

First Measurement of Time-Dependent CP Violation in the Flavor-Changing Neutral-Current Decay $B^0 \rightarrow K_S^0 \mu^+ \mu^-$

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A flavor-tagged time-dependent analysis of $B^0 \rightarrow K_S^0 \mu^+ \mu^-$ decays is performed across the full dimuon mass range excluding the J/ψ and $\psi(2S)$ resonance regions. The analysis uses proton-proton collision data collected by the LHCb experiment in 2011–2018 at center-of-mass energies of 7, 8, and 13 TeV, corresponding to an integrated luminosity of 9 fb^{-1} . The CP violation parameters are determined to be $C = -0.13 \pm 0.32 \pm 0.04$, $S = +0.82 \pm 0.29 \pm 0.05$, where the first uncertainties are statistical and the second are systematic. The results are consistent with the standard model prediction. This is the first experimental study of time-dependent CP violation in $b \rightarrow s \ell^+ \ell^-$ processes.

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Flavor-changing neutral-current decays [1], such as the rare $b \rightarrow s \ell^+ \ell^-$ transition, serve as powerful and sensitive probes for physics beyond the standard model (SM). Their inherent suppression within the SM makes any observed deviation in their decay properties a clear signature of new physics. Since beginning of operations, the LHCb experiment has performed extensive studies of a series of $b \rightarrow s \ell^+ \ell^-$ processes, which have revealed a compelling, albeit evolving, picture of anomalies. Most notably, the measurements of branching fractions and angular observables in several semileptonic B -meson decays performed by the LHCb, ATLAS, CMS, Belle, and BABAR collaborations [2–14] show a coherent and distinct pattern of tensions with the SM, which could be explained by new-physics contributions to the effective four-fermion $b \rightarrow s \ell^+ \ell^-$ couplings [15–17].

These persistent anomalies motivate the use of complementary experimental probes to better understand the underlying dynamics. In particular, time-dependent analyses of neutral B -meson decays provide theoretically clean observables to explore new-physics phenomena in $b \rightarrow s$ transitions [18–27]. The CP asymmetry arising from the interference between the B^0 – $\bar{B}^0$ mixing and decay amplitudes is sensitive to the imaginary parts of the Wilson coefficients governing these processes, yielding constraints on new CP -violating phases that are complementary to, and in many cases more direct and robust than, those obtained from the time-integrated or time-independent decay rates,

angular distributions, and CP asymmetries in decays such as $B^0 \rightarrow K^*(892)^0 \mu^+ \mu^-$ [28–30]. The power of the time-dependent approach is well established in hadronic $b \rightarrow s q \bar{q}$ ($q = d, s$) channels, such as $B^0 \rightarrow \eta' K_S^0$ and $B^0 \rightarrow \phi(1020) K_S^0$ [31,32]. (The inclusion of charge-conjugate processes is implied throughout this Letter unless otherwise stated.) The decay $B^0 \rightarrow K_S^0 \mu^+ \mu^-$ thus enables the first time-dependent CP violation measurement in a $b \rightarrow s \ell^+ \ell^-$ process, opening a crucial new window to CP -violating new physics in these rare modes.

In general, the $K_S^0 \mu^+ \mu^-$ final state is an admixture of CP -even and odd eigenstates, thus a full time-dependent angular analysis is required to perform the most complete test of CP violation [19,33]. Given the limited statistics of the data sample considered in this Letter, this study focuses on measuring the overall time-dependent CP asymmetry after integrating over the lepton helicity angle in the dimuon rest frame. The time-dependent CP asymmetry between the decay rates of initial $\bar{B}^0$ and B^0 mesons to the $K_S^0 \mu^+ \mu^-$ final state is defined as

$$\mathcal{A}^{CP}(t) \equiv \frac{\Gamma(\bar{B}^0(t) \rightarrow K_S^0 \mu^+ \mu^-) - \Gamma(B^0(t) \rightarrow K_S^0 \mu^+ \mu^-)}{\Gamma(\bar{B}^0(t) \rightarrow K_S^0 \mu^+ \mu^-) + \Gamma(B^0(t) \rightarrow K_S^0 \mu^+ \mu^-)} \simeq S \sin(\Delta m_d t) - C \cos(\Delta m_d t), \quad (1)$$

