Published for SISSA by Springer

Received: *July 18, 2024*
Accepted: *October 10, 2024*
Published: *October 31, 2024*

Measurement of the $B_s^0 \to J/\psi K_S^0$ effective lifetime from proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS collaboration

E-mail: cms-publication-committee-chair@cern.ch

Abstract: The effective lifetime of the B_s^0 meson in the decay $B_s^0 \to J/\psi K_S^0$ is measured using data collected during 2016–2018 with the CMS detector in $\sqrt{s} = 13$ TeV proton-proton collisions at the LHC, corresponding to an integrated luminosity of 140 fb^{-1}. The effective lifetime is determined by performing a two-dimensional unbinned maximum likelihood fit to the B_s^0 meson invariant mass and proper decay time distributions. The resulting value of $1.59 \pm 0.07(\text{stat}) \pm 0.03(\text{syst})$ ps is the most precise measurement to date and is in good agreement with the expected value.

Keywords: B Physics, Hadron-Hadron Scattering, Lifetime

ArXiv ePrint: 2407.13441

https://doi.org/10.1007/JHEP10(2024)247

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1 Introduction

Measurements using b hadron decays have dramatically improved our knowledge of the standard model (SM) flavor sector. An important aspect of B meson studies is determining whether the SM correctly describes the violation of charge-parity (*CP*) symmetry observed in nature. The oscillations of B^0 and B^0_s mesons provide a valuable tool in the study of *CP* violation [1]. At hadron colliders, neutral B mesons are produced as flavor eigenstates, but they propagate as mass eigenstates, referred to as the light and heavy states, which are linear combinations of the two flavor states. In the limit of *CP* conservation in the flavor mixing, the mass and *CP* eigenstates are identical. These mass eigenstates have different lifetimes, both of which differ from the average lifetime of the corresponding B meson.

In the SM, quark flavor transitions occur through the weak interaction according to the Cabibbo-Kobayashi-Maskawa (CKM) matrix. Unitarity triangles can be derived from this matrix, with a nonzero area indicating *CP* violation [2, 3]. Measurements of the angles and sides of the unitarity triangles can be used to constrain SM parameters and search for physics beyond the SM. The parameter β is one of the angles of the most commonly used unitarity triangle and is most precisely determined by measuring the phase ϕ_d in a time-dependent *CP* asymmetry analysis of $B^0 \to J/\psi K^0_S$ decays, where ϕ_d arises from the interference between the direct decay of B^0 and the decay after oscillating to $\overline{B}^0$. In the SM, $\phi_d = 2\beta$. However, the value of the phase measured in $B^0 \to J/\psi K^0_S$ may not exactly

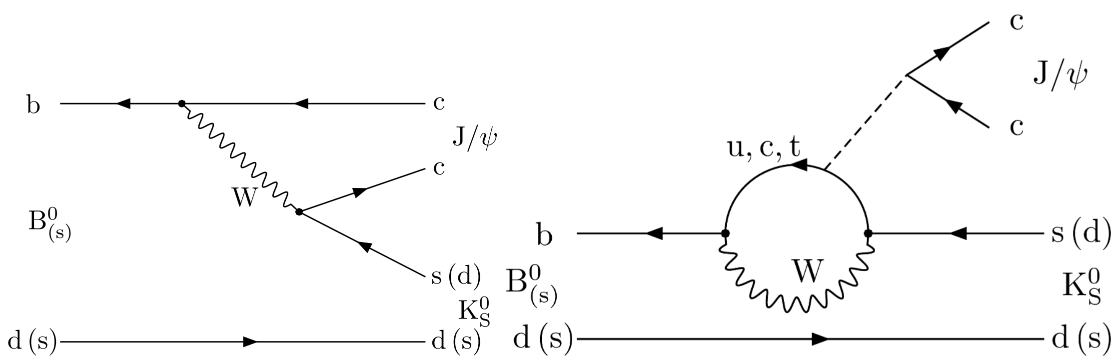

Figure 1. The tree-level (left) and penguin (right) Feynman diagrams for the decays $B^0 \to J/\psi K^0_S$ and $B^0_s \to J/\psi K^0_S$.

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equal ϕ_d since there is a small contribution to the decay from doubly-Cabibbo-suppressed penguin decays, with a different phase [4–7]. Since the value of $\sin(2\beta)$ is now known to better than 2% [8], understanding the penguin contribution is becoming more important in determining ϕ_d. This can be accomplished by studying the decay $B^0_s \to J/\psi K^0_S$, where the penguin contribution is much larger, since it is not Cabibbo suppressed relative to the tree diagram, and it is related to the $B^0 \to J/\psi K^0_S$ decay through the U-spin flavor symmetry of the strong interaction (swapping s and d quarks) [9–13].

In this paper, we measure the effective lifetime of the B^0_s meson in its decay to $J/\psi K^0_S$. Charge conjugate states and decays are implied unless otherwise indicated. Figure 1 shows the tree-level and penguin Feynman diagrams for the decay modes $B^0 \to J/\psi K^0_S$ and $B^0_s \to J/\psi K^0_S$. The effective lifetime is theoretically defined as the time expectation value of the untagged decay rate [14], where untagged means that no requirements are made that would bias one B^0_s mass eigenstate over the other. Typically, an untagged rate is characterized by two exponentials, corresponding to the two mass eigenstates with distinct lifetimes, while a single exponential fit serves as an approximation. The CMS Collaboration has measured the effective lifetime in the decay $B^0_s \to \mu^+\mu^-$ [15, 16], a *CP*-odd final state, as well as other B^0_s meson decay channels [17]. The ATLAS and LHCb experiments have also measured the effective lifetimes for a variety of decay modes [18–30]. The effective lifetime of a particular decay channel can be experimentally determined by fitting a single exponential function to its untagged rate. The $J/\psi K^0_S$ state can be considered a pure *CP*-odd state [31], with *CP* violation in the kaon system being neglected [32]. This allows us to accurately measure the B^0_s heavy-state lifetime.

