

# Angular analysis of the decay $B_s^0 \rightarrow \phi e^+ e^-$

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## The LHCb collaboration

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**ABSTRACT:** An angular analysis of the decay  $B_s^0 \rightarrow \phi e^+ e^-$  is presented, using proton-proton collision data collected with the LHCb detector between 2011 and 2018 at centre-of-mass energies of 7, 8 and 13 TeV. The combined dataset corresponds to an integrated luminosity of  $9 \text{ fb}^{-1}$ . Observables are determined by fitting time-integrated projections of the angular distribution in three bins of dielectron mass squared,  $q^2$ , corresponding to  $[0.1, 1.1]$ ,  $[1.1, 6.0]$  and  $[15.0, 19.0] \text{ GeV}^2/c^4$ . The results are compatible with predictions based on the Standard Model of particle physics.

**KEYWORDS:** B Physics, Flavour Changing Neutral Currents, Hadron-Hadron Scattering, Rare Decay

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**Contents**

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>Angular distribution</b>	<b>3</b>
<b>3</b>	<b>Detector and simulation</b>	<b>5</b>
<b>4</b>	<b>Candidate selection</b>	<b>5</b>
<b>5</b>	<b>Angular and time-dependent efficiency</b>	<b>6</b>
<b>6</b>	<b>Mass and angular distributions</b>	<b>8</b>
<b>7</b>	<b>Validation</b>	<b>9</b>
<b>8</b>	<b>Systematic uncertainties</b>	<b>10</b>
<b>9</b>	<b>Results</b>	<b>13</b>
<b>10</b>	<b>Summary</b>	<b>13</b>
	<b>The LHCb collaboration</b>	<b>21</b>

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**1 Introduction**

The  $B_s^0 \rightarrow \phi \ell^+ \ell^-$  decays, where  $\ell$  represents an electron, a muon or a tau lepton, proceed through a  $b$ - to  $s$ -quark flavour-changing neutral-current transition. Such processes are suppressed in the Standard Model (SM) of particle physics. The rate and angular distribution of these decay can be modified in many SM extensions, with distinct effects possible in final states involving different lepton flavours. Interestingly, measurements of a variety of decays involving  $b \rightarrow s \ell^+ \ell^-$  transitions are found to be in tension with SM predictions. The largest discrepancies between measurements and predictions are seen in the rates of  $B \rightarrow K \mu^+ \mu^-$  [1–3] and  $B_s^0 \rightarrow \phi \mu^+ \mu^-$  [4] decays, as well as in the rate and angular distribution of  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$  decays [5–12]. Unfortunately, the interpretation of these discrepancies is complicated by long-distance contributions to the decay rate, which are difficult to estimate reliably in the SM (see for example refs. [13, 14]). Such contributions do not impact comparisons between decays to different lepton flavours and significant discrepancies between measurements of observables in dielectron and dimuon final states would indicate a breakdown of the SM.

The consistency between the rates of the  $B^{(+,0)} \rightarrow K^{(+,*0)} \mu^+ \mu^-$  and  $B^{(+,0)} \rightarrow K^{(+,*0)} e^+ e^-$  decays has been studied extensively in recent years.<sup>1</sup> Measurements of the rates of decays to dielectron and dimuon final states are found to be compatible [15, 16], showing a similar

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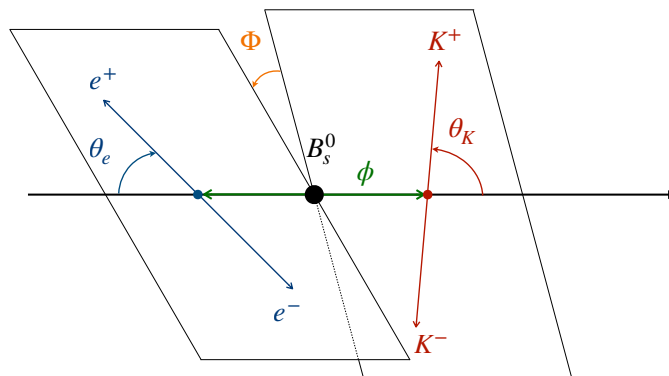
<sup>1</sup>The symbols  $K^*$  and  $\phi$  are used to refer to the  $K^*(892)$  and  $\phi(1020)$  mesons, respectively, throughout the paper.

pattern of tensions with SM predictions, consistent with universal couplings to the different lepton flavours. The results of a study of the angular distributions of  $B^0 \rightarrow K^{*0}e^+e^-$  decays are also in agreement with similar measurements of the  $B^0 \rightarrow K^{*0}\mu^+\mu^-$  final state [5, 17]. A recent study of the  $B_s^0 \rightarrow \phi e^+e^-$  decay rate in bins of dilepton mass squared,  $q^2$ , likewise found consistent values with those measured in  $B_s^0 \rightarrow \phi\mu^+\mu^-$  decays [18]. A separate study of the angular distribution of the  $B_s^0 \rightarrow \phi e^+e^-$  decay with  $q^2$  in the range  $[0.0009, 0.2615] \text{ GeV}^2/c^4$ , obtained results compatible with SM predictions [19]. It is therefore of interest to study angular observables in  $B_s^0 \rightarrow \phi e^+e^-$  decays at higher  $q^2$  values, to test whether they are consistent with SM predictions and with the measurements made in  $B_s^0 \rightarrow \phi\mu^+\mu^-$  decays [20].

This paper describes the first angular analysis of the  $B_s^0 \rightarrow \phi e^+e^-$  decay in the  $q^2$  ranges  $[0.1, 1.1]$ ,  $[1.1, 6.0]$  and  $[15.0, 19.0] \text{ GeV}^2/c^4$ . The  $q^2$  range  $[6.0, 15.0] \text{ GeV}^2/c^4$  is dominated by contributions from  $B_s^0 \rightarrow J/\psi\phi$  and  $B_s^0 \rightarrow \psi(2S)\phi$  decays, involving  $b \rightarrow c\bar{c}s$  quark-level transitions. This  $q^2$  range is used as a control region for the analysis. The results presented in this paper are based on a proton-proton collision dataset, corresponding to  $9 \text{ fb}^{-1}$  of integrated luminosity, collected with the LHCb detector between 2011 and 2018. Since the final state of this decay is not flavour specific, the notation  $B_s^0 \rightarrow \phi e^+e^-$  is used to refer to the sum of both  $B_s^0$  and  $\bar{B}_s^0$  meson decays to the same final state.

The angular distribution of the  $B_s^0 \rightarrow \phi e^+e^-$  decay, where the  $\phi$  meson decays to  $K^+K^-$ , can be parametrised by three decay angles: the angle  $\theta_K$  between the  $K^+$  direction and the direction opposite that of the  $B_s^0$  meson in the  $\phi$  meson rest frame; the angle  $\theta_e$  between the  $e^+$  direction and the direction opposite that of the  $B_s^0$  meson in the dielectron rest frame; and the angle  $\Phi$  between the decay planes of the  $\phi$  meson and dielectron pair in the rest frame of the  $B_s^0$  meson. The angles are illustrated in figure 1. The decay-time-dependent angular distribution of the decay is described in section 2, following the formalism of ref. [21]. Due to the limited size of the data sample it is not possible to determine the full three-dimensional angular distribution, neither is it feasible to apply initial-state flavour-tagging to distinguish  $B_s^0$  from  $\bar{B}_s^0$  decays. A subset of the angular observables,  $F_L$ ,  $A_6$ ,  $S_3$  and  $A_9$  are determined by analysing reduced angular distributions of the decay, separately in the  $\theta_e$  and  $\theta_K$  angles and in  $\Phi$ . The observable  $F_L$  is the longitudinal polarisation fraction of the  $\phi$  meson. The asymmetry  $A_6$  is even under time-reversal and generates a forward-backward asymmetry in the dilepton system. Conversely, the asymmetry  $A_9$  is odd under time-reversal [22]. The observable  $S_3$  is proportional to the difference between the magnitude squared of the  $CP$ -odd and  $CP$ -even amplitudes that contribute to the transverse polarisation of the  $\phi$  meson. The observables  $S_3$  and  $A_9$  are associated with  $\cos 2\Phi$  and  $\sin 2\Phi$  variations of the  $\Phi$  distribution, respectively.

The remainder of the paper is organised as follows: the parametrisation used to describe the angular distribution of the  $B_s^0 \rightarrow \phi e^+e^-$  decay is introduced in section 2; section 3 contains a description of the LHCb detector and the production of simulated samples used in the analysis; in section 4 the selection of  $B_s^0$  candidates is discussed; corrections for the nonuniform efficiency of the event reconstruction and candidate selection are described in section 5; the determination of the observables from the candidates  $K^+K^-e^+e^-$  mass,  $m(K^+K^-e^+e^-)$ , and angular distributions is described in section 6; section 7 is focussed on the validation of the analysis using pseudoexperiments and  $B_s^0 \rightarrow J/\psi\phi$  decays in data; sources of systematic uncertainty are discussed in section 8; and results are presented in section 9.



**Figure 1.** Illustration of the three decay angles that define the angular basis used for the  $B_s^0 \rightarrow \phi e^+ e^-$  decay.

