Precision Measurement of *CP* Violation in the Penguin-Mediated Decay $B_s^0 \to \phi\phi$

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 20 April 2023; revised 28 June 2023; accepted 1 August 2023; published 23 October 2023)

A flavor-tagged time-dependent angular analysis of the decay $B_s^0 \to \phi\phi$ is performed using pp collision data collected by the LHCb experiment at the center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 6 fb^{-1}. The CP-violating phase and direct CP-violation parameter are measured to be $\phi_s^{s\bar{s}s} = -0.042 \pm 0.075 \pm 0.009$ rad and $|\lambda| = 1.004 \pm 0.030 \pm 0.009$, respectively, assuming the same values for all polarization states of the $\phi\phi$ system. In these results, the first uncertainties are statistical and the second systematic. These parameters are also determined separately for each polarization state, showing no evidence for polarization dependence. The results are combined with previous LHCb measurements using pp collisions at center-of-mass energies of 7 and 8 TeV, yielding $\phi_s^{s\bar{s}s} = -0.074 \pm 0.069$ rad and $|\lambda| = 1.009 \pm 0.030$. This is the most precise study of time-dependent CP violation in a penguin-dominated B meson decay. The results are consistent with CP symmetry and with the standard model predictions.

DOI: 10.1103/PhysRevLett.131.171802

Probing the nature of CP violation is central to understanding how the matter-dominated universe came to existence. Precision studies of time-dependent CP asymmetries in $b \to c\bar{c}s$ decays at the e^+e^- B factories [1,2] helped establish the Cabibbo-Kobayashi-Maskawa mechanism [3,4] as the dominant source of CP violation in the standard model (SM). However, the amount of CP violation provided by this mechanism is insufficient to explain the observed matter-antimatter asymmetry [5]. Flavor-changing neutral current decays of B mesons are highly sensitive to new physics contributions entering via loop (penguin) processes and provide excellent opportunities to reveal new sources of CP violation.

The penguin-dominated decay $B_s^0 \to \phi\phi$, which proceeds via a $b \to s\bar{s}s$ transition, is a benchmark channel to study CP violation in flavor-changing neutral current decays at the LHCb experiment. (Charge-conjugation processes are implied throughout this Letter.) Time-dependent CP violation in this decay, arising from the interference between the direct decay and the decay after B_s^0 mixing, is characterized by the CP-violating phase $\phi_s^{s\bar{s}s}$ and the parameter $|\lambda|$, which is related to direct CP violation. In the SM, the phase $\phi_s^{s\bar{s}s}$ is expected to be very close to zero due to a cancellation of the mixing and decay weak phases [6–10], and the parameter $|\lambda|$ is expected to be close to unity, indicating vanishing direct CP asymmetry [7–11]. However, new physics contributions in the penguin decay or the B_s^0 mixing could significantly alter the values of $\phi_s^{s\bar{s}s}$ and $|\lambda|$ [12–15].

In addition, the $\phi\phi$ system in this decay is produced in three linear polarization states, and the effects of new physics may be polarization dependent [14,15]. This is in contrast to the $B_s^0 \to J/\psi\phi$ decay, where potential new physics would mainly affect the mixing process and the polarization dependence is expected to be less pronounced, since the decay amplitude is dominated by a tree-level $b \to c\bar{c}s$ diagram. With no hint of new physics found in the B_s^0 mixing, this study of CP violation in $B_s^0 \to \phi\phi$ decays aims to probe new physics in $b \to s$ penguin processes.

The LHCb Collaboration has previously studied CP violation in the decay $B_s^0 \to \phi\phi$ [16–18]. The most precise measurements, $\phi_s^{s\bar{s}s} = -0.073 \pm 0.115(\mathrm{stat}) \pm 0.027(\mathrm{syst})$ rad and $|\lambda| = 0.99 \pm 0.05(\mathrm{stat}) \pm 0.01(\mathrm{syst})$ [18], are based on a data sample collected before 2017, corresponding to an integrated luminosity of 5 fb^{-1}. Because of the limited size of the data sample, a full polarization-dependent analysis was not performed. Instead, the CP-violating phases for the parallel and perpendicular polarization states were measured separately, with the phase of the longitudinal polarization fixed to zero. No evidence for polarization-dependent CP violation was observed.

This Letter reports an updated measurement of the CP-violation parameters in $B_s^0 \to \phi\phi$ decays using the full data sample of pp collisions collected with the LHCb detector at a center-of-mass energy of 13 TeV in 2015–2018 (Run 2), corresponding to an integrated luminosity of 6 fb^{-1}. The results are then combined with the LHCb result based on

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[*] Full author list given at the end of the Letter.