The $B^0_s \to J/\psi K^0_S$ effective lifetime is defined as

$$\tau(B^0_s \to J/\psi K^0_S) \equiv \frac{\int_0^\infty t\,\{\Gamma[B^0_s(t) \to J/\psi K^0_S] + \Gamma[\overline{B}^0_s(t) \to J/\psi K^0_S]\}\,dt}{\int_0^\infty \{\Gamma[B^0_s(t) \to J/\psi K^0_S] + \Gamma[\overline{B}^0_s(t) \to J/\psi K^0_S]\}\,dt}, \tag{1.1}$$

where t is the proper decay time of the B^0_s meson. The effective lifetime can also be expressed as [33]

$$\tau(B^0_s \to J/\psi K^0_S) = \frac{\tau_{B^0_s}}{1 - y_s^2}\left(\frac{1 + 2\,y_s A_{\Delta\Gamma} + y_s^2}{1 + y_s A_{\Delta\Gamma}}\right), \tag{1.2}$$

where $A_{\Delta\Gamma}$ is the mass eigenstate rate asymmetry, y_s is the normalized decay width difference, defined as $y_s = \tau_{B_s^0}\Delta\Gamma/2$, $\Delta\Gamma$ is the decay width difference between the heavy and light B_s^0 mass eigenstates, and $\tau_{B_s^0}$ denotes the mean B_s^0 lifetime. Using the most recent measurements [31, 34] of these observables, the SM prediction for the $B_s^0 \to J/\psi K_S^0$ effective lifetime is 1.62 ± 0.02 ps, where the uncertainty is derived from the uncertainties in the observables in eq. (1.2). The only previous measurement of this effective lifetime is from the LHCb Collaboration, which reported $\tau(B_s^0 \to J/\psi K_S^0) = 1.75 \pm 0.12\,(\text{stat}) \pm 0.07\,(\text{syst})$ ps from data collected in 2011 [27]. The analysis described in this paper uses two variables, the $J/\psi K_S^0$ invariant mass and proper decay time, to extract the effective lifetime. The decay $B^0 \to J/\psi K_S^0$ is used as a control channel for various bias tests and validations.

2 The CMS detector

The central feature of the CMS detector is a 6 m internal diameter superconducting solenoid that provides a magnetic field of 3.8 T. Within this solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. Each of them is composed of a barrel and two endcap sections. The silicon tracker used in 2016 measured charged particles within the pseudorapidity range $|\eta| < 2.5$. For nonisolated particles of transverse momentum $1 < p_T < 10$ GeV and $|\eta| < 1.4$, the track resolutions were typically 1.5% in p_T and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [35]. At the start of 2017, a new pixel detector was installed [36]; the upgraded tracker measured particles up to $|\eta| < 3.0$ with typical resolutions of 1.5% in p_T and 20–75 μm in the transverse impact parameter [37] for nonisolated particles of $1 < p_T < 10$ GeV. Muons with $|\eta| < 2.4$ are measured with gas-ionization chambers embedded in the steel flux-return yoke that resides outside the solenoid. A more detailed description of the CMS detector, definition of the coordinate system used, and the other relevant kinematic variables, can be found in ref. [38].

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of 4 μs [39]. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [40].

3 Data and simulation samples

Data used in the analysis correspond to an integrated luminosity of 140 fb^{-1} [41–43], collected by the CMS experiment during 2016–2018 in proton-proton (pp) collisions at a center-of-mass energy of 13 TeV.

The analysis uses Monte Carlo (MC) samples to estimate the detector acceptance and the trigger and reconstruction efficiencies. The MC event samples are simulated using PYTHIA v8.240 [44] and the unstable particle decays are modeled by EVTGEN v1.6.0 [45]. Final-state radiation is included in EVTGEN using PHOTOS v3.61 [46]. The particles are propagated

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through a detailed model of the CMS detector using GEANT4 [47]. The simulated events follow the same reconstruction algorithm and selection criteria as the collision data. To take into account the effect of additional pp collision vertices in the same or nearby bunch crossings, the number and spatial distribution of collision vertices in simulated events are matched to those from data.

4 Event selection

The events used in this analysis were collected by an HLT path that required two oppositely charged muons with a distance of closest approach less than 0.5 cm, a vertex fit χ^2 probability greater than 0.5%, and an invariant mass in the range 2.9–3.3 GeV. The muons were required to pass within 2 mm of the beamline and the dimuon system was required to have $|\eta| < 2.5$ and $p_{\mathrm{T}} > 19.9$ GeV in 2016 and $p_{\mathrm{T}} > 24.9$ GeV in 2017–2018. These requirements are also applied on the corresponding offline quantities, with an additional requirement of the muon candidates satisfying the soft muon identification criteria [48].

The $\mathrm{J}/\psi\mathrm{K}^0_\mathrm{S}$ candidates are reconstructed using the J/ψ meson decay to $\mu^+\mu^-$ and K^0_S meson decay to $\pi^+\pi^-$. After the standard track selection criteria [49], the two daughter tracks assumed to be from the K^0_S decay are given charged pion mass assignments and fit to a common vertex. The fitted two-track vertex must have a $\chi^2 < 7$ [50] and be located at a distance from the beamline that is at least 15 times larger than its uncertainty. The $\pi^+\pi^-$ and $\mu^+\mu^-$ invariant mass distributions are each fit with a sum of two Gaussian functions with a common mean for the signal component and an exponential function for the background. The effective invariant mass resolutions are evaluated as $\sigma_{\text{eff}} = \sqrt{f\sigma_1^2 + (1-f)\sigma_2^2}$, where σ_1 and σ_2 are the individual widths of the two Gaussian functions and f is the fraction of events associated with the first Gaussian function. The effective mass resolutions are approximately 5.5 and 30 MeV for the K^0_S and J/ψ, respectively. The $\pi^+\pi^-$ and $\mu^+\mu^-$ candidates are then required to have invariant masses within $2.5\,\sigma_{\text{eff}}$ from the corresponding common mean value found in the fit. The contamination in the K^0_S candidates from $\Lambda \to \mathrm{p}\pi^-$ decay, where the proton track is reconstructed as a pion, is removed using a requirement on the momentum asymmetry between the two daughters with the Armenteros-Podolanski method [51].

The two tracks from the $\mathrm{K}^0_\mathrm{S} \to \pi^+\pi^-$ candidate decay are fit to a common vertex with the invariant mass constrained to the K^0_S world-average mass value [34]. The B meson candidates are obtained from a vertex fit of $\mathrm{K}^0_\mathrm{S}\,\mu^+\mu^-$, with the dimuon mass constrained to the world-average J/ψ meson mass. The refitted momenta are then used to determine the reconstructed invariant mass m of the B candidate, which is required to satisfy $4.9 < m < 6.0$ GeV.

The distance between the B and K^0_S decay vertices in the transverse plane, referred to as the K^0_S decay length, is required to be greater than 5 times its uncertainty. This is done to further suppress background events that do not contain genuine K^0_S decays, such as $\mathrm{B}^0 \to \mathrm{J}/\psi\mathrm{K}^*(892)^0$ where the $\mathrm{K}^*(892)^0$ decays to $\mathrm{K}^+\pi^-$ and the K^+ is reconstructed as a π^+.

The measurement of the B meson decay length requires a precise reconstruction of both the production and decay vertices of the B meson. The proper decay time t of the

B meson candidate is determined using

$$t = m\frac{\vec{L}_{xy}\cdot\vec{p}_{\mathrm{T}}^{\mathrm{B}}}{\left(\vec{p}_{\mathrm{T}}^{\mathrm{B}}\right)^{2}}, \tag{4.1}$$

where m and $\vec{p}_{\mathrm{T}}^{\mathrm{B}}$ are the invariant mass and transverse momentum of the B candidate, respectively, and $\vec{L}_{xy}$ is the vector in the transverse plane from the beamline to the B meson candidate fitted decay vertex. The uncertainty in the proper decay time is determined by propagating the uncertainties in the decay length, invariant mass, and momentum of the B candidate.