where t is the time interval between the production and decay of the $\bar{B}^0$ or B^0 meson in its rest frame, Δm_d is the B^0 – $\bar{B}^0$ oscillation frequency, and Γ is the decay rate for corresponding processes. The decay-width difference of the two B^0 mass eigenstates, $\Delta\Gamma_d$ is assumed to be zero in the equation. The parameters S and C quantify the mixing-induced and direct CP violation, respectively. In the SM, the $B^0 \rightarrow K_S^0 \mu^+ \mu^-$ decay proceeds dominantly to a CP -odd state and the expectation is $C \approx 0$ and

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$S = \sqrt{(1 - C^2)} \sin(2\beta + \Delta\phi_d) \approx \sin(2\beta)$. Here β is the CKM angle measured in $B^0 \rightarrow J/\psi K_S^0$ decays [34], and $\Delta\phi_d$ is a small phase shift due to the interference of the B^0 mixing and $b \rightarrow s$ decay amplitudes. For the dimuon mass-squared range $1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$, the mixing-induced CP asymmetry is explicitly predicted to be $S = 0.72 \pm 0.02$ in the SM [35]. However, various new-physics models with new interactions or additional weak phases can lead to a significant deviation of S and C from their SM predictions [36].

This Letter reports the first measurement of the CP -violating parameters in $B^0 \rightarrow K_S^0 \mu^+ \mu^-$ decays using pp collision data collected with the LHCb detector in 2011–2012 (Run 1) and 2015–2018 (Run 2), corresponding to an integrated luminosity of 9 fb^{-1} . The CP -violating observables C and S are measured from a time-dependent analysis in the full range of dimuon masses, q^2 , excluding the J/ψ ($8.0 < q^2 < 11.0 \text{ GeV}^2/c^4$) and $\psi(2S)$ ($15.0 < q^2 < 17.5 \text{ GeV}^2/c^4$) regions. The control channel $B^0 \rightarrow J/\psi(\rightarrow \mu^+ \mu^-) K_S^0$ is used to study the difference between the simulation and data and to validate the fit procedure.

The LHCb detector [37,38] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. It employs a dipole magnet with periodically reversed polarity for momentum determination. The detector used to collect the data analyzed in this Letter includes a high-precision tracking system consisting of silicon-strip [39,40] and straw drift-tube [40] detectors. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors [41]. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers, achieving high efficiency and excellent momentum resolution [42,43].

The simulated samples used to study the decay properties of the signal, control, and background channels are generated using the software described in Refs. [44–50]. Simulated signal decays are generated according to the theoretical calculation for $b \rightarrow s$ transitions in Ref. [51]. The data-simulation difference is studied using the control channel $B^0 \rightarrow J/\psi K_S^0$, and applied to the signal simulation to match the B^0 kinematic distributions and the particle identification (PID) performance in data [43,50,52].

The online event selection is performed by a trigger [53], which consists of a hardware stage followed by a two-stage software trigger. The hardware trigger for this Letter employs information from the muon system. Subsequently, the software trigger imposes requirements on the muon transverse momentum and track reconstruction quality, or on the output of a multibody topological b -hadron trigger [54]. Triggered data further undergo a centralized, offline processing step across the entire LHCb physics program [55].

