and a left-right asymmetry due to particles of different charges being deflected to opposite sides of the detector by the magnet. The component of the detection asymmetry from muon reconstruction is small and neglected. Since the LHCb experiment reverses the magnetic field, about half of the data used in the analysis is taken with each polarity. Therefore, an average of the measurements with the two polarities is used to suppress significantly the second effect. To account for both the detection and production asymmetries, the decay \( B^+ \rightarrow J/\psi K^+ \) is used, which has the same final-state particles as \( B^+ \rightarrow K^+ \mu^+ \mu^- \) and very similar kinematic properties. The CP asymmetry in \( B^+ \rightarrow J/\psi K^+ \) decays has been measured as \((1 \pm 7) \times 10^{-3} [20,21]\). Neglecting the difference in the final-state kinematic properties of the kaon, the production and detection asymmetries are the same for both modes, and the value of the CP asymmetry can be obtained via

\[
\mathcal{A}_{CP} = \mathcal{A}_{RAW}(K \mu \mu) - \mathcal{A}_{RAW}(J/\psi K)
\]

\[
+ \mathcal{A}_{CP}(J/\psi K). \tag{5}
\]

Differences in the kinematic properties are accounted for by a systematic uncertainty.

In the data set, approximately 1330 \( B^+ \rightarrow K^+ \mu^+ \mu^- \) and 218 000 \( B^+ \rightarrow J/\psi K^+ \) signal decays are reconstructed. To measure any variation in \( \mathcal{A}_{CP} \) as a function of \( q^2 \), which improves the sensitivity of the measurement to physics beyond the SM, the \( B^+ \rightarrow K^+ \mu^+ \mu^- \) data set is divided into the seven \( q^2 \) bins used in Ref. [1]. The measurement is made in a bin of \( 1 < q^2 < 6 \) GeV\(^2\)/c\(^4\), which is of particular theoretical interest. To determine the number of \( B^+ \) decays in each bin, a simultaneous unbinned maximum likelihood fit is performed to the invariant mass distributions of the \( B^+ \rightarrow K^+ \mu^+ \mu^- \) and \( B^+ \rightarrow J/\psi K^+ \) candidates in the range 5.10 < \( m_{K\mu\mu} \) < 5.60 GeV/c\(^2\). The signal shape is parametrized by a Cruijff function [22], and the combinatorial background is described by an exponential function. All parameters of the signal and combinatorial background are allowed to vary freely in the fit. Additionally, there is background from partially reconstructed decays such as \( B^0 \rightarrow K^{0*} (\rightarrow K^+ \pi^-) \mu^+ \mu^- \) or \( B^0 \rightarrow J/\psi K^{0*} (\rightarrow K^+ \pi^-) \) where the pion is undetected. For the \( B^+ \rightarrow K^+ \mu^+ \mu^- \) distribution, these decays are fitted by an ARGUS function [23] convolved with a Gaussian function to account for detector resolution. For the \( B^+ \rightarrow J/\psi K^+ \) decays, the partially reconstructed background is modeled by another Cruijff function. The shapes of the peaking backgrounds, due to \( B^+ \rightarrow K^+ \pi^+ \pi^- \) and \( B^+ \rightarrow \pi^+ \mu^+ \mu^- \) decays, are taken from fits to simulated events.
In each $q^2$ bin, the $B^+ \to J/\psi K^+$ and $B^+ \to K^+ \mu^+ \mu^-$ data sets are divided according to the charge of the $B^+$ meson and magnet polarity, providing eight distinct subsets. These are fitted simultaneously with the parameters of the signal Cruijff function common for all eight subsets. The partially reconstructed background is assumed to exhibit no CP asymmetry in the $q^2$ range. The four data sets are divided according to the charge of the kaon in the detector. The difference between the two decays are reweighted to match those of $B^+ \to K^+ \mu^+ \mu^-$, and the value of $\mathcal{A}_{\text{RAW}}$ is recalculated. The variables used are the momentum, $p_T$, and pseudorapidity of the $B^+$ and $K^+$ mesons, as well as the $B^+$ decay time and the position of the kaon in the detector. The difference between the two values of $\mathcal{A}_{\text{RAW}}$ for each variable is taken as the systematic uncertainty. The total systematic uncertainty associated with the different kinematic behavior of the two decays in each $q^2$ bin is calculated by adding each individual contribution in quadrature.