## 2 Angular distribution

The full angular distribution of  $B_s^0$  and  $\bar{B}_s^0$  mesons decaying to  $\phi e^+ e^-$  can be expressed as [21]

$$\frac{d^4[\Gamma(t) + \bar{\Gamma}(t)]}{dq^2 d\cos\theta_K d\cos\theta_e d\Phi} = \sum_i \left[ J_i(q^2, t) + \tilde{J}_i(q^2, t) \right] f_i(\cos\theta_K, \cos\theta_e, \Phi), \quad (2.1)$$

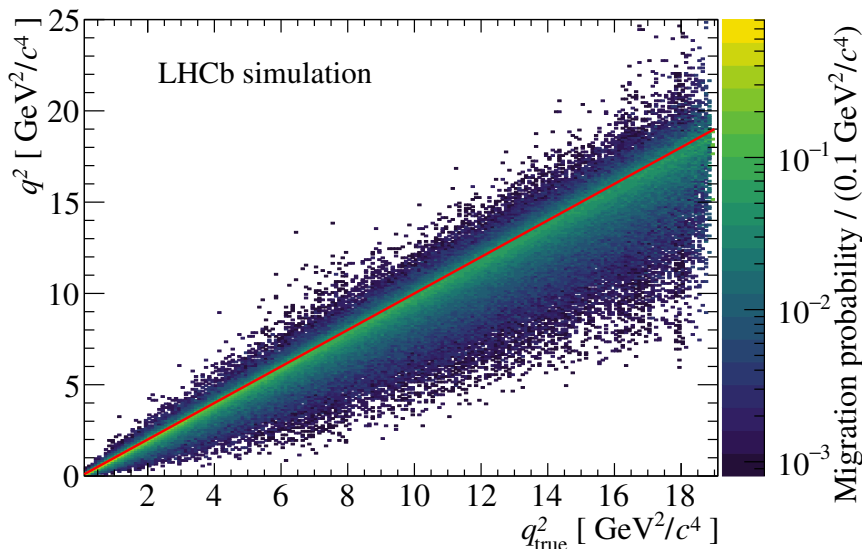
where the  $f_i$  are functions of the decay angles. The decay-time- and  $q^2$ -dependent angular coefficients have a decay-time dependence given by

$$J_i(q^2, t) + \tilde{J}_i(q^2, t) = e^{-\Gamma_s t} \left\{ \left[ J_i(q^2, 0) + \tilde{J}_i(q^2, 0) \right] \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - h_i(q^2) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \right\}. \quad (2.2)$$

Here,  $\Gamma_s$  is the average of, and  $\Delta\Gamma_s$  the difference between, the light and heavy  $B_s^0$  mass eigenstates' widths. The coefficients  $J_i$ ,  $\tilde{J}_i$  and  $h_i$  at  $t = 0$  can be expressed in terms of bilinear combinations of decay amplitudes. Due to the limited size of the available dataset, the measurement is performed integrated in decay time. Neglecting for now decay-time acceptance effects, the term involving  $h_i$  is diluted relative to that involving  $J_i + \tilde{J}_i$  by a factor  $y_s = \frac{\Delta\Gamma_s}{2\Gamma_s} \approx 0.06$  [23], *i.e.*

$$\int_0^\infty [J_i(q^2, t) + \tilde{J}_i(q^2, t)] dt = \frac{1}{(1 - y_s^2)\Gamma_s} \left[ \left( J_i(q^2, 0) + \tilde{J}_i(q^2, 0) \right) - y_s h_i(q^2) \right]. \quad (2.3)$$

Reduced distributions are obtained integrating either over  $\Phi$  or over both  $\cos\theta_K$  and  $\cos\theta_e$ , with the result that many of the terms in the sum of eq. (2.1) vanish. After integration over  $\Phi$  and decay time, and neglecting contributions that are suppressed by the small electron mass, the distribution contains only terms with  $i \in [1c, 1s, 2c, 2s, 6s]$ . In the notation of



**Figure 2.** Correlation between reconstructed ( $q^2$ ) and true ( $q_{\text{true}}^2$ ) values of the dilepton mass squared in simulated  $B_s^0 \rightarrow \phi e^+ e^-$  decays. The distribution is normalised such that, at a fixed value of  $q_{\text{true}}^2$ , the migration probability in bins of reconstructed  $q^2$  sums to unity. The true value is determined from the  $B_s^0$  and  $\phi$  meson four-momenta and does not include effects from final-state radiation. The red line corresponds to reconstructed  $q^2 = q_{\text{true}}^2$ .

refs. [21, 24], it can be written as

$$\begin{aligned} \frac{1}{d[\Gamma + \tilde{\Gamma}]/dq^2} \frac{d^3[\Gamma + \tilde{\Gamma}]}{dq^2 d\cos\theta_K d\cos\theta_e} &= \frac{9}{16} \left[ \frac{3}{4} (1 - \langle F_L \rangle) \sin^2\theta_K \left( 1 + \frac{1}{3} \cos 2\theta_e \right) \right. \\ &\quad \left. + \langle F_L \rangle \cos^2\theta_K (1 - \cos 2\theta_e) \right. \\ &\quad \left. + \langle A_6 \rangle \sin^2\theta_K \cos\theta_e \right]. \end{aligned} \quad (2.4)$$

The last term can also be expressed in terms of  $\langle A'_6 \rangle = \langle A_6 \rangle / (1 - \langle F_L \rangle)$ . The reduced distribution after integration over  $\cos\theta_K$ ,  $\cos\theta_e$  and decay time contains only terms with  $i \in [3, 9]$ , and can be expressed as

$$\frac{1}{d[\Gamma + \tilde{\Gamma}]/dq^2} \frac{d^2[\Gamma + \tilde{\Gamma}]}{dq^2 d\Phi} = \frac{1}{2\pi} [1 + \langle S_3 \rangle \cos 2\Phi + \langle A_9 \rangle \sin 2\Phi]. \quad (2.5)$$

Here, the triangular braces indicate that the observables include contributions from the  $h_i$  terms and are different from the observables at  $t = 0$ , which will be referred to without the braces. These reduced distributions neglect contributions that are suppressed by the small size of the electron mass squared compared to  $q^2$ .

The analysis is performed in bins of reconstructed  $q^2$  and the measurements correspond to rate-averages of the observables over the  $q^2$  bin. The reconstructed values of  $q^2$  differ from the true values due to experimental resolution and radiative losses from the electrons that are not recovered in the event reconstruction. The correlation between the reconstructed  $q^2$  value and the true value in simulation is illustrated in figure 2.

### 3 Detector and simulation

The LHCb detector [25–27] 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 elements that are particularly relevant for this analysis are: a silicon-strip vertex detector surrounding the proton-proton interaction region that allows  $c$  and  $b$  hadrons to be identified from their characteristically long flight distance; a tracking system that provides a measurement of the momentum,  $p$ , of charged particles; two ring-imaging Cherenkov detectors that are able to discriminate between different species of charged hadrons; an electromagnetic calorimeter to reconstruct electrons and photons energy deposits; and a muon system to identify muons. Energy loss from the electrons by bremsstrahlung is recovered using a dedicated algorithm, which associates energy in the calorimeter to the electrons based on their trajectories. Events are selected online using a trigger [28, 29] that consists of a hardware and a software stage.

Simulated samples are used to determine the efficiency of the candidate selection as well as the distributions of specific sources of background. In the simulation, proton-proton collisions are generated using PYTHIA [30] with a specific LHCb configuration [31]. Decays of unstable particles are described by EVTGEN [32], using PHOTOS [33] to generate final-state radiation from the electrons and kaons. Simulated  $B_s^0 \rightarrow \phi e^+ e^-$  decays are generated according to two models: a SM-like model based on refs. [21, 34, 35]; and a model that is uniform in  $q^2$  and the decay angles. The interactions of the generated particles with the detector, and its response, are simulated using the GEANT4 toolkit [36] as described in ref. [37]. The simulated samples are corrected to account for known differences between simulation and data. These discrepancies involve the production kinematics of the  $B_s^0$  meson, the occupancy of the detector, and the efficiencies related to tracking and particle identification.

### 4 Candidate selection

The candidate selection used in this analysis is identical to that in ref. [18]. Online, candidates are selected from events that are either triggered at hardware level by an electron with large transverse energy, with a threshold in the range 2.4–3.0 GeV, or by particles from the event that do not form part of the signal candidate. In the software trigger, events are selected if they contain at least one reconstructed track with large transverse momentum and a significant impact parameter (IP) with respect to every proton-proton collision vertex (PV) in the bunch-crossing event. Two or more tracks are required to form a vertex that is displaced from every PV and fulfills a set of topological criteria [38, 39].

Offline,  $B_s^0 \rightarrow \phi e^+ e^-$  candidates are formed by combining  $e^+$  and  $e^-$  with  $K^+$  and  $K^-$  candidates. The electrons and kaons are required to have a significant IP with respect to every PV and fulfil a set of particle identification criteria. The kaon pair is required to have a mass within  $\pm 12 \text{ MeV}/c^2$  of the known  $\phi$  meson mass [40]; this narrow mass window suppresses many potential sources of misidentified background. The resulting  $B_s^0$  candidate vertex is required to have a good vertex-fit quality and to be significantly displaced from every PV. The  $B_s^0$  candidate is required to be consistent with originating from a PV by requiring a small  $B_s^0$  IP and good alignment between the  $B_s^0$  momentum and displacement vectors.

Combinatorial background, formed by tracks from two or more different  $b$ -hadron decays, is suppressed using a boosted decision tree classifier [41]. The classifier is trained using simulated signal decays, generated with a SM-like distribution in  $q^2$  and the decay angles, and a background sample comprised of candidates from an upper  $m(K^+K^-e^+e^-)$  sideband. The classifier uses kinematic and topological information that is characteristic of the signal decay. The classifier working point is chosen separately for each  $q^2$  region. A second multivariate classifier is trained for the high- $q^2$  region to reject background involving poorly reconstructed electron candidates. This classifier is trained on simulated samples and uses kinematic information as well as information related to the bremsstrahlung recovery procedure.

There are relatively few specific background sources that the selection criteria does not suppress to negligible levels. Potential background from decays with similar topologies, *e.g.* from  $B^0 \rightarrow K^{*0}e^+e^-$  decays where the  $K^{*0}$  meson decays to  $K^+\pi^-$ , is suppressed by the narrow  $\phi$  mass window and particle identification requirements applied to the kaon candidates.<sup>2</sup> Background from semileptonic  $B_s^0 \rightarrow D_s^-(\rightarrow \phi\pi^-)e^+\nu_e$  decays, where the negative pion is mistakenly identified as an electron, is removed by rejecting candidates where the  $\phi e^-$  mass is consistent with that of a  $D_s^-$  meson, where a relatively broad range [1920, 2000] MeV/ $c^2$  is vetoed to account for the misidentification. Background from doubly semileptonic  $B_s^0 \rightarrow D_s^-(\rightarrow \phi e^- \bar{\nu}_e)e^+\nu_e$  decays cannot be fully suppressed and is accounted for in the fits. Sources of potential background from other partially reconstructed decays typically involve either a kaon or multiple particles that are not reconstructed, and typically populate regions in  $K^+K^-e^+e^-$  mass outside the range considered in the analysis. The decays  $B_s^0 \rightarrow J/\psi\phi$  and  $B_s^0 \rightarrow \psi(2S)\phi$  with  $J/\psi$  and  $\psi(2S) \rightarrow e^+e^-$  form background in the central- and high- $q^2$  regions if too little or too much bremsstrahlung energy is added back to the candidate, respectively. Background from these decays is also accounted for in the fits.