In the offline analysis, K_S^0 candidates are reconstructed from two oppositely charged tracks considered as pions. They are categorized according to the position of the K_S^0 decay vertex. For K_S^0 mesons that decay inside the vertex locator (VELO), the resulting tracks are classified as long tracks and are reconstructed using hits from both the VELO and the main tracking stations, thereby providing the best momentum resolution. For particles that decay outside the VELO, the tracks are classified as downstream tracks; these are reconstructed using only hits from the tracking stations. The mass of the $\pi^+ \pi^-$ pair is required to be within $20 \text{ MeV}/c^2$ of the known K_S^0 mass [56]. These K_S^0 candidates are then combined with a pair of oppositely charged muons to form B^0 candidates. All tracks and vertices are required to have a good fit quality. Furthermore, PID criteria are applied to ensure that the charged tracks are consistent with the hypothesis of being pions or muons, as required by the decay chain. The PID observables of the charged tracks are calculated using multivariate techniques to combine information from different subsystems [43,50,52]. A kinematic fit is performed to improve the B^0 mass resolution by constraining the mass of the $\pi^+ \pi^-$ pair to the known K_S^0 mass [56].

This analysis considers specific backgrounds that can contaminate the $B^0 \rightarrow K_S^0 \mu^+ \mu^-$ signal sample. These include $\Lambda_b^0 \rightarrow \Lambda(\rightarrow p \pi^-) \mu^+ \mu^-$ decays where the proton is misidentified as a pion, and $B^0 \rightarrow D^-(\rightarrow K_S^0 \pi^-) \pi^+$ and $B^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays where two pions are misidentified as muons. These backgrounds are highly suppressed through mass vetos and PID requirements. Evaluation using simulation samples confirms that their residual contamination to the final signal sample is negligible after these requirements. The q^2 value is required to be outside the two defined charmonium regions, except when selecting the control channel $B^0 \rightarrow J/\psi(\rightarrow \mu^+ \mu^-) K_S^0$.

To further suppress the combinatorial background arising from the random combination of unrelated tracks, a multivariate analysis based on a gradient boosted decision tree (BDTG) technique is carried out [57]. The BDTG classifier is trained using simulated $B^0 \rightarrow K_S^0 \mu^+ \mu^-$ signal decays and data candidates in the high $K_S^0 \mu^+ \mu^-$ mass sideband of $[5700, 6000] \text{ MeV}/c^2$ to represent the background. The BDTG classifier incorporates a set of kinematic and topological variables, such as the transverse momentum (p_T) and η of the B^0 and K_S^0 candidates, their impact parameters with respect to the primary vertex (PV), and PID variables of the final state particles. These inputs show good agreement between the background-subtracted data and simulation in both the signal and control channel $B^0 \rightarrow J/\psi K_S^0$. The requirement on the BDTG output is chosen to maximize the expected signal significance.

Eight categories of $B^0 \rightarrow K_S^0 \mu^+ \mu^-$ candidates are selected using separate BDTG classifiers, corresponding to the combinations of four data-taking periods with

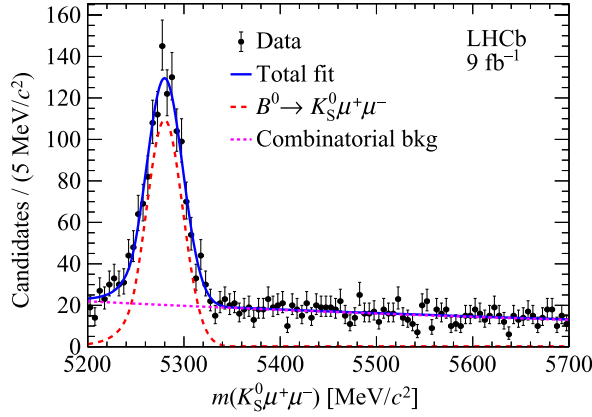


FIG. 1. Mass distribution of the selected $B^0 \rightarrow K_S^0 \mu^+ \mu^-$ candidates, with the fit result also shown.

roughly equal signal yields (2011–2012, 2015–2016, 2017, 2018) and two K_S^0 categories (with long or downstream track types). An unbinned extended maximum-likelihood fit is performed to the B^0 mass distribution to determine the signal and background yields in each category. The B^0 signal is modeled by a crystal ball function [58], with tail parameters fixed from simulation and the width and peak position allowed to vary in the fit. The combinatorial background is modeled with an exponential function.