Several assumptions are made about the backgrounds. The partially reconstructed background is assumed to exhibit no CP asymmetry. For $B^+ \to \pi^+ \mu^+ \mu^-$, $\mathcal{A}_{\text{CP}}$ is also assumed to be zero [24]. For the $B^+ \to K^+ \pi^+ \pi^-$ decay, $\mathcal{A}_{\text{CP}}$ in each $q^2$ bin is taken from a recent LHCb measurement [25]. The effect of these assumptions on the result is investigated as a systematic uncertainty.

Various sources of systematic uncertainty are considered. The analysis relies on the assumption that the $B^+ \to K^+ \mu^+ \mu^-$ and $B^+ \to J/\psi K^+$ decays have the same final-state kinematic distributions, so that the relation in Eq. (5) is exact. To estimate the bias associated with this assumption, the kinematic distributions of $B^+ \to J/\psi K^+$ decays are reweighted to match those of $B^+ \to K^+ \mu^+ \mu^-$, and the value of $\mathcal{A}_{\text{RAW}}$ is recalculated. The variables used are the momentum, $p_T$, and pseudorapidity of the $B^+$ and $K^+$ mesons, as well as the $B^+$ decay time and the position of the kaon in the detector. The difference between the two values of $\mathcal{A}_{\text{RAW}}$ for each variable is taken as the systematic uncertainty. The total systematic uncertainty associated with the different kinematic behavior of the two decays in each $q^2$ bin is calculated by adding each individual contribution in quadrature.

The choice of fit model also introduces systematic uncertainties. The fit is repeated using a different signal model, replacing the Cruijff function with the sum of two Crystal Ball functions [26] that have the same mean and tail parameters but different Gaussian widths. The

---

**FIG. 1 (color online).** Invariant mass distributions of $B^+ \to K^+ \mu^+ \mu^-$ candidates for the full $q^2$ range. The results of the unbinned maximum likelihood fits are shown with solid blue lines. Also shown are the signal component (short-dashed red line), the combinatorial background (long-dashed gray line), and the partially reconstructed background (dot-dashed magenta line). The peaking backgrounds $B^+ \to K^+ \pi^+ \pi^-$ (double-dot-dashed green line) and $B^+ \to \pi^+ \mu^+ \mu^-$ (dotted teal line) are also shown under the signal peak. The four data sets are (a) $B^+$ and (b) $B^-$ for one magnet polarity and (c) $B^+$ and (d) $B^-$ for the other.
difference in the value of $A_{CP}$ using these two fits is assigned as the uncertainty. The fit is also repeated using a reduced mass range of 5.17 $< m_{K_{S} \mu \mu} < 5.60$ GeV/$c^2$ to investigate the effect of excluding the partially reconstructed background. The difference in results obtained by modeling the combinatorial background using a second-order polynomial, rather than an exponential function, produces a small systematic uncertainty.