## 5 Angular and time-dependent efficiency

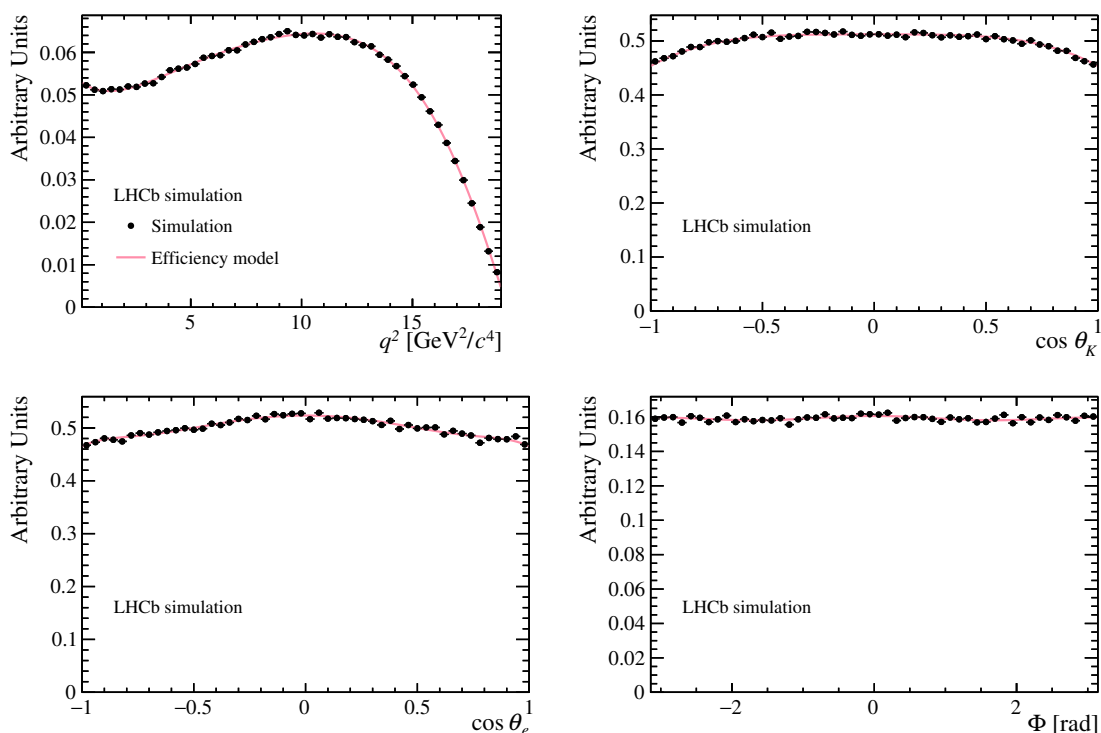
The event reconstruction and candidate selection distort the measured angular distributions of the candidates in particular due to kinematic and IP requirements. The decay-time-integrated efficiency is parametrised using sets of orthogonal functions as

$$\varepsilon(q^2, \cos\theta_K, \cos\theta_e, \Phi) = \sum_{klmn} c_{klmn} P_k(\tilde{q}^2) P_l(\cos\theta_K) P_m(\cos\theta_e) \cos(n\Phi), \quad (5.1)$$

where the  $P_i$  are Legendre polynomials of degree  $i$  and  $\tilde{q}^2$  is a linear transformation of  $q^2$  to the range  $[-1, +1]$ . The orthogonality of the functions used to construct the efficiency models allows for the coefficients to be extracted using a moment analysis. This is done using simulated signal decays generated uniformly in  $q^2$  and the decay angles, corrected for data-simulation differences following the procedures described in refs. [15, 18]. The efficiency is parametrised by functions with  $k \leq 6$ ,  $l \leq 4$ ,  $m \leq 8$ , and  $n \leq 2$ , where the maximum orders are found empirically to be those necessary to describe the efficiency across the entire phase space. Only even-ordered terms are considered for  $\cos\theta_K$  and  $\cos\theta_e$  as differences in the interaction probabilities in the detector between  $K^+$  and  $K^-$  mesons and between

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<sup>2</sup>The inclusion of charge conjugate processes is implied when discussing backgrounds.



**Figure 3.** Distributions of simulated  $B_s^0 \rightarrow \phi e^+ e^-$  decays, generated uniformly in  $q^2$  and the decay angles, in (top left)  $q^2$ , (top right)  $\cos \theta_K$ , (bottom left)  $\cos \theta_e$ , and (bottom right)  $\Phi$ . All selection criteria except the  $D_s^-$  veto are applied to the simulation. The efficiency model integrated over the other variables is also shown.

$e^+$  and  $e^-$  leptons are sufficiently small that they do not introduce significant asymmetries in the angular distributions. The  $D_s^-$  veto suppresses a narrow region of phase space in  $q^2$  and  $\cos \theta_e$ . This cannot be modelled without very high-degree polynomials and is therefore treated separately. The ratio of the  $\cos \theta_e$  distribution of the simulated candidates with and without the veto is determined after integrating over  $q^2$ , separately in each  $q^2$  bin, and used to obtain a parametric description of the veto effect. The efficiency in  $\cos \theta_e$  is multiplied by this function to account for the effect of the veto.

One-dimensional projections of the efficiency function  $\varepsilon(q^2, \cos \theta_K, \cos \theta_e, \Phi)$  in each of the variables are compared in figure 3 to the distributions in the simulation. The drop-off in efficiency at high- $q^2$  is due to the IP requirements on the  $K^\pm$  tracks in the candidate selection.

The reduced angular distributions are obtained by fixing  $q^2$  to the median value of the  $q^2$  bin and integrating the product of the three-dimensional angular distribution and  $\varepsilon$  over the relevant angles. Due to the efficiency not being perfectly uniform, the resulting distributions feature additional terms that are not present in eqs. (2.4) and (2.5). These are suppressed by small numerical factors and are neglected, but considered as a source of systematic uncertainty.

The selection requirements are correlated with the  $B_s^0$  candidate decay time and modify the dilution factor that appears in front of the  $h_i$  terms in eq. (2.3) from the value  $\mathcal{D} = y_s$  that is obtained with uniform decay-time acceptance. If  $\epsilon(t)$  is the decay-time dependence

of the selection efficiency, the dilution is instead

$$\mathcal{D} = \int_0^{\infty} \epsilon(t) e^{-\Gamma_s t} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) dt \Big/ \int_0^{\infty} \epsilon(t) e^{-\Gamma_s t} \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) dt. \quad (5.2)$$

The decay-time-dependent efficiency is well described by the function [42]

$$\epsilon(t) = \frac{a(t - t_0)^c}{1 + a(t - t_0)^c} (1 + bt). \quad (5.3)$$

Using values of  $t_0$ ,  $a$ ,  $b$  and  $c$  determined from simulation, the dilution is  $\mathcal{D} = 0.122 \pm 0.015$ .

## 6 Mass and angular distributions

The angular observables are determined by performing unbinned maximum-likelihood fits, simultaneously to the  $K^+K^-e^+e^-$  mass and angular distributions of the selected candidates. The inclusion of  $m(K^+K^-e^+e^-)$  in the fit aids discrimination between signal and various sources of background. Two separate fits are performed in each  $q^2$  bin, one to the three dimensional distribution of candidates in  $m(K^+K^-e^+e^-)$ ,  $\cos\theta_K$  and  $\cos\theta_e$ , and the second to the two dimensional distribution of candidates in  $m(K^+K^-e^+e^-)$  and  $\Phi$ . The description of the  $m(K^+K^-e^+e^-)$  distribution of each fit component is identical to that in ref. [18].

The signal mass distribution is described by a Gaussian function with power-law tails on the left- and right-hand side of the spectrum. Bremsstrahlung, and the imperfect nature of the recovery procedure, leads to a tail that is more pronounced on the left-hand side of the distribution. The tails are further modified by sigmoid activation functions, which are used to account for phase-space related effects. The tail parameters are fixed from simulation. For each  $q^2$  bin, the values of the peak position and width from simulation are corrected based on results of fits to the  $B_s^0 \rightarrow J/\psi\phi$  data sample.

In the low- and central- $q^2$  regions, the  $m(K^+K^-e^+e^-)$  distribution of the combinatorial background is described by an exponential function. In the high- $q^2$  region, the exponential background shape is modified at small  $m(K^+K^-e^+e^-)$  values to account for the limited phase space due to the large dielectron mass. The phase-space turn-on is modelled assuming that the background is exponentially distributed in  $q^2$  with a shape derived at large  $m(K^+K^-e^+e^-)$  values. The angular distribution of the combinatorial background is modelled by sums of Chebyshev polynomial functions, with each sum describing one of the  $\cos\theta_K$ ,  $\cos\theta_e$  and  $\Phi$  distributions. The parameters of the polynomials are constrained from same-sign  $K^+K^-e^\pm e^\pm$  or  $K^\pm K^\pm e^+e^-$  candidates. The orders of the polynomials are chosen empirically based on the distributions of candidates in the upper mass sideband and same-sign data.

The shape of the background from doubly semileptonic decays is taken from simulation. The simulation samples include cases where the  $B_s^0$  directly produces a  $D_s^-$  meson and cases where the  $B_s^0$  produces an excited  $D_s^-$  meson that subsequently decays to the ground state. This component is described by a nonparametric kernel-density estimate.

The shapes of the backgrounds from  $B_s^0 \rightarrow J/\psi\phi$  and  $B_s^0 \rightarrow \psi(2S)\phi$  decays with too little or too much bremsstrahlung energy recovered, which leak into other  $q^2$  regions, are taken from simulation. The mass distribution of the  $B_s^0 \rightarrow J/\psi\phi$  background in the central- $q^2$  region

is parametrised by the tail of a Gaussian function. In the high- $q^2$  region, the backgrounds are described using kernel-density estimates. The yields of these backgrounds are each constrained from their respective simulated samples, normalised to the yield of  $B_s^0 \rightarrow J/\psi\phi$  decays in data in the range  $6 < q^2 < 11 \text{ GeV}^2/c^4$ .