To reduce contributions from non-signal processes, a multivariate selection is employed, based on a boosted decision tree (BDT). This BDT relies on 8 discriminating variables, which are associated with the properties of the B meson candidate and the final-state particles. Variables with minimal correlation to the proper decay time are used. These variables are: the angle between $\vec{L}_{xy}$ and the $\vec{p}_{\mathrm{T}}^{\mathrm{B}}$; the B and $\mathrm{K_S^0}$ vertex χ^2 fit probabilities; the p_{T} of the J/ψ and $\mathrm{K_S^0}$ candidates; the η of the B candidate; the angle in the transverse plane between the $\mathrm{K_S^0}$ momentum vector and the line joining the B and $\mathrm{K_S^0}$ candidate decay vertices; and the impact parameter of the B candidate with respect to the beamline divided by its uncertainty.

The BDT classifier uses two input samples containing signal and background decays, respectively. The signal sample is selected from MC events, and the background sample is made up of data events with the B meson candidate invariant mass in the high sideband region of 5.6–6.0 GeV. A distinct BDT is used for each of the three data-taking years to account for variations in the data-simulation agreement and different detector conditions. The optimization of the BDT threshold is done by minimizing the statistical uncertainty in the effective lifetime measurement based on studies using pseudo-experiments. In events with more than one B meson candidate satisfying the signal requirements, the one with the highest BDT discriminant value is chosen. To validate the reliability of the BDT approach, different kinematic distributions are compared and found to be consistent between the MC samples and the background-subtracted data for the control channel decay $\mathrm{B^0} \to \mathrm{J/\psi K_S^0}$.

5 Effective lifetime measurement

The effective lifetime for the signal $\mathrm{B_s^0}$ meson is extracted using a single two-dimensional unbinned extended maximum likelihood (2D UML) fit to the $\mathrm{J/\psi K_S^0}$ invariant mass (m) and the proper decay time (t) distributions, with the calculated uncertainty in the proper decay time (σ_t) as a conditional parameter in the fit. This fit is performed simultaneously to each of the three data-taking years, with independent parameters for each year except for the effective lifetimes of the signal and control channels, which are each represented by a single parameter. The decay time and invariant mass range used in the fit is $0.2 < t < 10\,\mathrm{ps}$ and $5.17 < m < 5.57\,\mathrm{GeV}$, respectively, with the mass range not extended below 5.17 GeV to avoid contributions from partially reconstructed decays of b hadrons. The signal efficiency as a function of decay time is determined from simulated samples and is used to account for the distortion of the measured decay time distribution caused by the selection criteria.

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The unnormalized probability density function (pdf) $\mathcal{L}$ is expressed as

$$\begin{aligned}\mathcal{L}(m,t;\,\sigma_t) = {} & N_{\mathrm{B_s^0}}\, M_{\mathrm{B_s^0}}(m)\, T_{\mathrm{B_s^0}}(t;\,\sigma_t)\, \varepsilon_{\mathrm{B_s^0}}(t) + N_{\mathrm{B^0}}\, M_{\mathrm{B^0}}(m)\, T_{\mathrm{B^0}}(t;\,\sigma_t)\, \varepsilon_{\mathrm{B^0}}(t) \\ & + N_{\mathrm{bkg}}\, M_{\mathrm{bkg}}(m)\, T_{\mathrm{bkg}}(t;\,\sigma_t).\end{aligned} \tag{5.1}$$

Here, $M(m)$ and $T(t;\,\sigma_t)$ are the invariant mass and decay time pdfs, respectively. The pdfs for the signal, control channel, and background components are labeled with the subscripts $\mathrm{B_s^0}$, $\mathrm{B^0}$, and bkg, respectively. The signal and control channel efficiencies are given by $\varepsilon_{\mathrm{B_s^0}}$ and $\varepsilon_{\mathrm{B^0}}$, respectively. The parameters $N_{\mathrm{B_s^0}}$, $N_{\mathrm{B^0}}$, and N_{bkg} correspond to the signal, control channel, and background yields, respectively.

The invariant mass distribution from simulated $\mathrm{B^0} \to \mathrm{J/\psi K_S^0}$ events is fit with a sum of three Gaussian functions with a common mean. This fitted function, with the two parameters governing the relative amplitude of each Gaussian fixed, is used in fitting the data. Before fitting the data, the function is fit to simulated $\mathrm{B_s^0} \to \mathrm{J/\psi K_S^0}$ events with the yield, mean, and a single scale factor ($\mathrm{B_s^0}$ MC) multiplying each of the widths as the free parameters. In fitting the data, the two invariant mass signal functions for $\mathrm{B^0}$ and $\mathrm{B_s^0}$ have a total of four free parameters: two yields, one mean, and one width scale factor. The world-average value for the difference in masses of the $\mathrm{B_s^0}$ and $\mathrm{B^0}$ mesons of $87.26 \pm 0.24\,\mathrm{MeV}$ [34] is applied as a Gaussian constraint to the difference of the means of the two corresponding invariant mass functions. The width scale factor multiplies all of the width parameters of each function, with the $\mathrm{B_s^0}$ signal function widths also multiplied by the $\mathrm{B_s^0}$ MC scale factor. The shape of the invariant mass distribution for the background is parametrized by an exponential function with a free slope parameter.

The pdfs $T_{\mathrm{B_s^0}}$ and $T_{\mathrm{B^0}}$ are exponential functions convolved with a Gaussian function to account for the detector resolution. These are multiplied by their respective efficiency functions $\varepsilon_{\mathrm{B_s^0}}(t)$ and $\varepsilon_{\mathrm{B^0}}(t)$. A sum of two exponential functions is used to model T_{bkg}, with all parameters left free in the fit.

The efficiencies are obtained by dividing the distribution of the reconstructed decay time in the MC by the distribution of the generated decay time convolved with the time resolution function and are fitted with the function:

$$\varepsilon(t;\,p_0,p_1,p_2,p_3,p_4) = p_0 + p_1 t + p_2 t^2 + \frac{p_3}{1+\exp(-p_4 t)}, \tag{5.2}$$

where p_i ($i = 0$–4) are free parameters in the fit. The efficiencies, along with the fitted ε functions, are shown in figure 2 for each of the three data-taking years. The ratio of the two efficiencies for each year is consistent with unity and shows no dependence on the decay time.