The mass distribution of the selected B^0 candidates combining all categories is shown in Fig. 1, together with the combined fit results. The total signal yield is 941 ± 55 . All selected candidates are then sorted into two groups corresponding to the Run 1 and Run 2 periods, respectively, which are used in the subsequent decay-time fit to determine the CP violation parameters.

The decay-time distribution of B^0 ($\bar{B}^0$) mesons produced in pp collisions is described by

$$P_{B^0(\bar{B}^0)}(t) \propto e^{-t/\tau_{B^0}} \left[\cosh\left(\frac{\Delta\Gamma_d t}{2}\right) \mp S \sin(\Delta m_d t) \pm C \cos(\Delta m_d t) + D \sinh\left(\frac{\Delta\Gamma_d t}{2}\right) \right], \quad (2)$$

where τ_{B^0} is the lifetime of the B^0 meson. The upper (lower) sign corresponds to B^0 ($\bar{B}^0$) decays. The parameter D parametrizes CP -violating effects originating from $\Delta\Gamma_d$. Since $\Delta\Gamma_d$ is compatible with zero [56], the $\cosh(\Delta\Gamma_d t/2)$ term is approximated to 1, and the $\sinh(\Delta\Gamma_d t/2)$ term in Eq. (2) is neglected in the baseline measurement. The reconstructed decay-time distribution is affected by the experimental effects discussed below.

The flavor of the B^0 or $\bar{B}^0$ meson at production is identified using both the same-side (SS) [59] and opposite-side (OS) [60] flavor tagging algorithms. The SS algorithm exploits charged particles from the signal b -quark fragmentation, such as pions and protons. The OS algorithm

utilizes decay products from the associated partner b -hadron, including kaons, leptons, reconstructed charm hadrons, and the charge information from its decay vertex. Each algorithm provides a tagging decision d with an estimated mistag probability, where $d = +1, -1$, or 0 if the meson is classified as B^0 , $\bar{B}^0$ or untagged, respectively. The estimated mistag probability is calibrated with a dedicated software package [61], using $B^+ \rightarrow J/\psi K^+$ and $B^0 \rightarrow J/\psi K^{*(892)^0}$ decays for the OS and SS tagging method, respectively. The calibration samples are weighted to match the distributions in the signal sample of kinematic properties (p_T , η , and azimuthal angle of the signal B^0 candidates) and event characteristics (PV and track multiplicities). The package yields the calibrated mistag probability ω for each candidate. The OS and SS tagging decisions and mistag probabilities are then combined to give the final tagging decision and mistag probability for each B meson. The total effective tagging efficiency is $\varepsilon_{\text{tag}}\langle D^2 \rangle = (2.7 \pm 1.1)\%$ and $(4.1 \pm 0.6)\%$ for the Run 1 and Run 2 samples, respectively. Here ε_{tag} is the fraction of B candidates that have a nonzero tagging decision, and D^2 is the effective dilution squared depending on the event-by-event mistag probability [59,60].

Assuming no production or tagging asymmetries for B^0 and $\bar{B}^0$ mesons, the decay-time distribution becomes

$$P(t, d, \omega) \propto [1 + d(1 - 2\omega)]P_{B^0}(t) + [1 - d(1 - 2\omega)]P_{\bar{B}^0}(t). \quad (3)$$

The decay-time resolution is accounted for by convolving Eq. (3) with a resolution function consisting of the sum of three Gaussian functions. Each Gaussian has the same mean and a width depending linearly on the per-candidate decay-time uncertainty. The parameters of the resolution model are obtained by fitting the samples of prompt $K_S^0 \mu^+ \mu^-$ candidates, which are constructed from a K_S^0 and two muon candidates passing the same selection criteria as that for the signal channel, except the minimum requirement on the B meson decay time. The resulting resolution model, with an effective resolution of about 60 fs, affects the CP -violating parameters by less than 0.1%, which is negligible compared to the statistical uncertainties.

The reconstruction, trigger, and selection requirements result in a decay-time-dependent signal efficiency. This effect is accounted for by multiplying the decay-time distribution by an acceptance function parameterized by a cubic spline function [62] with six knots at 0.5, 1.0, 1.5, 2.0, 3.0, 8.0 ps and eight coefficients. One coefficient is fixed to unity for normalization, and the remaining coefficients are allowed to vary in the fit to data described below.