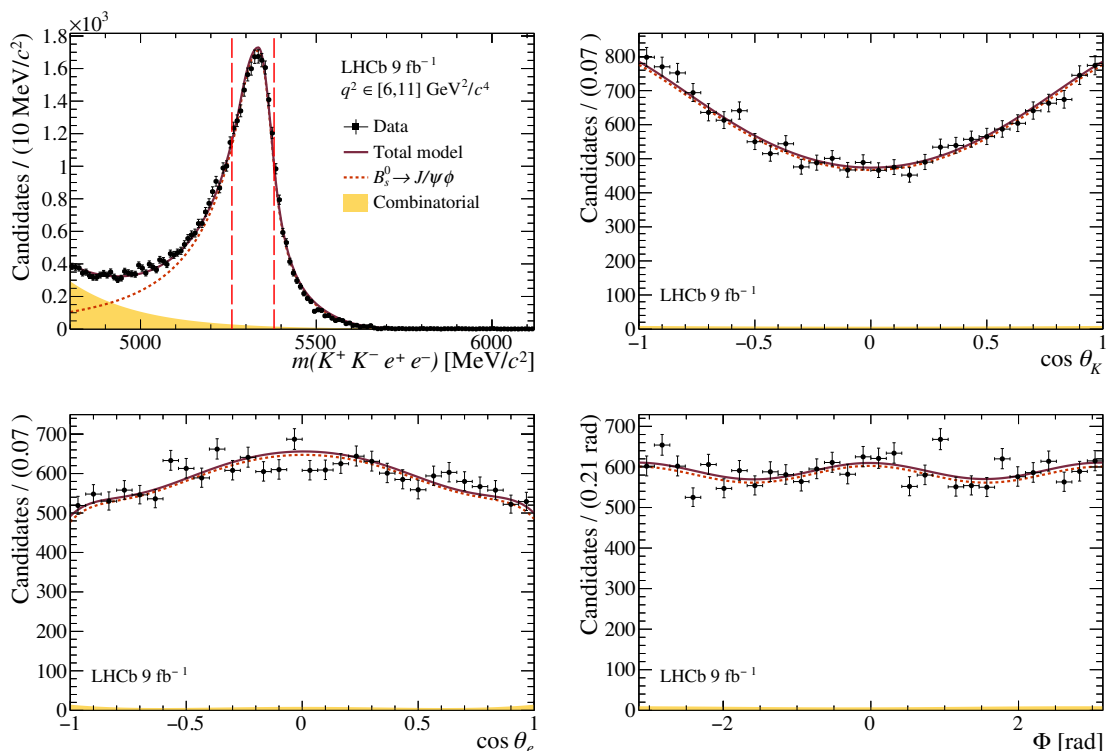
The background from misidentified decays is taken from control samples in data, where one or both electrons fail the particle-identification requirements used in the analysis. The control samples are weighted following the procedure in refs. [15, 16] to determine the shape and level of the misidentified background in the dataset. This component is described by a nonparametric kernel-density estimate.

## 7 Validation

The analysis procedure is validated using pseudoexperiments and the SM-like simulated samples. The pseudoexperiments are generated with values of the observables from ref. [20] for the signal. Fits to datasets much larger than that used in this analysis yield unbiased results with appropriate uncertainty estimates. Fits to pseudoexperiments generated with representative yields (from ref. [18]) are observed to provide unreliable uncertainty estimates in some of the  $q^2$  bins and have a non-negligible failure rate. This behaviour is caused by fits converging to values close to the boundaries in the allowed parameter space:  $F_L \leq 1$ ,  $A_6 \leq (1 - F_L)$  and  $(S_3^2 + A_9^2) \leq 1$ . The stability of the fit is improved by fitting for  $\langle A'_6 \rangle$  instead of  $\langle A_6 \rangle$ . To obtain correct coverage, the Feldman-Cousins procedure is used to determine confidence intervals on the observables [43].

The analysis procedure is also validated using  $B_s^0 \rightarrow J/\psi\phi$  and  $B_s^0 \rightarrow \psi(2S)\phi$  decays in data with the same final states as the signal. The  $B_s^0 \rightarrow J/\psi\phi$  and  $B_s^0 \rightarrow \psi(2S)\phi$  decays are selected following the same candidate selection procedure as  $B_s^0 \rightarrow \phi e^+ e^-$  candidates but with  $6 < q^2 < 11 \text{ GeV}^2/c^4$  and  $11 < q^2 < 15 \text{ GeV}^2/c^4$ , respectively. To simplify the modelling of background in the fits to the  $B_s^0 \rightarrow J/\psi\phi$  and  $B_s^0 \rightarrow \psi(2S)\phi$  datasets, the analysis is performed in two steps. First, the  $m(K^+ K^- e^+ e^-)$  distribution is fitted to determine the relative contribution of the signal and different background components. The angular variables are then determined over the reduced  $m(K^+ K^- e^+ e^-)$  range,  $5260 < m(K^+ K^- e^+ e^-) < 5380 \text{ MeV}/c^2$ , taking into account only contributions from signal, combinatorial background and, for  $B_s^0 \rightarrow \psi(2S)\phi$  decays, leakage from  $B_s^0 \rightarrow J/\psi\phi$  decays. The angular distribution of the combinatorial background is constrained from a fit to candidates with  $5600 < m(K^+ K^- e^+ e^-) < 6800 \text{ GeV}/c^2$ .

Figures 4 and 5 show the results of the fits to the  $B_s^0 \rightarrow J/\psi\phi$  and  $B_s^0 \rightarrow \psi(2S)\phi$  samples, respectively. The observables  $\langle F_L \rangle$  and  $\langle S_3 \rangle$  are reinterpreted in terms of the squared transversity amplitudes  $|A_0|^2$  and  $|A_\perp|^2$ , correcting for the effect of integration over decay time. The values of the squared amplitudes are found to be consistent with, but less precise than, those obtained in the same  $B_s^0$  decays with  $J/\psi$  and  $\psi(2S) \rightarrow \mu^+ \mu^-$ , derived from the amplitudes determined in refs. [44, 45], as shown in figure 6.

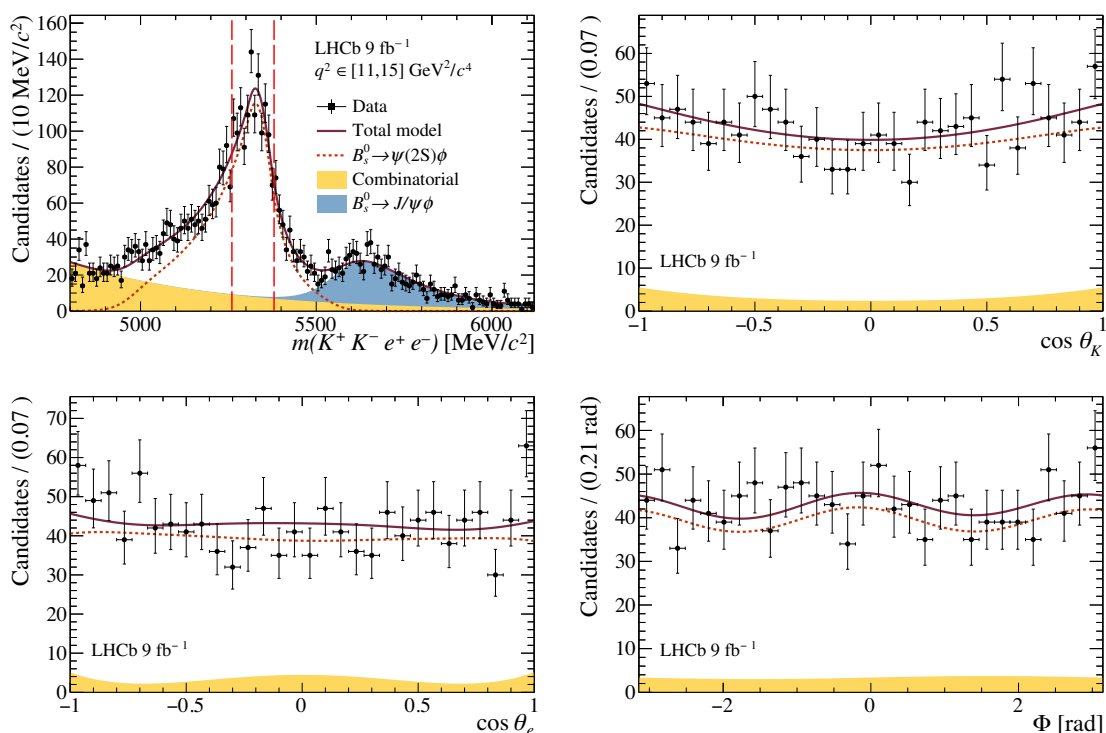


**Figure 4.** Distributions of selected  $B_s^0 \rightarrow J/\psi\phi$  decays in (top left)  $m(K^+K^-e^+e^-)$ , (top right)  $\cos\theta_K$ , (bottom left)  $\cos\theta_e$  and (bottom right)  $\Phi$ . The  $\cos\theta_K$ ,  $\cos\theta_e$  and  $\Phi$  distributions are given in the reduced mass window indicated in the top-left figure by the vertical dashed red lines. The results of the fit with the model described in the text are also shown.

## 8 Systematic uncertainties

Sources of systematic uncertainty are considered if they could modify the mass or angular distribution of the signal or background components in the analysis. The uncertainties assigned for the different sources are determined using pseudoexperiments. The pseudoexperiments are generated with an alternative set of assumptions, with sample size much larger than that analysed in this paper, and fitted according to the nominal model. A systematic uncertainty is assigned adding the bias on the parameter of interest and its uncertainty in quadrature. A summary of the most relevant sources of systematic uncertainty on the observables is presented in table 1. The total systematic uncertainty on each observable is obtained by summing the contributions from individual sources in quadrature. The transformation from  $\langle A_6 \rangle$  to  $\langle A'_6 \rangle$  tends to make uncertainties on  $\langle A'_6 \rangle$  larger than those on other observables, particularly in regions where  $\langle F_L \rangle$  is large.