Uncertainties also arise from the assumptions made about the asymmetries in background events. Phenomena beyond the SM could cause the $CP$ asymmetry in $B^+ \rightarrow \pi^+ \mu^+ \mu^-$ decays to be large [24], and so the analysis is performed again for values of $A_{CP}(B^+ \rightarrow \pi^+ \mu^+ \mu^-) = \pm 0.5$, with the larger of the two deviations in $A_{CP}(B^+ \rightarrow K^+ \mu^+ \mu^-)$ taken as the systematic uncertainty. As the partially reconstructed background can arise from $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays, the value of $A_{CP}$ for this background source is taken to be $-0.072$ [7], the value from the LHCb measurement, neglecting any further $CP$ violation in angular distributions. The difference in the fit result compared to the zero $A_{CP}$ hypothesis is taken as the systematic uncertainty. Variations in $A_{CP}(B^+ \rightarrow K^+ \pi^+ \pi^-)$ have a negligible effect on the final result. A summary of the systematic uncertainties is shown in Table I. The value of $A_{CP}$ calculated by performing the fits on the data set integrated over $q^2$ is consistent with that from the weighted average of the $q^2$ bins.

The results for $A_{CP}$ in each $q^2$ bin and the weighted average are displayed in Table II, as well as in Fig. 2. The value of the raw asymmetry in $B^+ \rightarrow J/\psi K^+$ determined from the fit is $-0.016 \pm 0.002$. The $CP$ asymmetry in $B^+ \rightarrow K^+ \mu^+ \mu^-$ decays is measured to be

$$A_{CP} = 0.000 \pm 0.033 \text{ (stat)} \pm 0.005 \text{ (syst)} \pm 0.007 (J/\psi K),$$

where the third uncertainty is due to the uncertainty on the known value of $A_{CP}(B^+ \rightarrow J/\psi K^+)$. This compares with the current world average of $-0.05 \pm 0.13$ [20] and previous measurements, including the dielectron final state [2,4]. This result is consistent with the SM, as well as the $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay mode, and improves the precision of the current world average for the dimuon mode by a factor of 4. With the recent observation of resonant structure in the low-recoil region above the $\psi(2S)$ resonance [27], care should be taken when interpreting the result in this region. Interesting effects due to physics beyond the SM are possible through interference with this resonant structure and could be investigated in a future update of the measurement of $A_{CP}$.

<table>
<thead>
<tr>
<th>$q^2$ bin (GeV$^2$/c$^4$)</th>
<th>Residual asymmetries</th>
<th>Signal shape</th>
<th>Mass range</th>
<th>Combinatorial shape</th>
<th>$A_{CP}$ in $B^+ \rightarrow \pi^+ \mu^+ \mu^-$</th>
<th>$A_{CP}$ in $B^+ \rightarrow \pi^+ \mu^+ \mu^-$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05 $&lt; q^2 &lt;$ 2.00</td>
<td>0.005</td>
<td>0.005</td>
<td>0.002</td>
<td>0.002</td>
<td>0.004</td>
<td>0.002</td>
<td>0.008</td>
</tr>
<tr>
<td>2.00 $&lt; q^2 &lt;$ 4.30</td>
<td>0.004</td>
<td>0.001</td>
<td>0.005</td>
<td>0.009</td>
<td>0.005</td>
<td>0.001</td>
<td>0.012</td>
</tr>
<tr>
<td>4.30 $&lt; q^2 &lt;$ 8.68</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.005</td>
<td>0.002</td>
<td>0.005</td>
</tr>
<tr>
<td>10.09 $&lt; q^2 &lt;$ 12.86</td>
<td>0.003</td>
<td>0.005</td>
<td>0.002</td>
<td>0.003</td>
<td>0.003</td>
<td>0.001</td>
<td>0.024</td>
</tr>
<tr>
<td>14.18 $&lt; q^2 &lt;$ 16.00</td>
<td>0.006</td>
<td>0.001</td>
<td>0.004</td>
<td>0.003</td>
<td>$&lt;$0.001</td>
<td>$&lt;$0.001</td>
<td>0.008</td>
</tr>
<tr>
<td>16.00 $&lt; q^2 &lt;$ 18.00</td>
<td>0.005</td>
<td>0.007</td>
<td>0.017</td>
<td>$&lt;$0.001</td>
<td>$&lt;$0.001</td>
<td>0.001</td>
<td>0.019</td>
</tr>
<tr>
<td>18.00 $&lt; q^2 &lt;$ 22.00</td>
<td>0.008</td>
<td>0.001</td>
<td>0.014</td>
<td>$&lt;$0.001</td>
<td>$&lt;$0.001</td>
<td>0.001</td>
<td>0.016</td>
</tr>
<tr>
<td>Weighted average</td>
<td>0.001</td>
<td>$&lt;$0.001</td>
<td>0.003</td>
<td>0.001</td>
<td>0.003</td>
<td>$&lt;$0.001</td>
<td>0.005</td>
</tr>
<tr>
<td>1.00 $&lt; q^2 &lt;$ 6.00</td>
<td>0.002</td>
<td>$&lt;$0.001</td>
<td>0.009</td>
<td>0.002</td>
<td>0.004</td>
<td>0.002</td>
<td>0.010</td>
</tr>
</tbody>
</table>