A weighted unbinned maximum-likelihood fit [63,64] is simultaneously performed on the Run 1 and Run 2 data

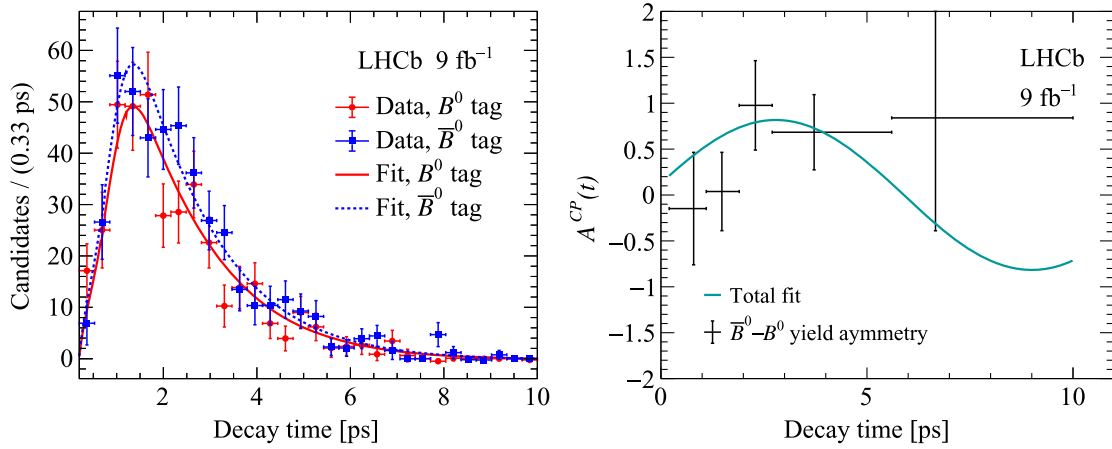


FIG. 2. Left: background-subtracted decay-time distributions for $\bar{B}^0$ and B^0 candidates identified through flavor tagging, where the fit result is also shown. The difference between $\bar{B}^0$ and B^0 distributions reveals the CP asymmetry. Right: time-dependent CP asymmetry. The data points show the binned signal yield asymmetry, with tagging dilution effects corrected for. The result of the maximum-likelihood fit is shown as the solid curve.

samples to the decay times of the $B^0 \rightarrow K_S^0 \mu^+ \mu^-$ candidates to determine the CP violation parameters S and C . In this fit, only the signal component is explicitly modeled while the background contributions are statistically subtracted via the signal weights calculated with the *sPlot* [65] method using the B^0 mass as the discriminating variable. This method assumes that the decay time and B^0 mass are uncorrelated in both the signal and individual background components. Potential correlations are treated as systematic uncertainties.

In the fit, the B^0 lifetime and the mass difference between the two neutral B mass eigenstates are constrained to their world-average values, $\tau_{B^0} = 1.517 \pm 0.004$ ps and $\Delta m_d = 0.507 \pm 0.002$ ps $^{-1}$ [56]. This allows the time acceptance parameters to be determined entirely from the fit to the signal data. The decay-time resolution and flavor-tagging calibration parameters are constrained to the fit results obtained in the corresponding calibration channels.

The background-subtracted decay-time distributions of the tagged $\bar{B}^0$ and B^0 signal candidates in the combined data sample are shown in Fig. 2, together with the baseline fit using Eq. (2). The corresponding time-dependent CP asymmetry is also presented, which is computed from the

tagged yields after correcting for the effects of flavor-tagging dilution. The CP violation parameters are determined from the time-dependent fits both for the entire kinematically allowed q^2 range [excluding the J/ψ and $\psi(2S)$ regions] and, to probe potential q^2 dependency, in the q^2 ranges below and above the J/ψ region. The results are summarized in Table I and Fig. 3. The 68.3%, 95.5%, and 99.7% confidence regions under the physical constraint $C^2 + S^2 \leq 1$ are further obtained for the total q^2 region using the Feldman-Cousins method [66,67] and shown in the End Matter.