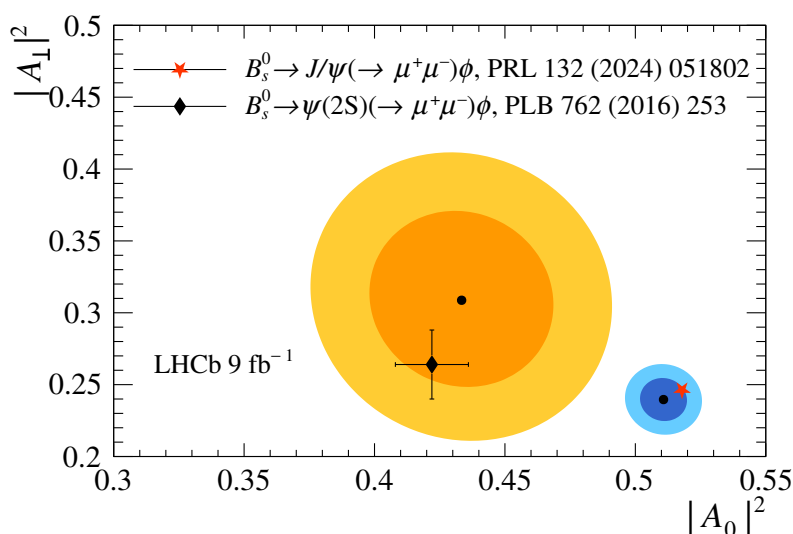
A variety of sources of uncertainty related to the efficiency model are considered. An uncertainty due to the limited order of the orthogonal functions used in the efficiency model is estimated by trialling different increases in order in the pseudoexperiment generation. An uncertainty is assigned to account for the unknown distribution of events in  $q^2$  by evaluating the efficiency model at alternative points in  $q^2$  in the pseudoexperiment generation, shifted from the median by the root-mean-square of the  $q^2$  distribution. The small contribution from



**Figure 5.** Distributions of selected  $B_s^0 \rightarrow \psi(2S)\phi$  decays in (top left)  $m(K^+K^-e^+e^-)$ , (top right)  $\cos\theta_K$ , (bottom left)  $\cos\theta_e$  and (bottom right)  $\Phi$ . The  $\cos\theta_K$ ,  $\cos\theta_e$  and  $\Phi$  distributions are given in the reduced mass window indicated in the top-left figure by the vertical dashed red lines. The results of the fit with the model described in the text are also shown.

observables that, due to nonuniform angular efficiency, do not vanish when projecting out the  $\Phi$  and two-dimensional  $\cos\theta_e$  and  $\cos\theta_K$  distributions is evaluated by including these additional terms in the generation. To assess the impact of the limited size of the simulated signal sample, new angular efficiency models are derived by bootstrapping the uniformly generated sample. Pseudoexperiments are generated according to the new efficiency models and fitted using the nominal one. A similar approach is used to assess the impact of the finite size of the simulated samples used to model the semileptonic background and the data sample used to derive the shape of the misidentified background. Uncertainties are also considered on the data-simulation corrections applied to the simulated samples. The resulting uncertainty is small, and removing the corrections entirely in the pseudoexperiment generation has only a limited impact on the resulting values of the observables. The angular efficiency is derived from simulated samples using reconstructed particles whose trajectories are well matched to particles in the signal decay. Relaxing the association requirements, in the efficiency model used in the pseudoexperiment generation, also has only a limited impact on the observables.

For the signal and background modelling, uncertainties are assigned based on the assumptions that the signal and different background components factorise in mass and angular distributions. To test the assumption on the signal factorisation, signal decays are sampled from the SM simulation and introduced in place of the signal component in the



**Figure 6.** Values of the squared transversity amplitudes  $|A_0|^2$  and  $|A_\perp|^2$  for (blue shaded areas)  $B_s^0 \rightarrow J/\psi\phi$  and (orange shaded areas)  $B_s^0 \rightarrow \psi(2S)\phi$  decays determined from  $\langle F_L \rangle$  and  $\langle S_3 \rangle$ . The darker and lighter shaded areas correspond to 68% and 95% confidence level intervals, respectively, accounting only for statistical uncertainties. The values of the squared transversity amplitudes for  $J/\psi$  and  $\psi(2S) \rightarrow \mu^+\mu^-$  decays from refs. [44] and [45] are indicated by the markers, where the uncertainties on the  $B_s^0 \rightarrow J/\psi\phi$  measurement are too small to be visible.

pseudoexperiment generation. A similar approach is used for the semileptonic backgrounds. For the remaining backgrounds, a moment analysis, similar to that used to derive the angular efficiency coefficients, is used to obtain models that take into account correlations. Due to the limited dataset size, the factorisation assumptions on the combinatorial and misidentified backgrounds are the largest sources of systematic uncertainty in the analysis, but are nonetheless well below the statistical uncertainties. An uncertainty is also assigned on the signal mass modelling by considering modifications to the tails of the signal mass model. Alternate models for the semileptonic background are considered based on kernel-density estimates and, for the angular variables, polynomial models. Other alternate models are derived by varying the form factors used in generation of the semileptonic samples. For the combinatorial background in the high- $q^2$  region, an alternate mass model is trialed based on a power-law turn-on and fall-off behaviour.

Uncertainties are also assigned to account for assumptions made when defining the signal angular distribution. A systematic uncertainty, due to neglecting angular resolution effects, is estimated by smearing the signal model based on a resolution model in the pseudoexperiment generation. The analysis also ignores small contributions from decays to the  $K^+K^-e^+e^-$  final state where the  $K^+K^-$  pair does not originate from a  $\phi$  meson. There is no evidence for such contributions in the data. To estimate a systematic uncertainty, a  $K^+K^-$  S-wave contribution is introduced at the level of 2% of the signal based on the analysis of  $B_s^0 \rightarrow \phi\mu^+\mu^-$  decays in ref. [20]. The uncertainty on  $\Gamma_s$  and  $\Delta\Gamma_s$  has a negligible impact on the measured values of the observables but does impact  $\mathcal{D}$  and the interpretation of the measurement. The  $\mathcal{O}(1\%)$  production asymmetry between  $\bar{B}_s^0$  and  $B_s^0$  mesons in proton-proton collisions [46] has

Source	$\langle F_L \rangle$	$\langle A'_6 \rangle$	$\langle S_3 \rangle$	$\langle A_9 \rangle$
Signal mass model	1.2 / 2.1 / 0.6	1.9 / 2.8 / 1.8	1.3 / 1.1 / 1.7	1.7 / 1.1 / 1.3
Efficiency model	1.3 / 1.9 / 1.9	2.6 / 5.0 / 2.3	2.1 / 1.9 / 1.9	1.8 / 1.7 / 1.7
S-wave contamination	0.5 / 1.6 / 0.8	1.3 / 1.8 / 0.8	1.3 / 0.8 / 1.4	0.9 / 0.9 / 0.7
Angular resolution	0.7 / 1.9 / 0.4	1.0 / 2.3 / 2.0	0.8 / 0.7 / 0.7	1.7 / 1.7 / 1.1
Misidentified background	5.6 / 2.8 / 3.1	2.3 / 4.0 / 2.3	4.3 / 5.4 / 7.1	1.9 / 1.5 / 2.4
Leakage background	0.0 / 1.6 / 1.7	0.0 / 3.2 / 2.4	0.0 / 2.1 / 2.9	0.0 / 1.4 / 2.2
Semileptonic background	1.4 / 1.1 / 0.0	2.0 / 3.8 / 0.0	1.4 / 3.0 / 0.0	1.4 / 1.4 / 0.0
Combinatorial background	2.0 / 3.2 / 1.5	1.2 / 4.0 / 1.9	4.3 / 0.9 / 1.1	1.0 / 1.3 / 2.3

**Table 1.** Absolute systematic uncertainties on  $\langle F_L \rangle$ ,  $\langle A'_6 \rangle$ ,  $\langle S_3 \rangle$  and  $\langle A_9 \rangle$  in units of  $10^{-2}$  in the  $q^2$  ranges  $[0.1, 1.1]/[1.1, 6.0]/[15.0, 19.0]$   $\text{GeV}^2/c^4$ . The contributions to each source of uncertainty are described in the text.

negligible impact on the measurements. A systematic uncertainty is estimated by including a small background contribution in the pseudoexperiment generation. At high  $q^2$  an uncertainty is also assigned in a similar way to account for backgrounds from partially reconstructed decays of  $b$  hadrons to final states including  $J/\psi$  and  $\phi$  mesons, with too much bremsstrahlung energy recovered.

## 9 Results

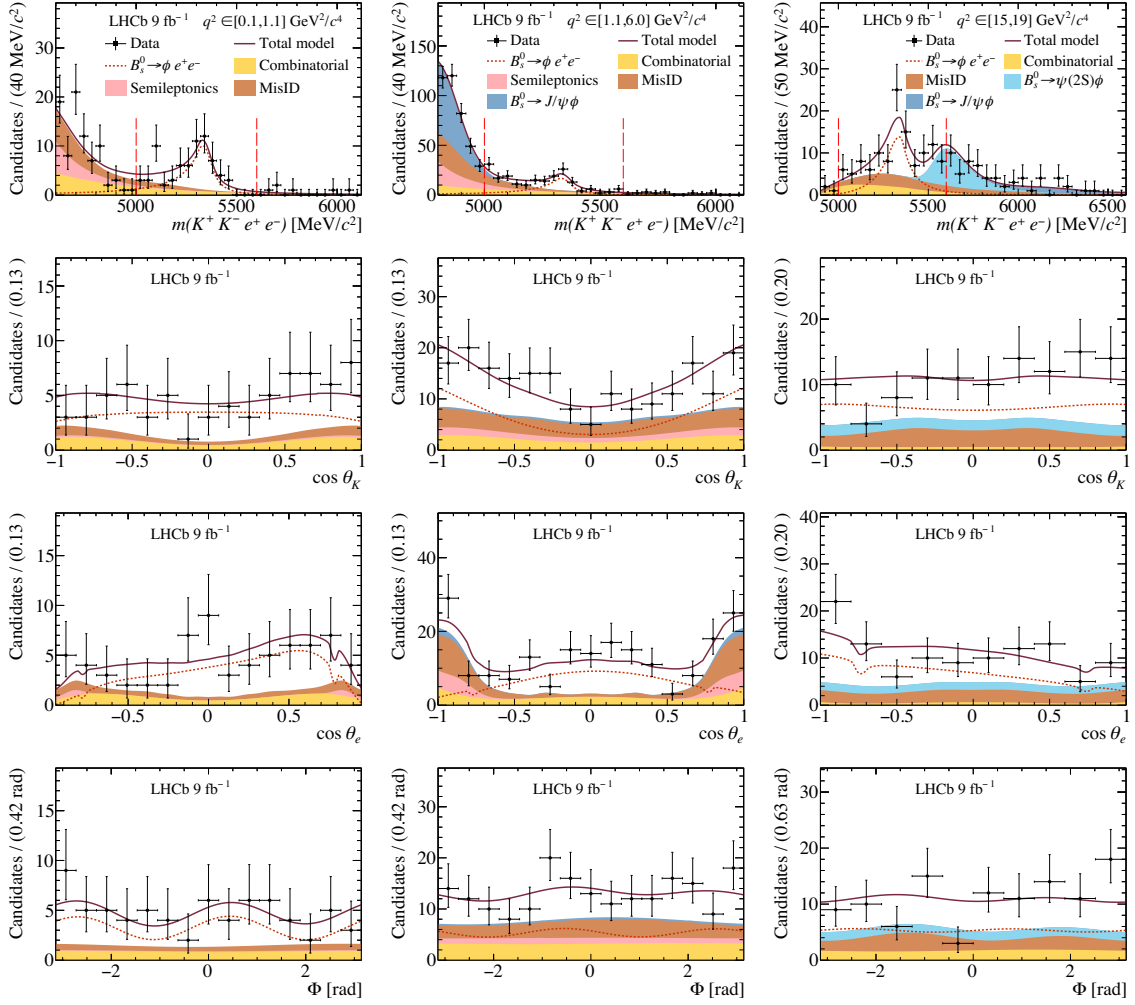
Figure 7 shows the distributions of the selected candidates in  $m(K^+K^-e^+e^-)$ ,  $\cos\theta_K$ ,  $\cos\theta_e$  and  $\Phi$ , in each of the  $q^2$  ranges, compared with the results of the fits. The data are well described by the model.