The measured m and t distributions are shown in figure 3, along with the projections of the 2D UML fit, in the full fit range and summed over all three data-taking years. The invariant mass projection from the 2D UML fit yields a χ^2 value of 82 with 80 bins, while the decay time projection results in a χ^2 value of 62 with 49 bins. For a better visualization of the signal component, the proper decay time projection is shown in figure 4 for events in the signal invariant mass range $5.34 < m < 5.42\,\mathrm{GeV}$, along with individual and total pdf components. The measured effective lifetime for the $\mathrm{B_s^0}$ from the simultaneous fit is

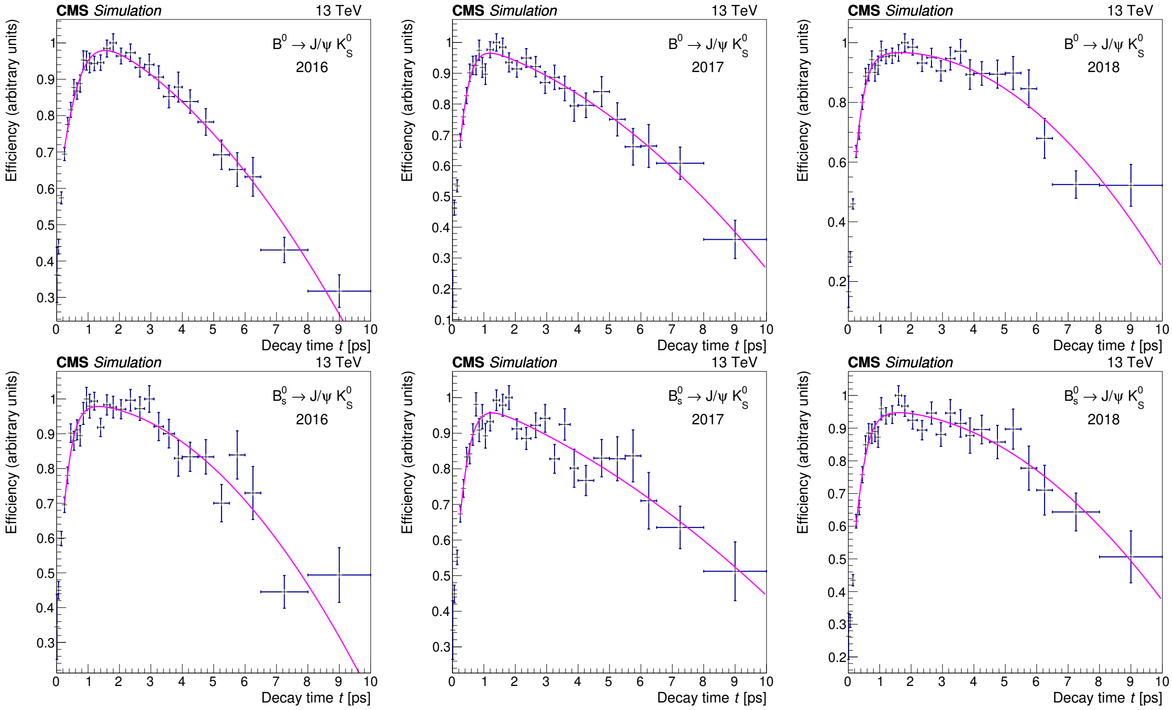

Figure 2. The signal efficiency as a function of the decay time for the $B^0 \to J/\psi K^0_S$ (upper) and $B^0_s \to J/\psi K^0_S$ (lower) decays from simulation for each of the three data-taking years. The vertical bars indicate the statistical uncertainty, and the horizontal bars give bin widths. The curves show the fit results.

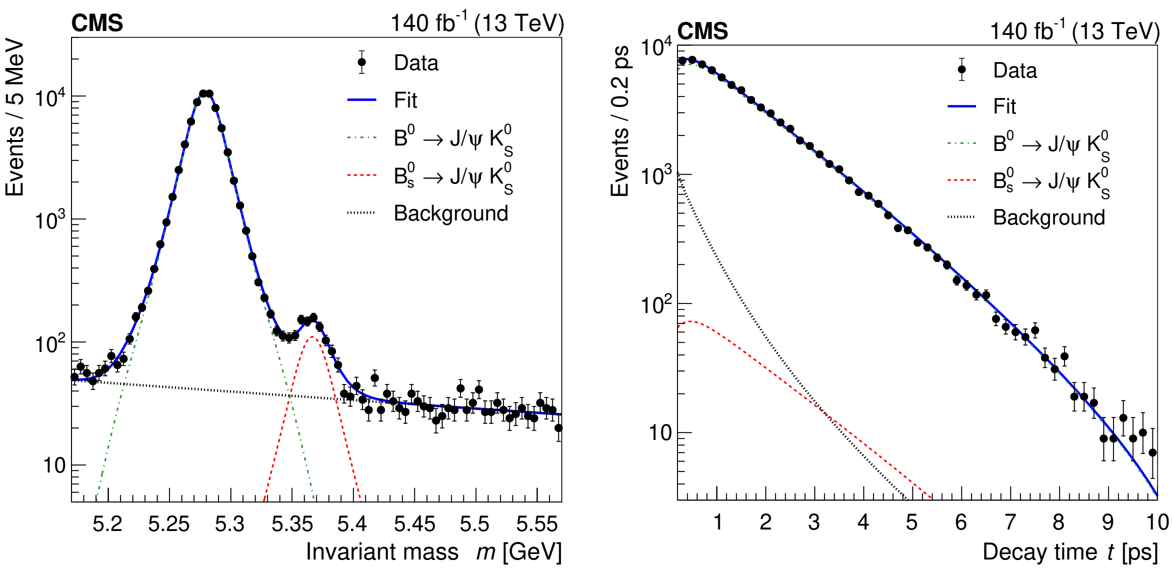

Figure 3. Distributions of the $J/\psi K^0_S$ invariant mass (left) and proper decay time (right) from data (points) and the results from the 2D UML fit projections (lines) for the 2016–2018 data set. The vertical bars on the data points indicate the statistical uncertainty. The solid, dotted-dashed, dashed, and dotted lines show the total fit, B^0 control channel, B^0_s signal, and background contributions, respectively.

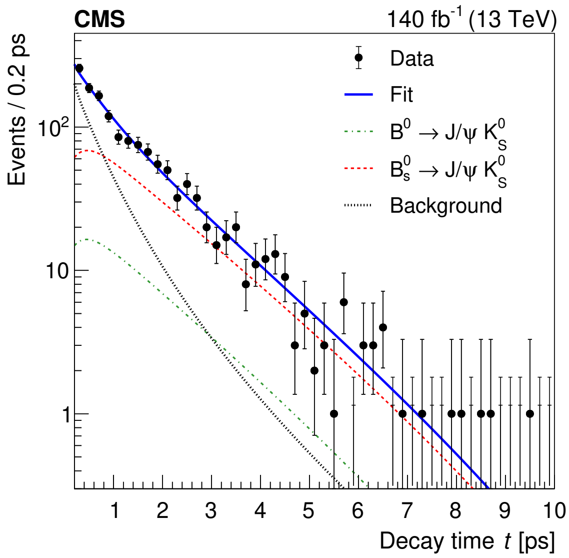

Figure 4. The proper decay time distribution from data (points) for events in the B^0_s signal region with $J/\psi K^0_S$ invariant mass in the range 5.34–5.42 GeV and the results from the 2D UML fit projections (lines) for the 2016–2018 data set. The vertical bars on the data points indicate the statistical uncertainty. The dashed, dotted-dashed, dotted, and solid lines show the B^0_s signal, B^0 control channel, background, and total fit contributions, respectively.