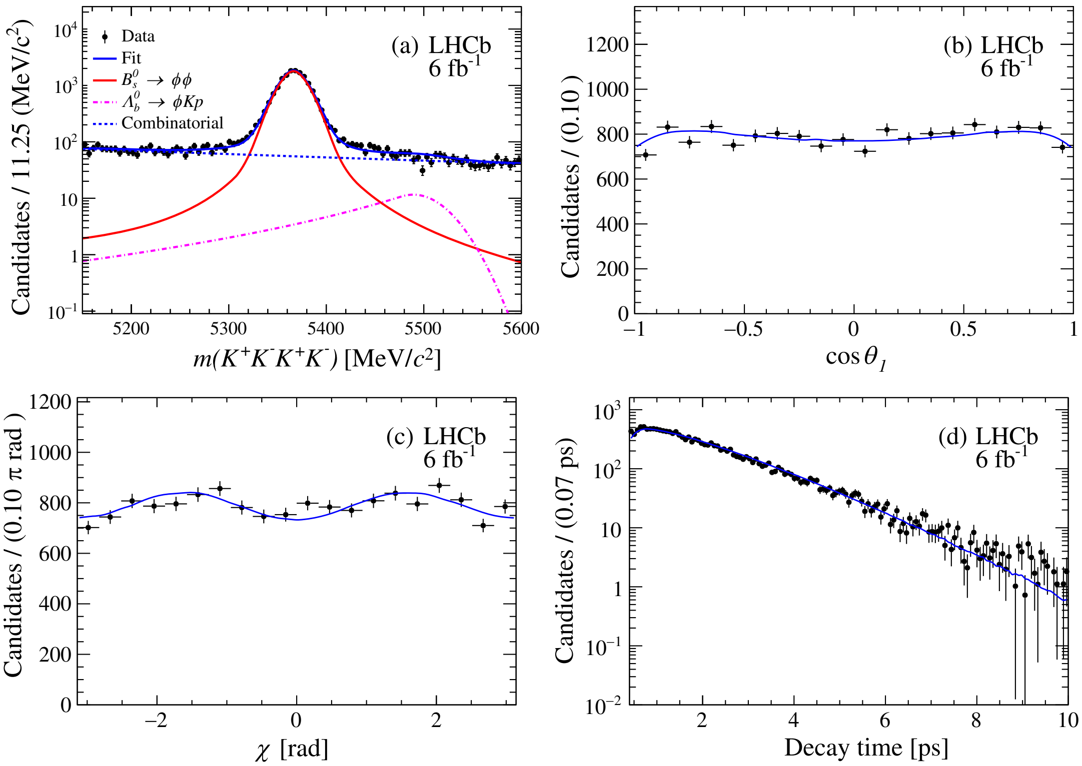

FIG. 1. (a) Mass distribution of the $B_s^0 \to \phi\phi$ candidates, superimposed by the fit projections. (b)–(d) Background-subtracted distributions of angular variables ($\cos\theta_1$ and χ) and decay time, superimposed by the fit projections.

the data collected at 7 and 8 TeV in 2011 and 2012 (Run 1) [17], corresponding to an integrated luminosity of 3 fb^{-1}. Apart from the increased data sample size, this analysis also benefits from recent software improvements, including new reconstruction algorithms for the vertex detectors that lead to a better decay-time resolution, and optimized flavor-tagging algorithms that increase the effective tagging efficiency. The flavor-tagged time-dependent angular analysis reported here largely follows the procedure described in Refs. [18]. New features related to the calibration of flavor tagging and decay-time resolution, and the modeling of decay-time acceptance are described in detail below. The increased sample size enables the *CP*-violation parameters in the decay $B_s^0 \to \phi\phi$ to be measured independently for all polarization states for the first time.

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$ and is described in detail in Refs. [19,20]. The simulated events used in this analysis are produced with the software described in Refs. [21–27]. The online event selection is performed by a trigger [28], which consists of a hardware trigger followed by a two-stage software trigger. For this analysis, the hardware trigger selects hadron or muon candidates with high transverse momentum (p_T). In the software trigger, $B_s^0 \to \phi\phi$ candidates are selected either by identifying events containing a pair of oppositely charged kaons with an invariant mass close to that of the ϕ meson, or by using a three-body topological b-hadron trigger [29].

In the off-line selection, $B_s^0 \to \phi\phi$ candidates, with the ϕ mesons decaying to a K^+K^- pair, are reconstructed by combining four high-quality charged tracks compatible with originating from the same vertex and identified as kaons. All tracks are required to have a p_T above 0.4 GeV$/c$. Two K^+K^- pairs, each with an invariant mass within 20 MeV$/c^2$ of the known mass of the ϕ meson [30], are combined to form $B_s^0 \to \phi\phi$ candidates and the product of their p_T is required to be above 1.2 GeV$^2/c^2$. The decay time of the B_s^0 candidates must be larger than 0.3 ps. The $K^+K^-K^+K^-$ invariant mass, $m(K^+K^-K^+K^-)$, must fall in the interval $[5000, 5800]$ MeV$/c^2$. Potential contamination from $B^0 \to \phi K^{*0}$ decays is largely suppressed by removing candidates that have a K^+K^- invariant mass within 30 MeV$/c^2$ of the known $K^*(892)^0$ mass [30] when the pion mass is assigned to a kaon candidate.

A multilayer perceptron (MLP) classifier [31,32] is used to further suppress background and improve the signal significance. The vertex fit χ^2 per degree of freedom, p_T and η of the B_s^0 candidate, the cosine of the angle between the B_s^0 momentum and its flight direction, as well as the p_T and η of the kaon and ϕ candidates are used as discriminating variables. The MLP classifier is trained using a sample of simulated $B_s^0 \to \phi\phi$ decays representing the signal and a background data sample consisting of $B_s^0 \to \phi\phi$ candidates with an invariant mass outside a ± 120 MeV$/c^2$ window around the known B_s^0 mass [30].

The k-fold method [33] with $k = 8$ is employed in the training of the MLP classifier. The lower threshold on the MLP output is chosen by maximizing the figure of merit defined as $N_s/\sqrt{N_s + N_b}$, where N_s is the expected signal yield in the signal region $[5322, 5412]\ \mathrm{MeV}/c^2$ and N_b is the expected background yield in this region estimated by interpolating the number of candidates observed in the sideband regions $[5100, 5160]\ \mathrm{MeV}/c^2$ and $[5487, 5547]\ \mathrm{MeV}/c^2$. Roughly 3% of the events contain more than one candidate. In these cases one candidate is chosen at random, and the influence of this choice is found to be negligible.

Selected $B_s^0 \to \phi\phi$ candidates in the mass range $[5150, 5600]\ \mathrm{MeV}/c^2$ are used in subsequent analysis. The mass distribution of these candidates is shown in Fig. 1(a). Two sources of background are identified: the combinatorial background and a peaking background component from $\Lambda_b^0 \to \phi K^- p$ decays due to misidentification of a proton as a kaon. A maximum-likelihood fit is performed to the mass distribution of selected $B_s^0 \to \phi\phi$ candidates. The signal shape is described by the sum of a double-sided crystal ball function [34] and a student's t-function [35] with all parameters fixed to the values estimated in the simulation except the peak position and resolution. The $\Lambda_b^0 \to \phi K^- p$ background is described by a double-sided crystal ball function with the shape parameters fixed to the values determined using the fast simulation package RAPIDSIM [36]. The combinatorial background is represented by an exponential function. The yields of the three components, the position and resolution of the signal component, and the slope of the background exponential function are allowed to vary in the fit. The $B_s^0 \to \phi\phi$ signal yield is measured to be 15840 ± 140. Based on the result of the fit to the mass distribution, a signal weight is assigned to each candidate using the *sPlot* method [37]. These signal weights are subsequently used in a maximum-likelihood fit [38] to the decay-time and angular distributions in order to statistically subtract the background contribution.