The Feldman-Cousins procedure is used to obtain confidence level intervals for each observable and for relevant pairs of observables. The likelihood ratio between the tested and best-fit points is used as a test-statistic. At each tested point pseudoexperiments are used to determine the expected distribution of the test-statistic and derive the corresponding confidence level of the data. In the pseudoexperiment generation, nuisance parameters are fixed to the values returned from the fit to the data at the given values of the parameters of interest, *i.e.* using the plug-in method [47].

The resulting intervals on individual parameters are shown in figure 8, along with two-dimensional intervals for  $(\langle F_L \rangle, \langle A'_6 \rangle)$  and  $(\langle S_3 \rangle, \langle A_9 \rangle)$  in figures 9 and 10, respectively. The values for the rate-averaged and decay-time-integrated observables and their 68% confidence level intervals are given in table 2.

## 10 Summary

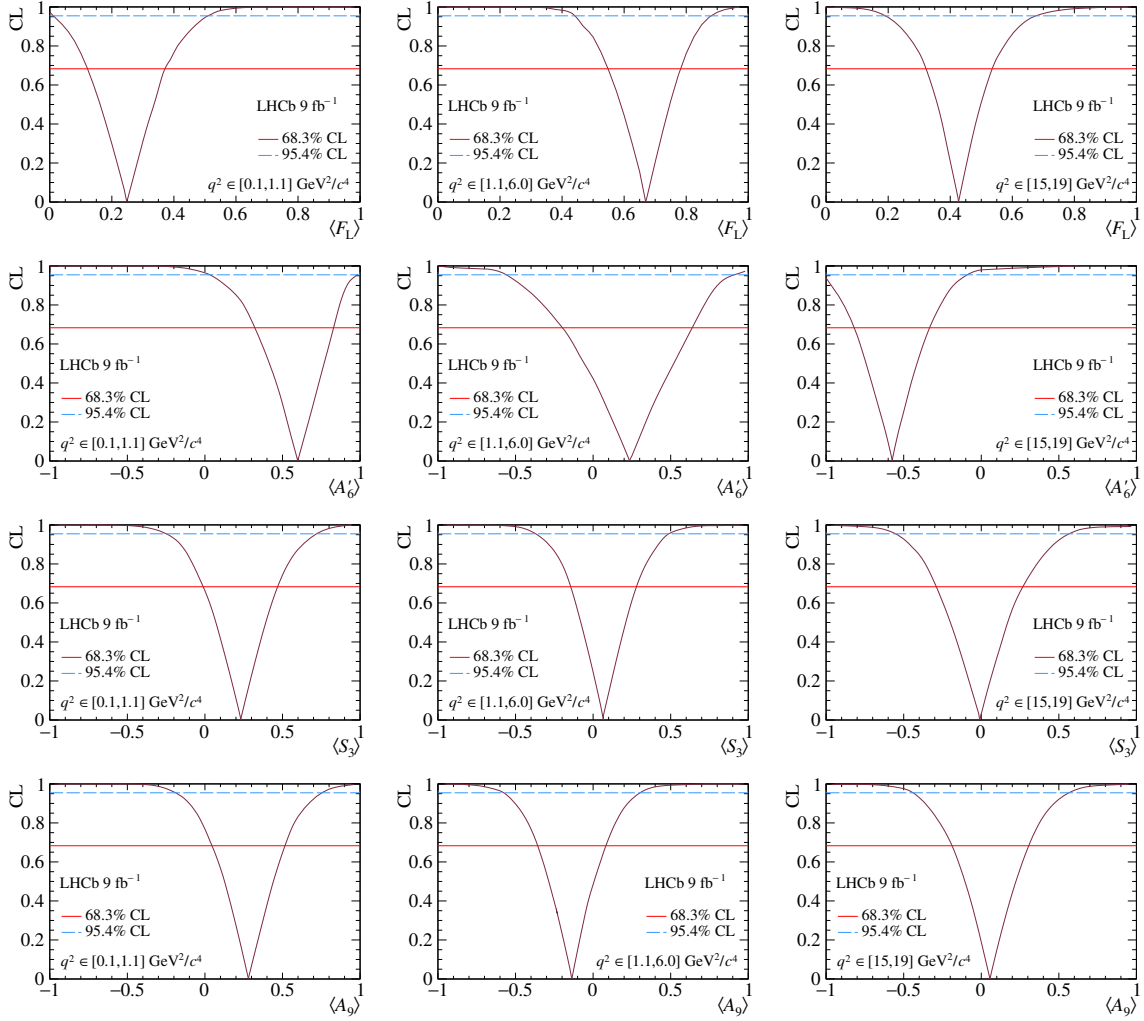
An angular analysis of the  $B_s^0 \rightarrow \phi e^+e^-$  decay has been performed, using a dataset collected with the LHCb detector between 2011 and 2018, corresponding to an integrated luminosity of  $9 \text{ fb}^{-1}$  of high energy proton-proton collisions. The analysis is performed in three bins of dielectron mass squared,  $q^2 \in [0.1, 1.1]$ ,  $[1.1, 6.0]$  and  $[15.0, 19.0]$   $\text{GeV}^2/c^4$ . The analysis is performed integrating over decay time, averaging over the range of  $q^2$  within each bin and



**Figure 7.** Distributions of selected  $B_s^0 \rightarrow \phi e^+ e^-$  candidates with  $q^2$  in the ranges (left to right)  $[0.1, 1.1]$ ,  $[1.1, 6.0]$  and  $[15.0, 19.0]$   $\text{GeV}^2/c^4$  in (top to bottom)  $m(K^+ K^- e^+ e^-)$ ,  $\cos \theta_K$ ,  $\cos \theta_e$  and  $\Phi$ . The angular distributions are shown in reduced mass windows indicated on the  $m(K^+ K^- e^+ e^-)$  figures by the vertical dashed red lines. The results of the fits with the model described in the text are also shown. The dips in the fit results at  $|\cos \theta_e| \sim 0.8$  are due to the  $D_s^-$  veto.

Observable	$0.1 < q^2 < 1.1 \text{ GeV}^2/c^4$	$1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$	$15.0 < q^2 < 19.0 \text{ GeV}^2/c^4$
$\langle F_L \rangle$	$0.25^{+0.12}_{-0.12} \pm 0.06$	$0.67^{+0.12}_{-0.13} \pm 0.06$	$0.43^{+0.11}_{-0.10} \pm 0.05$
$\langle A'_6 \rangle$	$0.60^{+0.23}_{-0.28} \pm 0.05$	$0.24^{+0.40}_{-0.42} \pm 0.09$	$-0.57^{+0.24}_{-0.25} \pm 0.05$
$\langle S_3 \rangle$	$0.23^{+0.24}_{-0.24} \pm 0.07$	$0.07^{+0.21}_{-0.21} \pm 0.07$	$-0.01^{+0.29}_{-0.28} \pm 0.08$
$\langle A_9 \rangle$	$0.28^{+0.23}_{-0.24} \pm 0.04$	$-0.14^{+0.23}_{-0.24} \pm 0.04$	$0.06^{+0.25}_{-0.25} \pm 0.05$

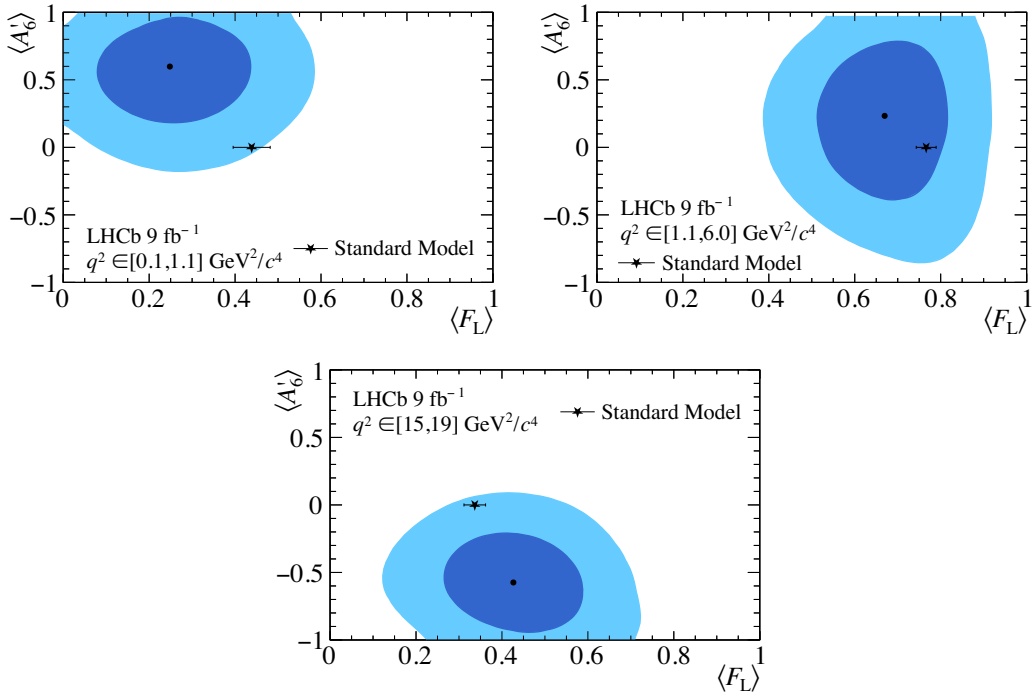
**Table 2.** Measured values of the observables in the three  $q^2$  bins. The central value indicates the best-fit point, the first set of uncertainties indicate the range of the 68% confidence level interval about the best-fit point, and the second correspond to the total systematic uncertainty.