$\tau(B^0_s \to J/\psi K^0_S) = 1.59 \pm 0.07\,(\text{stat})\,\text{ps}$. Projections in m and t of this fit are given for each of the three data-taking years in appendix A, along with the corresponding data results.

Consistency checks are conducted, such as examining the decay time projections in different B^0_s invariant mass ranges and the invariant mass projections for different decay time ranges. There is good agreement between the data and results from the fit in all cases. These projections are shown in appendix B.

6 Systematic uncertainties

Several sources of systematic uncertainty are investigated and their effects on the B^0_s effective lifetime measurement are estimated.

The finite number of simulated events introduces an uncertainty due to the statistical variation in the MC samples and its effect on the determination of the efficiency functions. This is studied by generating 400 alternative efficiency functions, produced by varying the fitted parameters of the default efficiency function by their uncertainties. Each of these functions is then used in the fit to data. The standard deviation of the resulting effective lifetime measurements from these fits is 0.006 ps, which is used as an estimate of the systematic uncertainty from this source.

Another source of uncertainty comes from the choice of the function used to parametrize the efficiency as a function of the decay time. To estimate this effect, two other analytical functions (variations of eq. (5.2)) are used for efficiency modeling and each is used in the data fit. The largest deviation in the measured value of the effective lifetime from the fit to data using these two functions with respect to the value obtained using the default efficiency function is 0.002 ps, which is taken as the uncertainty from this source.

The choice of pdfs for the modeling of the signal and background invariant mass distributions is another source of systematic uncertainty. To estimate the effect, alternative functions are used to fit the data. Three alternative signal functions for the invariant mass, the double-sided Crystal Ball function [52], the Johnson S_U function [53], and the Student's t-distribution [54], are chosen since they provide a good fit to the simulated signal events. The alternative background function for the invariant mass is a Bernstein polynomial. Additionally, the effect of the uncertainty in the $\mathrm{B_s^0}$-$\mathrm{B^0}$ mass difference evaluated by varying the mass difference in the fits. The largest variation from the nominal fit, considering all combinations of nominal and alternative functions as well as the different mass difference values, is 0.022 ps, which is taken as the systematic uncertainty.

Similarly, the pdf for the decay time distribution of the background is changed to the sum of three exponential functions and the resulting variation in the result is 0.014 ps.

The $\mathrm{B_s^0}$ MC scale factor that allows the widths of the three Gaussian functions to vary with equal proportion in the fit is considered as a source of uncertainty. The scale factor is changed by its uncertainty (from the fit to the $\mathrm{B_s^0} \to \mathrm{J}/\psi \mathrm{K_S^0}$ MC events) and the variation in the $\mathrm{B_s^0}$ effective lifetime is 0.004 ps.

An alternative 2D UML fit is performed in which the ratio of the $\mathrm{B_s^0}$ to $\mathrm{B^0}$ signal yields is constrained to be the same for all three data-taking years rather than being independent for each year. The change in the final result of 0.006 ps is taken as the corresponding systematic uncertainty. It is possible that a small number of reconstructed $\mathrm{B_s^0}$ mesons may come from $\mathrm{B_c^+}$ decays. A fit was performed that added a component with the same mass shape as the signal, a lifetime distribution given by an exponential with a time constant equal to the world-average $\mathrm{B_c^+}$ average lifetime plus the fitted $\mathrm{B_s^0}$ lifetime, and an unconstrained yield. The difference in $\mathrm{B_s^0}$ lifetime from the nominal fit of 0.002 ps is taken as a systematic uncertainty.

The systematic uncertainty from the BDT is negligible; varying the BDT threshold by $\pm 5\%$ resulted in consistent lifetime measurements. The invariant mass range used in the fit is changed from the default of 5.17–5.57 to 5.1–5.6 GeV, with no effect on the result. To determine the potential uncertainty arising from an inaccurate σ_t calculation, the values of σ_t have been scaled by 0.5 and 2 in the fit. No change in the lifetime is found and therefore no systematic uncertainty is assessed.

As previously noted, the control channel $\mathrm{B^0} \to \mathrm{J}/\psi \mathrm{K_S^0}$ has the same topology and very similar kinematics to those of the signal channel, and is therefore used in defining the analysis strategy and to perform various checks. As the $\mathrm{B^0}$ meson lifetime extracted in this analysis, $1.521 \pm 0.007\,(\mathrm{stat})$ ps, agrees with the world-average value of 1.517 ± 0.004 ps [34], we assign an uncertainty of 0.007 ps, based on the precision of this test, as an estimate of any unaccounted systematic uncertainties.

All the sources of systematic uncertainty and their estimated values are listed in table 1. The individual values are added in quadrature to obtain the total systematic uncertainty.

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Source	Value (ps)
Limited MC event count	0.006
Efficiency modeling	0.002
Signal and background invariant mass model	0.022
Background decay time model	0.014
Invariant mass shape variation	0.004
Different fit strategy	0.006
Contribution of B_s^0 from B_c^+ decays	0.002
Control channel lifetime uncertainty	0.007
Total	0.029

Table 1. Sources of systematic uncertainties in the $B_s^0 \to J/\psi K_S^0$ effective lifetime measurement and their estimated values, along with the total systematic uncertainty.

7 Results

The 2D UML fit to the complete data set determines the yields of the B_s^0 signal and B^0 control channel to be 727 ± 35 and $68\,460 \pm 270$, respectively, where the uncertainties are statistical only. The $B_s^0 \to J/\psi K_S^0$ effective lifetime is measured to be:

$$\tau(B_s^0 \to J/\psi K_S^0) = 1.59 \pm 0.07\,(\text{stat}) \pm 0.03\,(\text{syst})\,\text{ps}. \tag{7.1}$$

This result is consistent with the expectation from the SM of 1.62 ± 0.02 ps and is twice as precise as the only previous measurement of $1.75 \pm 0.12\,(\text{stat}) \pm 0.07\,(\text{syst})$ ps, reported by the LHCb Collaboration from data collected in 2011 [27]. Tabulated results for this analysis are provided in the HEPData record [55].