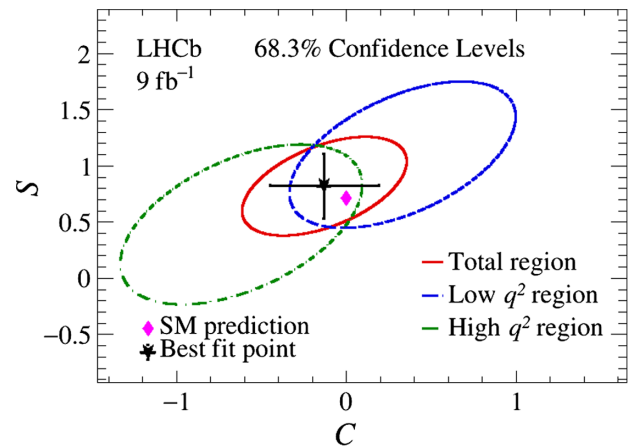


TABLE I. Summary of the CP violation parameters from the time-dependent fit to $B^0 \rightarrow K_S^0 \mu^+ \mu^-$ decays in the total, low and high q^2 ranges, excluding the charmonium regions. Only statistical uncertainties are considered.

q^2 range [GeV $^2/c^4$]	C	S
Total	-0.13 ± 0.32	$+0.82 \pm 0.29$
Low: $q^2 < 8.0$	$+0.33 \pm 0.44$	$+1.10 \pm 0.43$
High: $11.0 < q^2 < 15.0$ or $q^2 > 17.5$	-0.62 ± 0.47	$+0.48 \pm 0.47$

FIG. 3. Two-dimensional confidence regions for the parameters C and S from profile likelihood scans; only statistical uncertainties are considered in this plot. The green dash-dotted, blue dashed, and red solid contours represent the 68.3% confidence regions for the low- q^2 , high- q^2 , and total regions, respectively. The black marker with error bars represents the fit results in the total sample, while the magenta marker stands for the SM prediction.

TABLE II. Summary of absolute systematic uncertainties for the parameters C and S .

Sources	C	S
Fit bias	0.017	0.015
Flavor tagging	0.031	0.037
Mass fit models	0.010	0.011
Mass-time correlation	0.013	0.018
Nonzero $\Delta\Gamma_d$	0.007	0.005
Production asymmetry	0.006	0.004
Time acceptance and resolution	Negligible	Negligible
Total	0.041	0.046

Several sources of systematic uncertainties for the CP -violation observables are investigated and listed in Table II. A large ensemble of pseudoexperiments generated according to the baseline fit results is used to validate the fit procedure. The observed distributions of the parameters from these pseudoexperiments demonstrate that the statistical uncertainties are correctly treated. A bias in the C and S parameters is observed, which is due to the limited data sample size. The consistency of the tagging calibration parameters between the calibration and signal channels is tested using simulated samples, and that between B^0 and $\bar{B}^0$ mesons is investigated using the calibration channels $B^+ \rightarrow J/\psi K^+$ and $B^0 \rightarrow J/\psi K^{*0}$. The observed differences represent the leading source of systematic uncertainties. Systematic uncertainties associated with the modeling of the signal and background contributions are evaluated by repeating the mass fit with alternative functions, namely the sum of a Student's t distribution and a Gaussian function for the signal and a second-order polynomial for the combinatorial background. Then, the weighted maximum-likelihood fit is performed, and the differences in the resulting parameters from those of the baseline fit are assigned as systematic uncertainties. The effect of neglecting a small correlation between the reconstructed B^0 mass and decay time in the signal weight determination when applying the $sPlot$ method is studied by reevaluating the signal weights in bins of the decay time and performing the decay-time fit again. The effects of a nonzero B^0 - $\bar{B}^0$ production asymmetry and a nonzero $\Delta\Gamma_d$ are evaluated by varying their values within their uncertainties [56,68] and performing the fits again. The resulting largest variations in CP violation parameters are assigned as systematic uncertainties. The systematic uncertainties associated with the decay-time acceptance and resolution models are evaluated using splines with different knot numbers and positions and found to be negligible. The total systematic uncertainties, evaluated as the quadrature sums of the contributions discussed above, are significantly smaller than the statistical ones.