The decay of a B_s^0 meson to the $K^+K^-K^+K^-$ final state can proceed via the $\phi\phi$, ϕf_0 and $f_0 f_0$ intermediate states. Because of the small phase space of the decay $f_0 \to K^+K^-$ and the narrow K^+K^- mass window used to select the ϕ candidates, the latter two contributions are highly suppressed and found to be negligible from an angular fit that accounts for these contributions. Thus, in the subsequent analysis, only the $B_s^0 \to \phi\phi$ decay is considered. The differential decay rate is written as the sum of six terms, corresponding to contributions from the three polarization states and their interferences,

$$\frac{d^4\Gamma(t, \vec{\Omega})}{dt d\vec{\Omega}} \propto \sum_{k=1}^{6} h_k(t) f_k(\vec{\Omega}), \tag{1}$$

where t is the decay time of the B_s^0 meson, and $\vec{\Omega} = (\theta_1, \theta_2, \chi)$ denotes the helicity angles of the two K^+ mesons in the corresponding ϕ rest frame (θ_1, θ_2) and the angle between the two $\phi \to K^+K^-$ decay planes (χ). The angular functions $f_k(\vec{\Omega})$ are defined in Ref. [18]. The time-dependent functions $h_k(t)$ are given by [39]

$$h_k(t) = N_k e^{-\Gamma_s t}\left[a_k \cosh\left(\frac{\Delta\Gamma_s}{2} t\right) + b_k \sinh\left(\frac{\Delta\Gamma_s}{2} t\right) + Q c_k \cos(\Delta m_s t) + Q d_k \sin(\Delta m_s t)\right].$$

Here, Q equals $+1$ (-1) for an initial B_s^0 $(\bar{B}_s^0)$ state, Δm_s is the mass difference between the heavy and light B_s^0 mass eigenstates, $\Delta\Gamma_s$ is the decay width difference between the light and heavy mass eigenstates, and Γ_s is the average decay width. Ignoring CP violation in the B_s^0 mixing, in line with experimental measurements [40], the coefficients N_k, a_k, b_k, c_k, and d_k are defined [18] in terms of the magnitudes $|A_i|$, phases δ_i, CP-violating phases $\phi_{s,i}$ and direct CP-violation parameters $|\lambda_i|$ for the three polarization states of the B_s^0 decay at $t = 0$, with $i = 0, \parallel, \perp$. The three amplitudes satisfy $|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2 = 1$. The parameters $\phi_{s,i}$ and $|\lambda_i|$ are defined by the equation

$$\frac{q}{p}\frac{\bar{A}_i}{A_i} = \eta_i |\lambda_i| e^{-i\phi_{s,i}}, \tag{2}$$

where η_i is the CP eigenvalue of the polarization state i, q and p are complex numbers relating the B_s^0 mass eigenstates to the flavor eigenstates. A subset of parameters, chosen here as $(\phi_{s,i}, |\lambda_i|, |A_0|^2, |A_\perp|^2, \delta_\perp - \delta_0, \delta_\parallel - \delta_0)$, can be determined by performing a maximum-likelihood fit to the distributions of t, $\vec{\Omega}$, and Q. In the SM-like case or new physics scenarios where CP violation is polarization independent, the set of CP-violation observables can be reduced to $\phi_{s,i} = \phi_s^{s\bar{s}s}$ and $|\lambda_i| = |\lambda|$. In this analysis, the above formalism is used to obtain both polarization-independent and polarization-dependent results, taking into account the experimental effects discussed below.

The detector acceptance and selection requirements lead to a nonuniform efficiency as a function of the angular variables, referred to below as the angular acceptance. This effect is accounted for through the use of normalization factors calculated with simulated signal events subject to the same selection criteria as the data. Weights are assigned to the simulated events to improve the agreement with the data, in the shape of the kaon p_T distribution. These weights are determined with an iterative algorithm [18,41].

The reconstruction, trigger, and selection requirements result in a decay-time dependent efficiency. A cubic spline function [42], with 7 knots at [0.3, 0.5, 1.0, 1.5, 2.0, 3.0, 8.0] ps and 9 coefficients, is employed to describe the decay-time dependent efficiency function, referred to below as the decay-time acceptance. One coefficient is fixed to unity for normalization, and all the other coefficients are determined in the fit to the data, where the parameters Γ_s and $\Delta\Gamma_s$ are constrained to the recent measurements by the LHCb Collaboration in $B_s^0 \to J/\psi\phi$ decays [43]. Compared with the previous analysis in Ref. [18], which used $B_s^0 \to D_s^- \pi^+$ and $B^0 \to J/\psi K^{*0}$ decays as control channels to determine the decay-time acceptance, this method with free acceptance parameters simplifies the analysis without loss of precision for the physics parameters.

The dilution effect of the decay-time resolution on the B_s^0 oscillation is modeled by a Gaussian with a per-candidate width σ_t, which is related to the per-candidate decay-time uncertainty, δ_t, through a linear calibration function $\sigma_t = q_0 + q_1 \times \delta_t$. The parameters q_0 and q_1 are obtained using fictitious candidates formed of four prompt tracks from pp interactions, which have a decay time centered around 0. These prompt candidates are weighted to match the momentum and p_T distributions of the signal candidates and split into ten δ_t intervals. For each interval, the effective time resolution $\sigma_{t,i}$ is estimated by fitting the sum of three Gaussian functions with a common mean to the decay-time distribution of the prompt candidates and converting the resultant triple Gaussian into a single Gaussian that has the same damping effect on the observed B_s^0 oscillation amplitude [43]. A linear fit to the data points $(\delta_{t,i}, \sigma_{t,i})$ for all intervals provides the estimates of q_0 and q_1. The reliability of this calibration method is verified using simulated samples of signal decays and prompt candidates. The effective decay-time resolution is found to be between 42 and 44 fs, depending on the data-taking year.

The initial flavor of a B_s^0 meson is inferred using both opposite-side (OS) [44] and same-side (SS) [45] tagging algorithms. Each of the two methods yields a tagging decision Q with a mistag probability κ for each B_s^0 candidate, where $Q = +1, -1$ or 0, if the candidate is classified as B_s^0, $\bar{B}_s^0$, or untagged, respectively. The mistag probability is calibrated using a linear function $\omega = p_0 + p_1 \times \kappa$ for the OS tagging and a quadratic function $\omega = p_0 + p_1 \times \kappa + p_2 \times \kappa^2$ for the SS tagging, where ω is the corrected mistag probability. The calibration of the OS mistag probability uses $B^+ \to J/\psi K^+$ decays, for which the value of ω in an interval of κ can be obtained from the numbers of correct and wrong decisions. The calibration of the SS mistag probability uses flavor-specific $B_s^0 \to D_s^- \pi^+$ decays, for which the value of ω in an interval of κ is estimated by fitting the decay-time distribution. Detailed descriptions of the calibration procedures can be found in Refs. [18,41]. The effective tagging efficiency is estimated to be $(5.7 \pm 0.5)\%$, $(6.1 \pm 0.7)\%$, and $(6.3 \pm 0.5)\%$ for the 2015–2016, 2017, and 2018 data samples, respectively. Mistag asymmetries between B_s^0 and $\bar{B}_s^0$ decays are evaluated using $B^\pm \to J/\psi K^\pm$ decays for the OS tagging and prompt $D_s^\pm$ decays as a proxy for B_s^0 and $\bar{B}_s^0$ decays for the SS tagging, and accounted for in the subsequent signal fit.