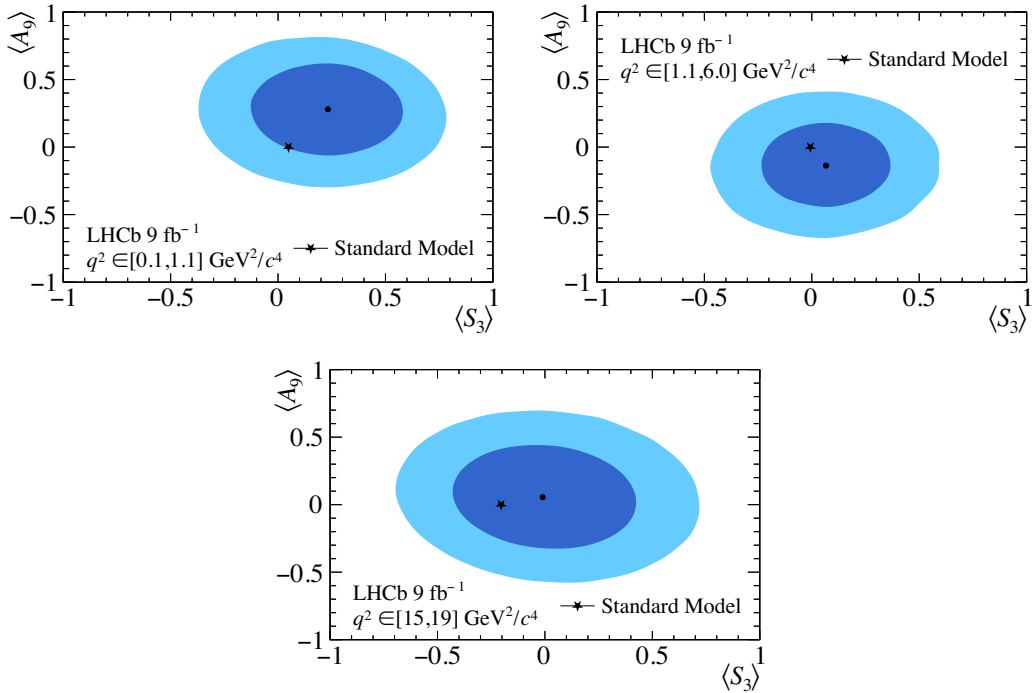
**Figure 8.** Results of the Feldman-Cousins procedure for the observables (top to bottom)  $\langle F_L \rangle$ ,  $\langle A'_6 \rangle$ ,  $\langle S_3 \rangle$  and  $\langle A_9 \rangle$  in the  $q^2$  ranges (left to right)  $[0.1, 1.0]$ ,  $[1.1, 6.0]$  and  $[15.0, 19.0]$   $\text{GeV}^2/c^4$ . The 68.3% (95.4%) confidence level is drawn as the red solid (blue dashed) line.

without distinguishing between  $B_s^0$  and  $\bar{B}_s^0$  decays. The observables  $\langle F_L \rangle$ ,  $\langle A'_6 \rangle$ ,  $\langle S_3 \rangle$  and  $\langle A_9 \rangle$  are measured for the first time in  $B_s^0 \rightarrow \phi e^+ e^-$  decays.

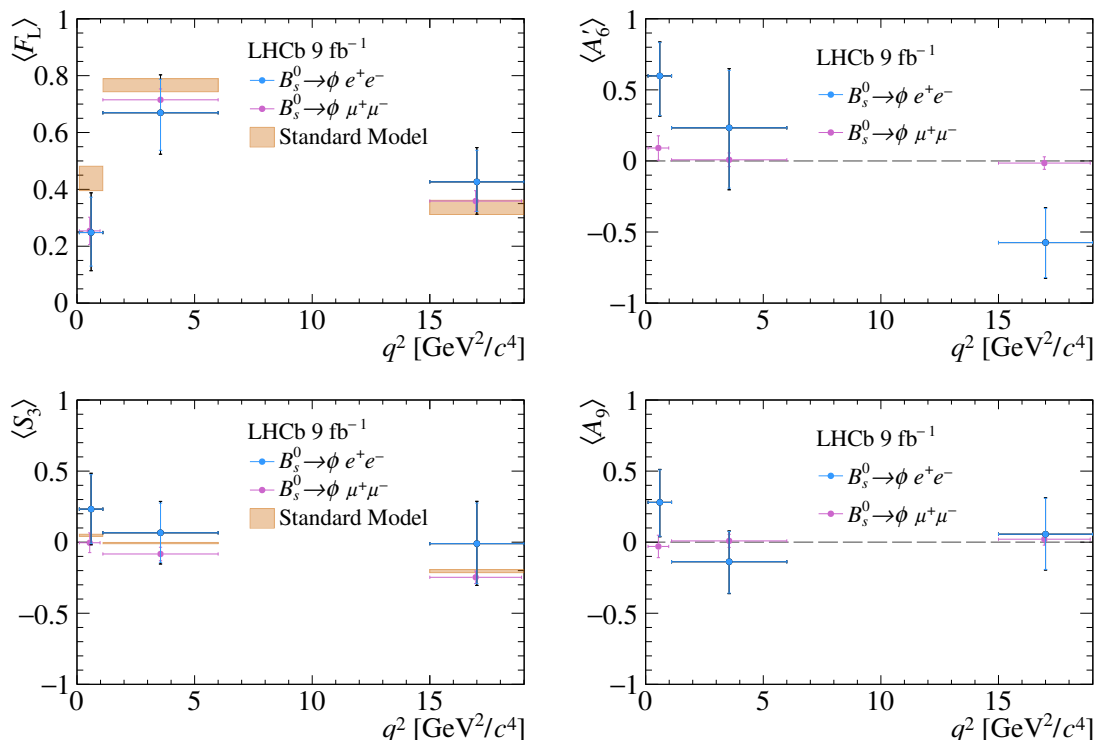
The results for the observables measured in the three  $q^2$  bins are compared to SM predictions in figure 11. The SM predictions are based on ref. [48], using form factors for the  $B_s^0 \rightarrow \phi$  transition from refs. [49, 50], modified to account for integration over decay time. Values of the angular observables measured in  $B_s^0 \rightarrow \phi \mu^+ \mu^-$  decays [20] are also shown for comparison. The results are seen to be consistent with both the SM predictions and the more precise measurements with  $B_s^0 \rightarrow \phi \mu^+ \mu^-$  decays. Further improvement in precision, which will allow more stringent tests of the SM, can be anticipated with larger data samples in future.



**Figure 9.** Two-dimensional 68.3% and 95.5% confidence level regions for the observables  $\langle F_L \rangle$  and  $\langle A'_6 \rangle$  in the  $q^2$  ranges (top left)  $[0.1, 1.0]$ , (top right)  $[1.1, 6.0]$  and (bottom)  $[15.0, 19.0]$   $\text{GeV}^2/c^4$ . Standard Model predictions, obtained from ref. [48], are also shown.



**Figure 10.** Two-dimensional 68.3% and 95.5% confidence level regions for the observables  $\langle S_3 \rangle$  and  $\langle A_9 \rangle$  in the  $q^2$  ranges (top left)  $[0.1, 1.0]$ , (top right)  $[1.1, 6.0]$  and (bottom)  $[15.0, 19.0]$   $\text{GeV}^2/c^4$ . Standard Model predictions, obtained from ref. [48], are also shown.



**Figure 11.** Rate-averaged angular observables as a function of  $q^2$ . The measured values are compared with SM predictions obtained using ref. [48]. The SM predictions for  $\langle A_6' \rangle$  and  $\langle A_9 \rangle$  are indistinguishable from zero.

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**Data Availability Statement.** This article has associated data in a data repository. Data associated with the plots in this publication as well as in supplementary materials are made available on the CERN document server at <https://cds.cern.ch/record/2929839/>.

**Code Availability Statement.** This article has no associated code or the code will not be deposited.

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 G. Graziani [ID](#), A.T. Grecu [ID](#)<sup>43</sup>, L.M. Greeven [ID](#)<sup>38</sup>, N.A. Grieser [ID](#)<sup>66</sup>, L. Grillo [ID](#)<sup>60</sup>, S. Gromov [ID](#)<sup>44</sup>,  
 C. Gu [ID](#)<sup>15</sup>, M. Guarise [ID](#)<sup>26</sup>, L. Guerry [ID](#)<sup>11</sup>, V. Guliaeva [ID](#)<sup>44</sup>, P.A. Günther [ID](#)<sup>22</sup>, A.-K. Guseinov [ID](#)<sup>50</sup>,  
 E. Gushchin [ID](#)<sup>44</sup>, Y. Guz [ID](#)<sup>6,49</sup>, T. Gys [ID](#)<sup>49</sup>, K. Habermann [ID](#)<sup>18</sup>, T. Hadavizadeh [ID](#)<sup>1</sup>,  
 C. Hadjivasiliou [ID](#)<sup>67</sup>, G. Haefeli [ID](#)<sup>50</sup>, C. Haen [ID](#)<sup>49</sup>, G. Hallett [ID](#)<sup>57</sup>, P.M. Hamilton [ID](#)<sup>67</sup>,  
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 C. Henderson [ID](#)<sup>66</sup>, R.D.L. Henderson [ID](#)<sup>1</sup>, A.M. Hennequin [ID](#)<sup>49</sup>, K. Hennessy [ID](#)<sup>61</sup>, L. Henry [ID](#)<sup>50</sup>,  
 J. Herd [ID](#)<sup>62</sup>, P. Herrero Gascon [ID](#)<sup>22</sup>, J. Heuel [ID](#)<sup>17</sup>, A. Hicheur [ID](#)<sup>3</sup>, G. Hijano Mendizabal [ID](#)<sup>51</sup>,  
 J. Horswill [ID](#)<sup>63</sup>, R. Hou [ID](#)<sup>8</sup>, Y. Hou [ID](#)<sup>11</sup>, N. Howarth [ID](#)<sup>61</sup>, J. Hu [ID](#)<sup>72</sup>, W. Hu [ID](#)<sup>7</sup>, X. Hu [ID](#)<sup>4,c</sup>,  
 W. Hulsbergen [ID](#)<sup>38</sup>, R.J. Hunter [ID](#)<sup>57</sup>, M. Hushchyn [ID](#)<sup>44</sup>, D. Hutchcroft [ID](#)<sup>61</sup>, M. Idzik [ID](#)<sup>40</sup>, D. Ilin [ID](#)<sup>44</sup>,