8 Summary

In this paper, a measurement of the effective lifetime of the B_s^0 meson in the $J/\psi K_S^0$ decay channel is presented. The analysis is performed using data collected by the CMS detector during proton-proton collisions at a center-of-mass energy of 13 TeV from 2016 to 2018, corresponding to an integrated luminosity of 140 fb^{-1}. The effective lifetime is extracted using a two-dimensional unbinned maximum likelihood fit to the invariant mass and proper decay time distributions of the B_s^0 meson. The decay $B^0 \to J/\psi K_S^0$, which has a much larger event yield than the corresponding B_s^0 decay, is used as a control channel for estimating resolutions and systematic uncertainties. The measured value of the effective lifetime is $\tau(B_s^0 \to J/\psi K_S^0) = 1.59 \pm 0.07\,(\text{stat}) \pm 0.03\,(\text{syst})$ ps, which is the most precise result to date. This measurement can be used to constrain the parameters that govern mixing and *CP* violation in the B_s^0 system and also to better understand the penguin contributions in measurements of $\sin(2\beta)$ from $B^0 \to J/\psi K_S^0$ decays.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at

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other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); ERC PRG, RVTT3 and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LMTLT (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (U.S.A.).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 101115353, 101002207, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee, project no. 22rl-037 (Armenia); the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science — EOS" — be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010 and Fundamental Research Funds for the Central Universities (China); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, grant FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), among others, under Germany's Excellence Strategy — EXC 2121 "Quantum Universe" — 390833306, and under project number 400140256 — GRK2497; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Hungarian Academy of Sciences, the New National Excellence Program — ÚNKP, the NKFIH research grants K 131991, K 133046, K 138136, K 143460, K 143477, K 146913, K 146914, K 147048, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; ICSC — National Research Center for High Performance Computing, Big Data and Quantum Computing and FAIR — Future Artificial Intelligence Research, funded by the NextGenerationEU program (Italy); the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF "a way of making

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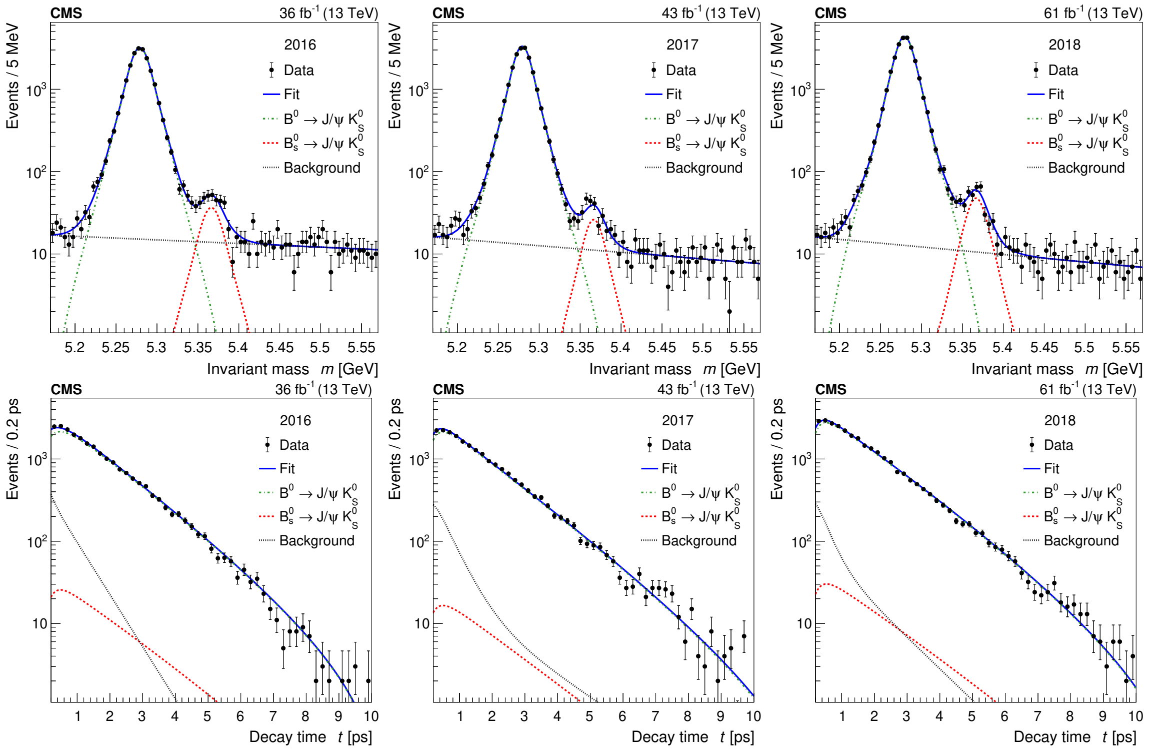

Figure 5. Distributions of the $J/\psi K^0_S$ invariant mass (upper) and decay time (lower) from data (points), along with the projections from the 2D UML fit for each year of data taking. The vertical bars on the data points indicate the statistical uncertainty. The dashed, dotted-dashed, dotted, and solid lines represent the signal, control channel, background, and total fit contributions, respectively.

Europe", and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B39G670016 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (U.S.A.).

A Projection plots from the 2D UML fits

The invariant mass and decay time projection plots from the 2D UML fit are presented in figure 5. The three plots in the upper row correspond to invariant mass projections for the 2016, 2017, and 2018 data-taking periods, respectively. The lower row displays the decay time projections for the data collected during the same periods.

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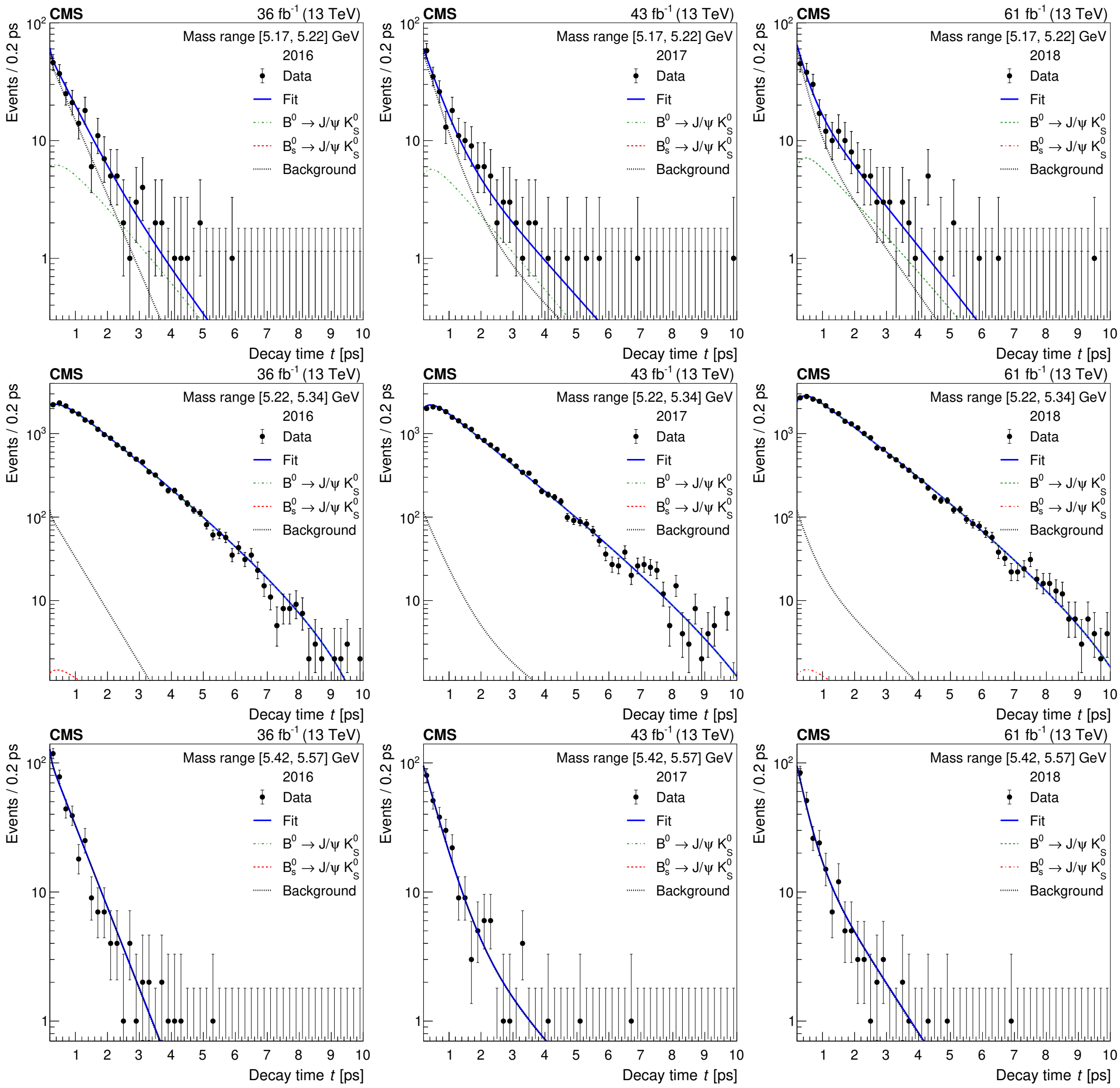