TABLE I. Measured observables in the polarization-independent fit. The first uncertainties are statistical and the second systematic.

Parameter	Result
$\phi_s^{s\bar{s}s}$ (rad)	$-0.042 \pm 0.075 \pm 0.009$
$\lvert\lambda\rvert$	$1.004 \pm 0.030 \pm 0.009$
$\lvert A_0\rvert^2$	$0.384 \pm 0.007 \pm 0.003$
$\lvert A_\perp\rvert^2$	$0.310 \pm 0.006 \pm 0.003$
$\delta_\parallel - \delta_0$ (rad)	$2.463 \pm 0.029 \pm 0.009$
$\delta_\perp - \delta_0$ (rad)	$2.769 \pm 0.105 \pm 0.011$

A weighted maximum-likelihood fit [38] is simultaneously performed to the three subsamples of data recorded in 2015–2016, 2017, and 2018. The probability density function for each period is based on Eq. (1) and takes into account the effects of angular acceptance, decay-time acceptance, decay-time resolution, and mistag probability. The parameter Δm_s is constrained to the measurement by the LHCb Collaboration, $\Delta m_s = 17.766 \pm 0.006\ \mathrm{ps}^{-1}$ [46].

The background-subtracted data distributions of the decay-time and angular variables with projections of the polarization-independent fit are shown in Figs. 1(b)–(d). The fit results are summarized in Table I, which include both statistical and systematic uncertainties. The correlation matrix is given in the Supplemental Material [47], as well as the observed time-dependent asymmetry between flavor-tagged B_s^0 and $\bar{B}_s^0$ decays.

A summary of the systematic uncertainties for the polarization-independent fit is reported in Table II. The total systematic uncertainty on $\phi_s^{s\bar{s}s}$, which is the sum in quadrature of the different contributions, is 0.009 rad, significantly smaller than the statistical uncertainty of 0.075 rad. This is also the case for the other physics parameters.

Inaccuracies in the determination of the calibration parameters of the decay-time resolution (q_0, q_1) and the flavor tagging (p_0, p_1, p_2) lead to systematic effects on the CP-violation observables. These parameters are fixed in the baseline fit, and their combined statistical and systematic uncertainties are propagated to the fit parameters as systematic uncertainties. The compatibility of the calibration parameter values in control and signal channels are checked using simulated samples, and the observed differences are treated as sources of systematic uncertainties. These uncertainties are taken to be fully correlated between different data-taking periods. A bias of roughly −5 fs on the reconstructed decay time is observed in the calibration of the decay-time resolution. Since this bias is much smaller than the effective resolution, neglecting it in

TABLE II. Systematic uncertainties for physics parameters in the polarization-independent fit; the values are given in units of 10^{-3} (10^{-3} rad for angles).

Source	$\phi_s^{s\bar{s}s}$	$\vert\lambda\vert$	$\vert A_0\vert^2$	$\vert A_\perp\vert^2$	$\delta_\parallel - \delta_0$	$\delta_\perp - \delta_0$
Time resolution	4.9	2.6	0.8	0.8	0.1	3.4
Flavor tagging	4.8	4.7	0.9	1.3	1.2	9.7
Angular acceptance	3.9	4.9	1.4	1.7	4.7	1.2
Time acceptance	2.3	1.7	0.1	0.1	5.6	0.7
Mass fit and factorization	2.2	4.4	1.9	2.3	2.3	2.5
MC truth match	1.1	0.2	0.1	0.1	0.2	0.3
Fit bias	0.8	0.7	0.9	0.3	3.6	0.7
Candidate multiplicity	0.3	0.2	0.1	0.8	0.2	0.1
Total	8.8	8.6	2.7	3.3	8.5	10.7

the analysis of the signal decays results in negligible effects on the physics parameters.

The systematic uncertainties related to the angular acceptance comprise the uncertainties due to the limited size of the simulation sample, evaluated using a bootstrapping [48] procedure, and uncertainties associated with convergence of the iterative correction procedure, estimated by comparing fit results with different numbers of iterations.

The systematic uncertainties related to the decay-time acceptance are found by varying the knot positions of the spline function to achieve similar fit quality of the decay-time distribution to that of the baseline fit. The maximum changes of the parameter estimates are assigned as systematic uncertainties.

The effects of mismodeling the signal and background mass distributions are studied by using alternative shape functions that can achieve similar fit quality to that of the baseline fit. The maximum changes of the parameter estimates are assigned as systematic uncertainties. The *sPlot* method used to subtract background in the time-dependent angular fit requires that the discriminating variable, $m(K^+K^-K^+K^-)$, is uncorrelated with the decay angles, $\vec{\Omega}$, and decay time, t. To evaluate the effects of possible correlations among these variables, the data sample is split into three subsamples according to the value of $\cos^2\theta_1 + \cos^2\theta_2$, χ, or t, respectively. A fit to the $m(K^+K^-K^+K^-)$ distribution of each subsample is performed, and signal weights are calculated accordingly. The three subsamples are then recombined and a new time-dependent angular fit is performed. The maximum changes of the parameter estimates are assigned as systematic uncertainties.

The intrinsic bias from the maximum-likelihood fit with a limited sample size is evaluated by performing pseudoexperiments, which also demonstrate that the parameter uncertainties estimated in the fit are reliable after correcting for the background dilution effect.

Various checks of the fit procedure are performed by splitting the data sample according to magnet polarity, trigger selection, tagging category, data-taking period, and multiple decay-time and B_s^0 -meson p_T intervals. The effect of tightening the kaon-identification and MLP-output requirements is also studied. The fit results are compatible between different subsamples in all checks.