The robustness of the analysis results is checked by splitting the data sample by K_S^0 reconstruction categories,

magnet polarities, and data-taking periods, by varying the B^0 mass and decay-time ranges, and by obtaining alternative determination of the S parameters from the time-integrated CP asymmetry. The results are all compatible with each other and with the baseline fit results. As a cross check, the analysis procedure has also been applied to the control channel $B^0 \rightarrow J/\psi K_S^0$. The corresponding results are consistent with those reported in Ref. [34].

In conclusion, this Letter reports a measurement of the time-dependent CP asymmetry in $B^0 \rightarrow K_S^0 \mu^+ \mu^-$ decays using data collected by the LHCb experiment during the Run 1 and Run 2 data-taking periods. The CP violation parameters in the full q^2 range, excluding the dimuon resonant regions due to J/ψ and $\psi(2S)$ states, are determined to be

$$C = -0.13 \pm 0.32(\text{stat}) \pm 0.04(\text{syst}),$$

$$S = +0.82 \pm 0.29(\text{stat}) \pm 0.05(\text{syst}),$$

with a statistical correlation coefficient of 0.50. This is the first measurement of time-dependent CP violation in $b \rightarrow s\ell^+\ell^-$ transitions, and the results are consistent with the SM prediction. This Letter demonstrates a new avenue to probe physics beyond the SM in $b \rightarrow s\ell^+\ell^-$ transitions, complementary to measurements of branching fractions, angular observables and lepton-flavor universality observables.

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Data availability—The data that support the findings of this article are openly available at [69].

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End Matter

Confidence regions within the physical boundary—The results shown in Fig. 3 are obtained without applying any physical constraint on the CP violation parameters. In fact, the normalization of the coefficients of the time-dependent decay rate requires $C^2 + S^2 \leq 1$. Confidence intervals satisfying this requirement are derived using a constrained likelihood-ratio test.

Specifically, the maximum-likelihood estimation and the ordering of parameter points are performed within the restricted domain defined by this inequality. The results are presented in Fig. 4. Systematic uncertainties are excluded from this evaluation as their contribution is negligible compared to the statistical uncertainties.

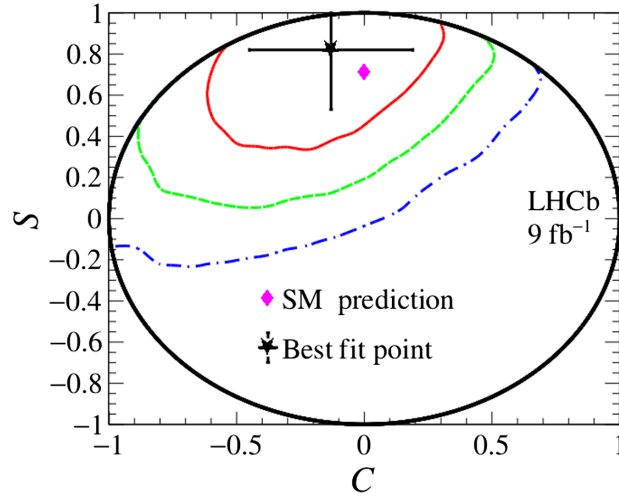


FIG. 4. Two-dimensional confidence regions for C and S based on a likelihood-ratio ordering technique, corresponding to the total q^2 range. The red solid, green dashed and blue dash-dotted contours represent the 68.3%, 95.5%, and 99.7% confidence intervals given the physical constraint $C^2 + S^2 \leq 1$. The black marker with error bands represents the fit results for C and S . The magenta diamond marker stands for the SM prediction. Only statistical uncertainties are considered in this plot.

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