Figure 6. The decay time distribution for events with $J/\psi K^0_S$ invariant mass in the range $5.17 < m < 5.22$ (upper), $5.22 < m < 5.34$ (center), and $5.42 < m < 5.57$ (lower) GeV and the fit results for the 2016 (left), 2017 (middle), and 2018 (right) data-taking years.

B Subrange projection plots

Projections of the decay time distributions for three different $J/\psi K^0_S$ invariant mass ranges and the results of the 2D UML fits are presented in figure 6 for each of the three data-taking years. The corresponding invariant mass projections for different decay time ranges are shown in figure 7.

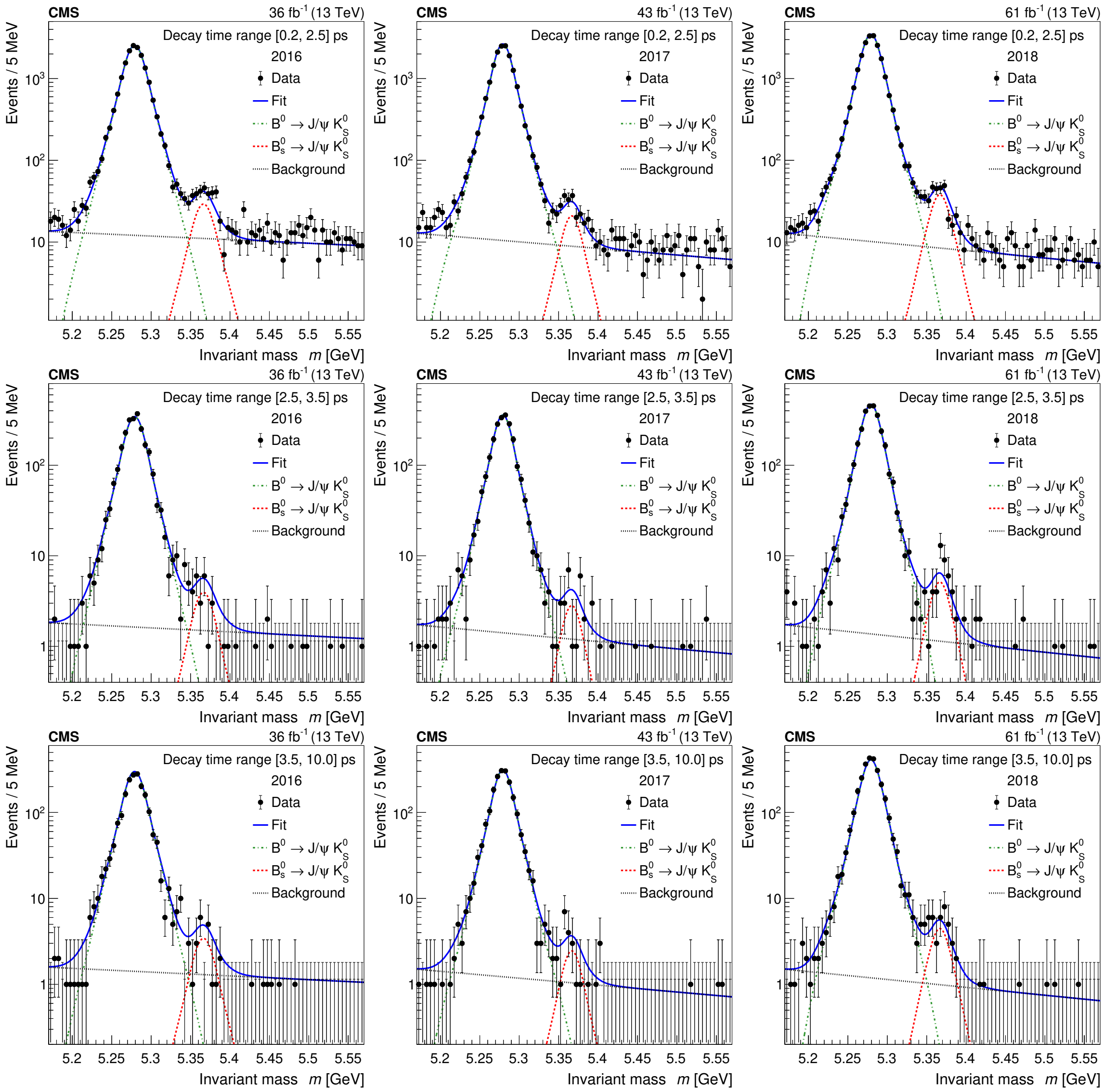

Figure 7. The invariant mass distribution for events with $J/\psi K^0_S$ decay time in the range $0.2 < t < 2.5$ (upper), $2.5 < t < 3.5$ (center), and $3.5 < t < 10.0$ (lower) ps and the fit results for the 2016 (left), 2017 (middle), and 2018 (right) data-taking years.

References

[1] J. Albrecht, F. Bernlochner, A. Lenz and A. Rusov, *Lifetimes of b-hadrons and mixing of neutral B-mesons: theoretical and experimental status*, *Eur. Phys. J. ST* **233** (2024) 359 [arXiv:2402.04224] [INSPIRE].

[2] N. Cabibbo, *Unitary symmetry and leptonic decays*, *Phys. Rev. Lett.* **10** (1963) 531 [INSPIRE].

[3] M. Kobayashi and T. Maskawa, *CP violation in the renormalizable theory of weak interaction*, *Prog. Theor. Phys.* **49** (1973) 652 [INSPIRE].

[4] M. Ciuchini, M. Pierini and L. Silvestrini, *The effect of penguins in the $B_d \to J/psiK^0$ CP asymmetry*, *Phys. Rev. Lett.* **95** (2005) 221804 [hep-ph/0507290] [INSPIRE].