The polarization-independent measurements of the CP-violation parameters $\phi_s^{s\bar{s}s}$ and $|\lambda|$ in $B_s^0 \to \phi\phi$ decays presented here are combined with the LHCb Run 1 measurements, $\phi_s^{s\bar{s}s} = -0.17 \pm 0.15(\text{stat}) \pm 0.03(\text{syst})$ rad and $|\lambda| = 1.04 \pm 0.07(\text{stat}) \pm 0.03(\text{syst})$ [17] using the procedure described in Ref. [43]. In the combination, those systematic uncertainties that arise from the same origin are taken to be completely correlated between the Run 1 and Run 2 results. The combined values of the CP-violation parameters are $\phi_s^{s\bar{s}s} = -0.074 \pm 0.069$ rad and $|\lambda| = 1.009 \pm 0.030$, with a correlation coefficient of -0.02. This is the most precise measurement of CP violation in $B_s^0 \to \phi\phi$ decays to date, as is illustrated in Fig. 2.

A polarization-dependent fit is performed using the same dataset, where the parameters $\phi_{s,i}$ and λ_i can take different values for the three polarization states. To reduce parameter correlations in the fit, the phase differences, $\phi_{s,\parallel} - \phi_{s,0}$ and

$$
\begin{aligned}
\phi_{s,0} &= -0.18 \pm 0.09 \text{ rad}\,, & |\lambda_0| &= 1.02 \pm 0.17\,, \\
\phi_{s,\parallel} - \phi_{s,0} &= 0.12 \pm 0.09 \text{ rad}\,, & |\lambda_\perp/\lambda_0| &= 0.97 \pm 0.22\,, \\
\phi_{s,\perp} - \phi_{s,0} &= 0.17 \pm 0.09 \text{ rad}\,, & |\lambda_\parallel/\lambda_0| &= 0.78 \pm 0.21\,,
\end{aligned}
$$

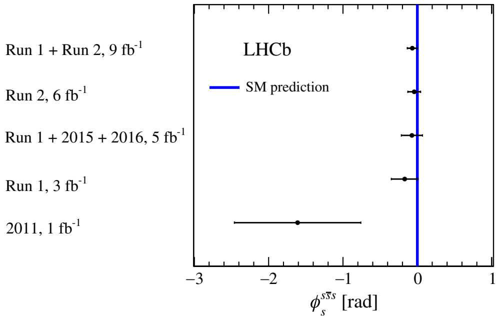

FIG. 2. Comparison of $\phi_s^{s\bar{s}s}$ measurements from this and previous analyses [16–18] by the LHCb Collaboration. The vertical band indicates the SM prediction [6,7,9].

$\phi_{s,\perp} - \phi_{s,0}$, and ratios, $|\lambda_\perp/\lambda_0|$ and $|\lambda_\parallel/\lambda_0|$, are used as fit parameters. The measured values are

$$\begin{aligned} \phi_{s,0} &= -0.18 \pm 0.09 \text{ rad}, & |\lambda_0| &= 1.02 \pm 0.17, \\ \phi_{s,\parallel} - \phi_{s,0} &= 0.12 \pm 0.09 \text{ rad}, & |\lambda_\perp/\lambda_0| &= 0.97 \pm 0.22, \\ \phi_{s,\perp} - \phi_{s,0} &= 0.17 \pm 0.09 \text{ rad}, & |\lambda_\parallel/\lambda_0| &= 0.78 \pm 0.21, \end{aligned}$$

where the uncertainties are statistical only. No significant difference between different polarization states is observed.

In conclusion, a measurement of the polarization-independent CP-violation observables in $B_s^0 \to \phi\phi$ decays is performed using data collected with the LHCb detector in 2015–2018, corresponding to a total integrated luminosity of 6 fb^{-1}. The results are

$$\begin{aligned} \phi_s^{s\bar{s}s} &= -0.042 \pm 0.075 \pm 0.009 \text{ rad}, \\ |\lambda| &= 1.004 \pm 0.030 \pm 0.009, \end{aligned}$$

where the first uncertainties are statistical and the second systematic. These results are combined with the LHCb measurements based on data taken in 2011 and 2012 to obtain $\phi_s^{s\bar{s}s} = -0.074 \pm 0.069$ rad and $|\lambda| = 1.009 \pm 0.030$. This is the most precise measurement of time-dependent CP asymmetry in the decay $B_s^0 \to \phi\phi$ and in any penguin-dominated B meson decay. The measurement is consistent with and supersedes the measurement in Ref. [18], and agrees with the SM expectation of tiny CP violation. For the first time, the polarization-dependent CP-violation parameters are measured, which show no significant difference between the three polarization states of $B_s^0 \to \phi\phi$ decays. These results can be used to constrain new physics contributions in $b \to s$ transitions [12–14].

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); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG, and MPG (Germany); INFN (Italy); NWO (Netherlands); MNiSW and NCN (Poland); MCID/IFA (Romania); MICINN (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); DOE NP and NSF (USA). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), PIC (Spain), GridPP (United Kingdom), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), Polish WLCG (Poland), and NERSC (USA). We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from ARC and ARDC (Australia); Minciencias (Colombia); AvH Foundation (Germany); EPLANET, Marie Skłodowska-Curie Actions, ERC and NextGenerationEU (European Union); A*MIDEX, ANR, IPhU and Labex P2IO, and Région Auvergne-Rhône-Alpes (France); Key Research Program of Frontier Sciences of CAS, CAS PIFI, CAS CCEPP, Fundamental Research Funds for the Central Universities, and Science and Tech. Program of Guangzhou (China); GVA, XuntaGal, GENCAT, Inditex, InTalent and Prog. Atracción Talento, CM (Spain); SRC (Sweden); the Leverhulme Trust, the Royal Society and UKRI (United Kingdom).