P. Ilten [ID](#)<sup>66</sup>, A. Inglessi [ID](#)<sup>44</sup>, A. Iniukhin [ID](#)<sup>44</sup>, A. Ishteev [ID](#)<sup>44</sup>, K. Ivshin [ID](#)<sup>44</sup>, H. Jage [ID](#)<sup>17</sup>,  
 S.J. Jaimes Elles [ID](#)<sup>76,49,48</sup>, S. Jakobsen [ID](#)<sup>49</sup>, E. Jans [ID](#)<sup>38</sup>, B.K. Jashal [ID](#)<sup>48</sup>, A. Jawahery [ID](#)<sup>67</sup>,  
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 A. John Rubesh Rajan [ID](#)<sup>23</sup>, D. Johnson [ID](#)<sup>54</sup>, C.R. Jones [ID](#)<sup>56</sup>, T.P. Jones [ID](#)<sup>57</sup>, S. Joshi [ID](#)<sup>42</sup>,  
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 O. Kshyvanskyi [ID](#)<sup>53</sup>, S. Kubis [ID](#)<sup>82</sup>, M. Kucharczyk [ID](#)<sup>41</sup>, V. Kudryavtsev [ID](#)<sup>44</sup>, E. Kulikova [ID](#)<sup>44</sup>,  
 A. Kupsc [ID](#)<sup>84</sup>, V. Kushnir [ID](#)<sup>52</sup>, B. Kutsenko [ID](#)<sup>13</sup>, I. Kyryllin [ID](#)<sup>52</sup>, D. Lacarrere [ID](#)<sup>49</sup>,  
 P. Laguarda Gonzalez [ID](#)<sup>45</sup>, A. Lai [ID](#)<sup>32</sup>, A. Lampis [ID](#)<sup>32</sup>, D. Lancierini [ID](#)<sup>62</sup>, C. Landesa Gomez [ID](#)<sup>47</sup>,  
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 S. Legotin [ID](#)<sup>44</sup>, M. Lehuraux [ID](#)<sup>57</sup>, E. Lemos Cid [ID](#)<sup>49</sup>, O. Leroy [ID](#)<sup>13</sup>, T. Lesiak [ID](#)<sup>41</sup>, E.D. Lesser [ID](#)<sup>49</sup>,  
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 D. Lucchesi [ID](#)<sup>33,q</sup>, M. Lucio Martinez [ID](#)<sup>48</sup>, Y. Luo [ID](#)<sup>6</sup>, A. Lupato [ID](#)<sup>33,i</sup>, E. Luppi [ID](#)<sup>26,l</sup>, K. Lynch [ID](#)<sup>23</sup>,  
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 D. Miao [ID](#)<sup>5,7</sup>, H. Miao [ID](#)<sup>7</sup>, M. Mikhasenko [ID](#)<sup>77</sup>, D.A. Milanés [ID](#)<sup>76,y</sup>, A. Minotti [ID](#)<sup>31,p</sup>, E. Minucci [ID](#)<sup>28</sup>,  
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 S. Monteil [ID](#)<sup>11</sup>, A. Morcillo Gomez [ID](#)<sup>47</sup>, G. Morello [ID](#)<sup>28</sup>, M.J. Morello [ID](#)<sup>35,s</sup>, M.P. Morgenthaler [ID](#)<sup>22</sup>,  
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Z.M. Mu [ID](#)<sup>6</sup>, E. Muhammad [ID](#)<sup>57</sup>, F. Muheim [ID](#)<sup>59</sup>, M. Mulder [ID](#)<sup>80</sup>, K. Müller [ID](#)<sup>51</sup>, F. Muñoz-Rojas [ID](#)<sup>9</sup>, R. Murta [ID](#)<sup>62</sup>, V. Mytrochenko [ID](#)<sup>52</sup>, P. Naik [ID](#)<sup>61</sup>, T. Nakada [ID](#)<sup>50</sup>, R. Nandakumar [ID](#)<sup>58</sup>, T. Nanut [ID](#)<sup>49</sup>, I. Nasteva [ID](#)<sup>3</sup>, M. Needham [ID](#)<sup>59</sup>, E. Nekrasova [ID](#)<sup>44</sup>, N. Neri [ID](#)<sup>30,o</sup>, S. Neubert [ID](#)<sup>18</sup>, N. Neufeld [ID](#)<sup>49</sup>, P. Neustroev [ID](#)<sup>44</sup>, J. Nicolini [ID](#)<sup>49</sup>, D. Nicotra [ID](#)<sup>81</sup>, E.M. Niel [ID](#)<sup>15</sup>, N. Nikitin [ID](#)<sup>44</sup>, Q. Niu [ID](#)<sup>73</sup>, P. Nogarolli [ID](#)<sup>3</sup>, P. Nogga [ID](#)<sup>18</sup>, C. Normand [ID](#)<sup>55</sup>, J. Novoa Fernandez [ID](#)<sup>47</sup>, G. Nowak [ID](#)<sup>66</sup>, C. Nunez [ID](#)<sup>86</sup>, H.N. Nur [ID](#)<sup>60</sup>, A. Oblakowska-Mucha [ID](#)<sup>40</sup>, V. Obraztsov [ID](#)<sup>44</sup>, T. Oeser [ID](#)<sup>17</sup>, S. Okamura [ID](#)<sup>26,l</sup>, A. Okhotnikov [ID](#)<sup>44</sup>, O. Okhrimenko [ID](#)<sup>53</sup>, R. Oldeman [ID](#)<sup>32,k</sup>, F. Oliva [ID](#)<sup>59</sup>, M. Olocco [ID](#)<sup>19</sup>, C.J.G. Onderwater [ID](#)<sup>81</sup>, R.H. O’Neil [ID](#)<sup>49</sup>, D. Osthues [ID](#)<sup>19</sup>, J.M. Otalora Goicochea [ID](#)<sup>3</sup>, P. Owen [ID](#)<sup>51</sup>, A. Oyanguren [ID](#)<sup>48</sup>, O. Ozcelik [ID](#)<sup>59</sup>, F. Paciolla [ID](#)<sup>35,w</sup>, A. Padee [ID](#)<sup>42</sup>, K.O. Padeken [ID](#)<sup>18</sup>, B. Pagare [ID](#)<sup>47</sup>, T. Pajero [ID](#)<sup>49</sup>, A. Palano [ID](#)<sup>24</sup>, M. Palutan [ID](#)<sup>28</sup>, X. Pan [ID](#)<sup>4,c</sup>, S. Panebianco [ID](#)<sup>12</sup>, G. Panshin [ID](#)<sup>5</sup>, L. Paolucci [ID](#)<sup>57,\*</sup>, A. Papanestis [ID](#)<sup>58,49</sup>, M. Pappagallo [ID](#)<sup>24,h</sup>, L.L. Pappalardo [ID](#)<sup>26</sup>, C. Pappenheimer [ID](#)<sup>66</sup>, C. Parkes [ID](#)<sup>63</sup>, D. Parmar [ID](#)<sup>77</sup>, B. Passalacqua [ID](#)<sup>26,l</sup>, G. Passaleva [ID](#)<sup>27</sup>, D. Passaro [ID](#)<sup>35,s,49</sup>, A. Pastore [ID](#)<sup>24</sup>, M. Patel [ID](#)<sup>62</sup>, J. Patoc [ID](#)<sup>64</sup>, C. Patrignani [ID](#)<sup>25,j</sup>, A. Paul [ID](#)<sup>69</sup>, C.J. Pawley [ID](#)<sup>81</sup>, A. Pellegrino [ID](#)<sup>38</sup>, J. Peng [ID](#)<sup>5,7</sup>, M. Pepe Altarelli [ID](#)<sup>28</sup>, S. Perazzini [ID](#)<sup>25</sup>, D. Pereima [ID](#)<sup>44</sup>, H. Pereira Da Costa [ID](#)<sup>68</sup>, A. Pereiro Castro [ID](#)<sup>47</sup>, P. Perret [ID](#)<sup>11</sup>, A. Perrevoort [ID](#)<sup>80</sup>, A. Perro [ID](#)<sup>49,13</sup>, M.J. Peters [ID](#)<sup>66</sup>, K. Petridis [ID](#)<sup>55</sup>, A. Petrolini [ID](#)<sup>29,n</sup>, J.P. Pfaller [ID](#)<sup>66</sup>, H. 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Qian [ID](#)<sup>7</sup>, N. Qin [ID](#)<sup>4,c</sup>, S. Qu [ID](#)<sup>4,c</sup>, R. Quagliani [ID](#)<sup>49</sup>, R.I. Rabadan Trejo [ID](#)<sup>57</sup>, J.H. Rademacker [ID](#)<sup>55</sup>, M. Rama [ID](#)<sup>35</sup>, M. Ramírez García [ID](#)<sup>86</sup>, V. Ramos De Oliveira [ID](#)<sup>70</sup>, M. Ramos Pernas [ID](#)<sup>57</sup>, M.S. Rangel [ID](#)<sup>3</sup>, F. Ratnikov [ID](#)<sup>44</sup>, G. Raven [ID](#)<sup>39</sup>, M. Rebollo De Miguel [ID](#)<sup>48</sup>, F. Redi [ID](#)<sup>30,i</sup>, J. Reich [ID](#)<sup>55</sup>, F. Reiss [ID](#)<sup>20</sup>, Z. Ren [ID](#)<sup>7</sup>, P.K. Resmi [ID](#)<sup>64</sup>, M. Ribalda Galvez [ID](#)<sup>45</sup>, R. Ribatti [ID](#)<sup>50</sup>, G. Ricart [ID](#)<sup>15,12</sup>, D. Ricciardi [ID](#)<sup>35,s</sup>, S. Ricciardi [ID](#)<sup>58</sup>, K. Richardson [ID](#)<sup>65</sup>, M. Richardson-Slipper [ID](#)<sup>59</sup>, K. Rinnert [ID](#)<sup>61</sup>, P. Robbe [ID](#)<sup>14,49</sup>, G. 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