Table II. Values of $A_{CP}$ and the signal yields in the seven $q^2$ bins, the weighted average, and their associated uncertainties.
FIG. 2 (color online). Measured value of $\mathcal{A}_{CP}$ in $B^+ \rightarrow K^+ \mu^+ \mu^-$ decays in bins of the $\mu^+ \mu^-$ invariant mass squared ($q^2$). The points are displayed at the mean value of $q^2$ in each bin. The uncertainties on each $\mathcal{A}_{CP}$ value are the statistical and systematic uncertainties added in quadrature. The excluded charmonium regions are represented by the vertical red lines, the dashed line is the weighted average, and the gray band indicates the $1\sigma$ uncertainty on the weighted average.

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 CEA/Saclay (France); BMBF, DFG, and MPG (Germany); SFI (Ireland); INFN (Italy); NWO (Netherlands); PIC (Italy); FOM (Netherlands); SCSR (Poland); MEN/IFA (Romania); “Kurchatov Institute” (Russia); MinECo, XuntaGal, and GENCAT (Spain); SNSF and SER (Switzerland); NAS Ukraine (Ukraine); STFC (United Kingdom); and NSF (U.S.A.). We also acknowledge the support received from the ERC under FP7. The Tier1 computing centers are supported by IN2P3 (France), KIT and BMBF (Germany), INFN (Italy), NWO and SURF (Netherlands), PIC (Spain), and 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.


(LHCb Collaboration)
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 Haluabei 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, Netherlands
41 Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, 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, Massachusetts, USA
56 University of Cincinnati, Cincinnati, Ohio, USA
57 University of Maryland, College Park, Maryland, USA
58 Syracuse University, Syracuse, New York, USA
59 Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil [associated with Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil]
60 Institut für Physik, Universität Rostock, Rostock, Germany [associated with Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany]
61 Celal Bayar University, Manisa, Turkey [associated with European Organization for Nuclear Research (CERN), Geneva, Switzerland]

a Also at P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia.
b Also at Università di Bari, Bari, Italy.
c Also at Università di Bologna, Bologna, Italy.
d Also at Università di Cagliari, Cagliari, Italy.
e Also at Università di Ferrara, Ferrara, Italy.
f Also at Università di Firenze, Firenze, Italy.
g Also at Università di Urbino, Urbino, Italy.
h Also at Università di Modena e Reggio Emilia, Modena, Italy.
i Also at Università di Genova, Genova, Italy.
j Also at Università di Milano Bicocca, Milano, Italy.
k Also at Università di Roma Tor Vergata, Roma, Italy.
Also at Università di Roma La Sapienza, Roma, Italy.

m Also at Università della Basilicata, Potenza, Italy.

n Also at LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain.

o Also at Hanoi University of Science, Hanoi, Vietnam.

p Also at Institute of Physics and Technology, Moscow, Russia.

q Also at Università di Padova, Padova, Italy.

r Also at Università di Pisa, Pisa, Italy.

s Also at Scuola Normale Superiore, Pisa, Italy.