[1] T. Abe *et al.* (Belle-II Collaboration), Report No. KEK-REPORT-2010-1, 2010, arXiv:1011.0352.
[2] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **91**, 071801 (2003).
[3] N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963).
[4] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).
[5] P. Huet and E. Sather, Phys. Rev. D **51**, 379 (1995).
[6] M. Raidal, Phys. Rev. Lett. **89**, 231803 (2002).
[7] M. Beneke, J. Rohrer, and D. Yang, Nucl. Phys. B **774**, 64 (2007).
[8] M. Bartsch, G. Buchalla, and C. Kraus, arXiv:0810.0249.
[9] H.-Y. Cheng and C.-K. Chua, Phys. Rev. D **80**, 114026 (2009).
[10] C. Wang, S.-H. Zhou, Y. Li, and C.-D. Lu, Phys. Rev. D **96**, 073004 (2017).
[11] D.-C. Yan, X. Liu, and Z.-J. Xiao, Nucl. Phys. B **935**, 17 (2018).
[12] D. Zhang, Z.-J. Xiao, and C. S. Li, Phys. Rev. D **64**, 014014 (2001).
[13] A. Datta, M. Duraisamy, and D. London, Phys. Rev. D **86**, 076011 (2012).
[14] B. Bhattacharya, A. Datta, M. Duraisamy, and D. London, Phys. Rev. D **88**, 016007 (2013).
[15] T. Kapoor and E. Kou, arXiv:2303.04494.
[16] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **110**, 241802 (2013).
[17] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. D **90**, 052011 (2014).
[18] R. Aaij *et al.* (LHCb Collaboration), J. High Energy Phys. 12 (2019) 155.
[19] A. A. Alves Jr. *et al.* (LHCb Collaboration), J. Instrum. **3**, S08005 (2008).
[20] R. Aaij *et al.* (LHCb Collaboration), Int. J. Mod. Phys. A **30**, 1530022 (2015).
[21] T. Sjöstrand, S. Mrenna, and P. Skands, Comput. Phys. Commun. **178**, 852 (2008).
[22] T. Sjöstrand, S. Mrenna, and P. Skands, J. High Energy Phys. 05 (2006) 026.
[23] I. Belyaev *et al.*, J. Phys. Conf. Ser. **331**, 032047 (2011).
[24] S. Agostinelli *et al.* (Geant4 Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003).
[25] J. Allison *et al.* (Geant4 Collaboration), IEEE Trans. Nucl. Sci. **53**, 270 (2006).
[26] M. Clemencic, G. Corti, S. Easo, C. R. Jones, S. Miglioranzi, M. Pappagallo, and P. Robbe, J. Phys. Conf. Ser. **331**, 032023 (2011).
[27] N. Davidson, T. Przedzinski, and Z. Was, Comput. Phys. Commun. **199**, 86 (2016).
[28] R. Aaij *et al.*, J. Instrum. **8**, P04022 (2013).

[29] T. Likhomanenko, P. Ilten, E. Khairullin, A. Rogozhnikov, A. Ustyuzhanin, and M. Williams, J. Phys. Conf. Ser. **664**, 082025 (2015).

[30] R. L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2022**, 083C01 (2022).

[31] H. Voss, A. Hoecker, J. Stelzer, and F. Tegenfeldt, Proc. Sci., ACAT2007 (**2007**) 040.

[32] T. Hastie, J. Friedman, and R. Tibshirani, in *Model Inference and Averaging* (Springer, New York, New York, NY, 2001), pp. 225–256.

[33] A. Blum, A. T. Kalai, and J. Langford, in *Proceedings of the Annual Conference Computational Learning Theory* (Association for Computing Machinery, New York, 1999).

[34] T. Skwarnicki, A study of the radiative cascade transitions between the Upsilon-prime and Upsilon resonances, Ph.D. thesis, Institute of Nuclear Physics, Krakow, 1986 [Report No. DESY-F31-86-02].

[35] C. Bishop, *Pattern Recognition and Machine Learning (Information Science and Statistics)* (Springer-Verlag, New York, Inc., Secaucus, 2007).

[36] G. A. Cowan, D. C. Craik, and M. D. Needham, Comput. Phys. Commun. **214**, 239 (2017).

[37] M. Pivk and F. R. Le Diberder, Nucl. Instrum. Methods Phys. Res., Sect. A **555**, 356 (2005).

[38] Y. Xie, arXiv:0905.0724.

[39] T. du Pree, Search for a strange phase in beautiful oscillations, Ph.D. thesis, Vrije University, Amsterdam, Vrije University, Amsterdam, 2010.

[40] Y. Amhis *et al.* (Heavy Flavor Averaging Group), Eur. Phys. J. C **81**, 226 (2021), updated results and plots available at https://hflav.web.cern.ch.

[41] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. D **87**, 112010 (2013).

[42] T. M. Karbach, G. Raven, and M. Schiller, arXiv: 1407.0748.

[43] R. Aaij *et al.* (LHCb Collaboration), Eur. Phys. J. C **79**, 706 (2019); **80**, 601(E) (2020).

[44] R. Aaij *et al.* (LHCb Collaboration), Eur. Phys. J. C **72**, 2022 (2012).

[45] R. Aaij *et al.* (LHCb Collaboration), J. Instrum. **11**, P05010 (2016).

[46] R. Aaij *et al.* (LHCb Collaboration), Nat. Phys. **18**, 1 (2022).

[47] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.131.171802 for the correlation matrix of the measured observables and a plot of the observed time-dependent asymmetries between B_s^0 and $\bar{B}_s^0$ decays.

[48] B. Efron and R. Tibshirani, Stat. Sci. **1**, 54 (1986).

R. Aaij,[32] A. S. W. Abdelmotteleb,[51] C. Abellan Beteta,[45] F. Abudinén,[51] T. Ackernley,[55] B. Adeva,[41]
M. Adinolfi,[49] P. Adlarson,[77] H. Afsharnia,[9] C. Agapopoulou,[43] C. A. Aidala,[78] Z. Ajaltouni,[9] S. Akar,[60]
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G. Raven,[33] M. Rebollo De Miguel,[42] F. Redi,[43] J. Reich,[49] F. Reiss,[57] Z. Ren,[3] P. K. Resmi,[58] R. Ribatti,[29,d]
A. M. Ricci,[27] S. Ricciardi,[52] K. Richardson,[59] M. Richardson-Slipper,[53] K. Rinnert,[55] P. Robbe,[11]
G. Robertson,[53] E. Rodrigues,[55,43] E. Rodriguez Fernandez,[41] J. A. Rodriguez Lopez,[70] E. Rodriguez Rodriguez,[41]
D. L. Rolf,[43] A. Rollings,[58] P. Roloff,[43] V. Romanovskiy,[38] M. Romero Lamas,[41] A. Romero Vidal,[41]
M. Rotondo,[23] M. S. Rudolph,[63] T. Ruf,[43] R. A. Ruiz Fernandez,[41] J. Ruiz Vidal,[42] A. Ryzhikov,[38] J. Ryzka,[34]
J. J. Saborido Silva,[41] N. Sagidova,[38] N. Sahoo,[48] B. Saitta,[27,s] M. Salomoni,[43] C. Sanchez Gras,[32]
I. Sanderswood,[42] R. Santacesaria,[30] C. Santamarina Rios,[41] M. Santimaria,[23] L. Santoro,[1] E. Santovetti,[31]
D. Saranin,[38] G. Sarpis,[53] M. Sarpis,[71] A. Sarti,[30] C. Satriano,[30,v] A. Satta,[31] M. Saur,[5] D. Savrina,[38]
H. Sazak,[9] L. G. Scantlebury Smead,[58] A. Scarabotto,[13] S. Schael,[14] S. Scherl,[55] A. M. Schertz,[72] M. Schiller,[54]
H. Schindler,[43] M. Schmelling,[16] B. Schmidt,[43] S. Schmitt,[14] O. Schneider,[44] A. Schopper,[43] M. Schubiger,[32]
N. Schulte,[15] S. Schulte,[44] M. H. Schune,[11] R. Schwemmer,[43] G. Schwering,[14] B. Sciascia,[23] A. Sciuccati,[43]
S. Sellam,[41] A. Semennikov,[38] M. Senghi Soares,[33] A. Sergi,[24,h] N. Serra,[45] L. Sestini,[28] A. Seuthe,[15]
Y. Shang,[5] D. M. Shangase,[78] M. Shapkin,[38] I. Shchemerov,[38] L. Shchutska,[44] T. Shears,[55] L. Shekhtman,[38]

Z. Shen,[5] S. Sheng,[4,6] V. Shevchenko,[38] B. Shi,[6] E. B. Shields,[26,f] Y. Shimizu,[11] E. Shmanin,[38] R. Shorkin,[38]
J. D. Shupperd,[63] B. G. Siddi,[21,e] R. Silva Coutinho,[63] G. Simi,[28] S. Simone,[19,k] M. Singla,[64] N. Skidmore,[57]
R. Skuza,[17] T. Skwarnicki,[63] M. W. Slater,[48] J. C. Smallwood,[58] J. G. Smeaton,[50] E. Smith,[45] K. Smith,[62]
M. Smith,[56] A. Snoch,[32] L. Soares Lavra,[9] M. D. Sokoloff,[60] F. J. P. Soler,[54] A. Solomin,[38,49] A. Solovev,[38]
I. Solovyev,[38] R. Song,[64] F. L. Souza De Almeida,[2] B. Souza De Paula,[2] E. Spadaro Norella,[25,m] E. Spedicato,[20]
J. G. Speer,[15] E. Spiridenkov,[38] P. Spradlin,[54] V. Sriskaran,[43] F. Stagni,[43] M. Stahl,[43] S. Stahl,[43] S. Stanislaus,[58]
E. N. Stein,[43] O. Steinkamp,[45] O. Stenyakin,[38] H. Stevens,[15] D. Strekalina,[38] Y. S Su,[6] F. Suljik,[58] J. Sun,[27]
L. Sun,[69] Y. Sun,[61] P. N. Swallow,[48] K. Swientek,[34] A. Szabelski,[36] T. Szumlak,[34] M. Szymanski,[43] Y. Tan,[3]
S. Taneja,[57] M. D. Tat,[58] A. Terentev,[45] F. Teubert,[43] E. Thomas,[43] D. J. D. Thompson,[48] H. Tilquin,[56]
V. Tisserand,[9] S. T'Jampens,[8] M. Tobin,[4] L. Tomassetti,[21,e] G. Tonani,[25,m] X. Tong,[5] D. Torres Machado,[1]
L. Toscano,[15] D. Y. Tou,[3] C. Trippl,[44] G. Tuci,[17] N. Tuning,[32] A. Ukleja,[36] D. J. Unverzagt,[17] A. Usachov,[33]
A. Ustyuzhanin,[38] U. Uwer,[17] V. Vagnoni,[20] A. Valassi,[43] G. Valenti,[20] N. Valls Canudas,[39] M. Van Dijk,[44]
H. Van Hecke,[62] E. van Herwijnen,[56] C. B. Van Hulse,[41,w] M. van Veghel,[32] R. Vazquez Gomez,[40]
P. Vazquez Regueiro,[41] C. Vázquez Sierra,[41] S. Vecchi,[21] J. J. Velthuis,[49] M. Veltri,[22,x] A. Venkateswaran,[44]
M. Vesterinen,[51] D. Vieira,[60] M. Vieites Diaz,[44] X. Vilasis-Cardona,[39] E. Vilella Figueras,[55] A. Villa,[20]
P. Vincent,[13] F. C. Volle,[11] D. vom Bruch,[10] V. Vorobyev,[38] N. Voropaev,[38] K. Vos,[75] C. Vrahas,[53] J. Walsh,[29]
E. J. Walton,[64] G. Wan,[5] C. Wang,[17] G. Wang,[7] J. Wang,[5] J. Wang,[4] J. Wang,[3] J. Wang,[69] M. Wang,[25]
R. Wang,[49] X. Wang,[67] Y. Wang,[7] Z. Wang,[45] Z. Wang,[3] Z. Wang,[6] J. A. Ward,[51,64] N. K. Watson,[48]
D. Websdale,[56] Y. Wei,[5] B. D. C. Westhenry,[49] D. J. White,[57] M. Whitehead,[54] A. R. Wiederhold,[51]
D. Wiedner,[15] G. Wilkinson,[58] M. K. Wilkinson,[60] I. Williams,[50] M. Williams,[59] M. R. J. Williams,[53]
R. Williams,[50] F. F. Wilson,[52] W. Wislicki,[36] M. Witek,[35] L. Witola,[17] C. P. Wong,[62] G. Wormser,[11]
S. A. Wotton,[50] H. Wu,[63] J. Wu,[7] Y. Wu,[5] K. Wyllie,[43] Z. Xiang,[6] Y. Xie,[7] A. Xu,[5] J. Xu,[6] L. Xu,[3] L. Xu,[3]
M. Xu,[51] Q. Xu,[6] Z. Xu,[9] Z. Xu,[6] Z. Xu,[4] D. Yang,[3] S. Yang,[6] X. Yang,[5] Y. Yang,[6] Z. Yang,[5] Z. Yang,[61]
V. Yeroshenko,[11] H. Yeung,[57] H. Yin,[7] J. Yu,[66] X. Yuan,[63] E. Zaffaroni,[44] M. Zavertyaev,[16] M. Zdybal,[35]
M. Zeng,[3] C. Zhang,[5] D. Zhang,[7] J. Z Zhang,[6] L. Zhang,[3] S. Zhang,[66] S. Zhang,[5] Y. Zhang,[5] Y. Zhang,[58]
Y. Zhao,[17] A. Zharkova,[38] A. Zhelezov,[17] Y. Zheng,[6] T. Zhou,[5] X. Zhou,[7] Y. Zhou,[6] V. Zhovkovska,[11]
X. Zhu,[3] X. Zhu,[7] Z. Zhu,[6] V. Zhukov,[14,38] J. Zhuo,[42] Q. Zou,[4,6] S. Zucchelli,[20,g]
D. Zuliani,[28] and G. Zunica[57]

(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]*Institute Of High Energy Physics (IHEP), Beijing, China*
[5]*School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[6]*University of Chinese Academy of Sciences, Beijing, China*
[7]*Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China*
[8]*Université Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France*
[9]*Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France*
[10]*Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France*
[11]*Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France*
[12]*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France*
[13]*LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France*
[14]*I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany*
[15]*Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*
[16]*Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany*
[17]*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[18]*School of Physics, University College Dublin, Dublin, Ireland*
[19]*INFN Sezione di Bari, Bari, Italy*
[20]*INFN Sezione di Bologna, Bologna, Italy*
[21]*INFN Sezione di Ferrara, Ferrara, Italy*

[22]*INFN Sezione di Firenze, Firenze, Italy*
[23]*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
[24]*INFN Sezione di Genova, Genova, Italy*
[25]*INFN Sezione di Milano, Milano, Italy*
[26]*INFN Sezione di Milano-Bicocca, Milano, Italy*
[27]*INFN Sezione di Cagliari, Monserrato, Italy*
[28]*Università degli Studi di Padova, Università e INFN, Padova, Padova, Italy*
[29]*INFN Sezione di Pisa, Pisa, Italy*
[30]*INFN Sezione di Roma La Sapienza, Roma, Italy*
[31]*INFN Sezione di Roma Tor Vergata, Roma, Italy*
[32]*Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands*
[33]*Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands*
[34]*AGH—University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland*
[35]*Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland*
[36]*National Center for Nuclear Research (NCBJ), Warsaw, Poland*
[37]*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania*
[38]*Affiliated with an institute covered by a cooperation agreement with CERN*
[39]*DS4DS, La Salle, Universitat Ramon Llull, Barcelona, Spain*
[40]*ICCUB, Universitat de Barcelona, Barcelona, Spain*
[41]*Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain*
[42]*Instituto de Fisica Corpuscular, Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain*
[43]*European Organization for Nuclear Research (CERN), Geneva, Switzerland*
[44]*Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
[45]*Physik-Institut, Universität Zürich, Zürich, Switzerland*
[46]*NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine*
[47]*Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine*
[48]*University of Birmingham, Birmingham, United Kingdom*
[49]*H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
[50]*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
[51]*Department of Physics, University of Warwick, Coventry, United Kingdom*
[52]*STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
[53]*School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
[54]*School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
[55]*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
[56]*Imperial College London, London, United Kingdom*
[57]*Department of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
[58]*Department of Physics, University of Oxford, Oxford, United Kingdom*
[59]*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
[60]*University of Cincinnati, Cincinnati, Ohio, USA*
[61]*University of Maryland, College Park, Maryland, USA*
[62]*Los Alamos National Laboratory (LANL), Los Alamos, New Mexico, USA*
[63]*Syracuse University, Syracuse, New York, USA*
[64]*School of Physics and Astronomy, Monash University, Melbourne, Australia*
(associated with Department of Physics, University of Warwick, Coventry, United Kingdom)
[65]*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)
[66]*Physics and Micro Electronic College, Hunan University, Changsha City, China*
(associated with Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China)
[67]*Guangdong Provincial Key Laboratory of Nuclear Science, Guangdong-Hong Kong Joint Laboratory of Quantum Matter,*
Institute of Quantum Matter, South China Normal University, Guangzhou, China
(associated with Center for High Energy Physics, Tsinghua University, Beijing, China)
[68]*Lanzhou University, Lanzhou, China (associated with Institute Of High Energy Physics (IHEP), Beijing, China)*
[69]*School of Physics and Technology, Wuhan University, Wuhan, China*
(associated with Center for High Energy Physics, Tsinghua University, Beijing, China)
[70]*Departamento de Fisica, Universidad Nacional de Colombia, Bogota, Colombia*
(associated with LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France)
[71]*Universität Bonn—Helmholtz-Institut für Strahlen und Kernphysik, Bonn, Germany*
(associated with Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany)
[72]*Eotvos Lorand University, Budapest, Hungary*
(associated with European Organization for Nuclear Research (CERN), Geneva, Switzerland)

[73]*INFN Sezione di Perugia, Perugia, Italy (associated with INFN Sezione di Ferrara, Ferrara, Italy)*
[74]*Van Swinderen Institute, University of Groningen, Groningen, Netherlands*
(associated with Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands)
[75]*Universiteit Maastricht, Maastricht, Netherlands*
(associated with Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands)
[76]*Faculty of Material Engineering and Physics, Cracow, Poland*
(associated with Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland)
[77]*Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden*
(associated with School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom)
[78]*University of Michigan, Ann Arbor, Michigan, USA (associated with Syracuse University, Syracuse, New York, USA)*

[a] Deceased.
[b] Also at Università di Roma Tor Vergata, Roma, Italy.
[c] Also at Università di Firenze, Firenze, Italy.
[d] Also at Scuola Normale Superiore, Pisa, Italy.
[e] Also at Università di Ferrara, Ferrara, Italy.
[f] Also at Università di Milano Bicocca, Milano, Italy.
[g] Also at Università di Bologna, Bologna, Italy.
[h] Also at Università di Genova, Genova, Italy.
[i] Also at Universidade da Coruña, Coruña, Spain.
[j] Also at Universidad Nacional Autónoma de Honduras, Tegucigalpa, Honduras.
[k] Also at Università di Bari, Bari, Italy.
[l] Also at Università di Perugia, Perugia, Italy.
[m] Also at Università degli Studi di Milano, Milano, Italy.
[n] Also at Universidade de Brasília, Brasília, Brazil.
[o] Also at Hangzhou Institute for Advanced Study, UCAS, Hangzhou, China.
[p] Also at Università di Pisa, Pisa, Italy.
[q] Also at Central South U., Changsha, China.
[r] Also at Università di Padova, Padova, Italy.
[s] Also at Università di Cagliari, Cagliari, Italy.
[t] Also at MSU—Iligan Institute of Technology (MSU-IIT), Iligan, Philippines.
[u] Also at Excellence Cluster ORIGINS, Munich, Germany.
[v] Also at Università della Basilicata, Potenza, Italy.
[w] Also at Universidad de Alcalá, Alcalá de Henares, Spain.
[x] Also at Università di Urbino, Urbino, Italy.