JHEP10(2024)247

[5] S. Faller, M. Jung, R. Fleischer and T. Mannel, *The golden modes $B^0 \to J/\psi K_{S,L}$ in the era of precision flavour physics*, Phys. Rev. D **79** (2009) 014030 [arXiv:0809.0842] [INSPIRE].

[6] M. Jung, *Determining weak phases from $B \to J/\psi P$ decays*, Phys. Rev. D **86** (2012) 053008 [arXiv:1206.2050] [INSPIRE].

[7] P. Frings, U. Nierste and M. Wiebusch, *Penguin contributions to CP phases in $B_{d,s}$ decays to charmonium*, Phys. Rev. Lett. **115** (2015) 061802 [arXiv:1503.00859] [INSPIRE].

[8] LHCb collaboration, *Measurement of CP violation in $B^0 \to \psi(\to \ell^+\ell^-)K^0_S(\to \pi^+\pi^-)$ decays*, Phys. Rev. Lett. **132** (2024) 021801 [arXiv:2309.09728] [INSPIRE].

[9] R. Fleischer, *Recent theoretical developments in CP violation in the B system*, Nucl. Instrum. Meth. A **446** (2000) 1 [hep-ph/9908340] [INSPIRE].

[10] K. De Bruyn, R. Fleischer and P. Koppenburg, *Extracting γ and penguin topologies through CP violation in $B^0_s \to J/\psi K_S$*, Eur. Phys. J. C **70** (2010) 1025 [arXiv:1010.0089] [INSPIRE].

[11] K. De Bruyn and R. Fleischer, *A roadmap to control penguin effects in $B^0_d \to J/\psi K^0_{\rm S}$ and $B^0_s \to J/\psi\phi$*, JHEP **03** (2015) 145 [arXiv:1412.6834] [INSPIRE].

[12] M.Z. Barel, K. De Bruyn, R. Fleischer and E. Malami, *In pursuit of new physics with $B^0_d \to J/\psi K^0$ and $B^0_s \to J/\psi\phi$ decays at the high-precision frontier*, J. Phys. G **48** (2021) 065002 [arXiv:2010.14423] [INSPIRE].

[13] M.Z. Barel, K. De Bruyn, R. Fleischer and E. Malami, *Penguin effects in $B^0_d \to J/\psi K^0_S$ and $B^0_s \to J/\psi\phi$*, PoS **CKM2021** (2023) 111 [arXiv:2203.14652] [INSPIRE].

[14] K. De Bruyn et al., *Branching ratio measurements of B_s decays*, Phys. Rev. D **86** (2012) 014027 [arXiv:1204.1735] [INSPIRE].

[15] CMS collaboration, *Measurement of the $B^0_S \to \mu^+\mu^-$ decay properties and search for the $B^0 \to \mu^+\mu^-$ decay in proton-proton collisions at $\sqrt{s} = 13$ TeV*, Phys. Lett. B **842** (2023) 137955 [arXiv:2212.10311] [INSPIRE].

[16] CMS collaboration, *Measurement of properties of $B^0_s \to \mu^+\mu^-$ decays and search for $B^0 \to \mu^+\mu^-$ with the CMS experiment*, JHEP **04** (2020) 188 [arXiv:1910.12127] [INSPIRE].

[17] CMS collaboration, *Measurement of b hadron lifetimes in pp collisions at $\sqrt{s} = 8$ TeV*, Eur. Phys. J. C **78** (2018) 457 [*Erratum ibid.* **78** (2018) 561] [arXiv:1710.08949] [INSPIRE].

[18] ATLAS collaboration, *Measurement of the $B^0_s \to \mu\mu$ effective lifetime with the ATLAS detector*, JHEP **09** (2023) 199 [arXiv:2308.01171] [INSPIRE].

[19] LHCb collaboration, *Measurement of τ_L using the $B^0_s \to J/\psi\eta$ decay mode*, Eur. Phys. J. C **83** (2023) 629 [arXiv:2206.03088] [INSPIRE].

[20] LHCb collaboration, *Analysis of neutral B-meson decays into two muons*, Phys. Rev. Lett. **128** (2022) 041801 [arXiv:2108.09284] [INSPIRE].

[21] LHCb collaboration, *Measurement of the $B^0_s \to \mu^+\mu^-$ decay properties and search for the $B^0 \to \mu^+\mu^-$ and $B^0_s \to \mu^+\mu^-\gamma$ decays*, Phys. Rev. D **105** (2022) 012010 [arXiv:2108.09283] [INSPIRE].

[22] LHCb collaboration, *Measurement of the $B^0_s \to \mu^+\mu^-$ branching fraction and effective lifetime and search for $B^0 \to \mu^+\mu^-$ decays*, Phys. Rev. Lett. **118** (2017) 191801 [arXiv:1703.05747] [INSPIRE].

[23] LHCb collaboration, *Measurement of the $B^0_s \to J/\psi\eta$ lifetime*, Phys. Lett. B **762** (2016) 484 [arXiv:1607.06314] [INSPIRE].

JHEP10(2024)247

[24] LHCb collaboration, *Effective lifetime measurements in the $B_s^0 \to K^+K^-$, $B^0 \to K^+\pi^-$ and $B_s^0 \to \pi^+K^-$ decays*, Phys. Lett. B **736** (2014) 446 [arXiv:1406.7204] [INSPIRE].

[25] LHCb collaboration, *Measurements of the B^+, B^0, B_s^0 meson and Λ_b^0 baryon lifetimes*, JHEP **04** (2014) 114 [arXiv:1402.2554] [INSPIRE].

[26] LHCb collaboration, *Measurement of the $\bar{B}_s^0 \to D_s^- D_s^+$ and $\bar{B}_s^0 \to D^- D_s^+$ effective lifetimes*, Phys. Rev. Lett. **112** (2014) 111802 [arXiv:1312.1217] [INSPIRE].

[27] LHCb collaboration, *Measurement of the effective $B_s^0 \to J/\psi K_S^0$ lifetime*, Nucl. Phys. B **873** (2013) 275 [arXiv:1304.4500] [INSPIRE].

[28] LHCb collaboration, *Measurement of the effective $B_s^0 \to K^+K^-$ lifetime*, Phys. Lett. B **707** (2012) 349 [arXiv:1111.0521] [INSPIRE].

[29] LHCb collaboration, *Measurement of the B_s effective lifetime in the $J/\psi f_0(980)$ final state*, Phys. Rev. Lett. **109** (2012) 152002 [arXiv:1207.0878] [INSPIRE].

[30] LHCb collaboration, *Measurement of the effective $B_s^0 \to K^+K^-$ lifetime*, Phys. Lett. B **716** (2012) 393 [arXiv:1207.5993] [INSPIRE].

[31] HFLAV collaboration, *Averages of b-hadron, c-hadron, and τ-lepton properties as of 2021*, Phys. Rev. D **107** (2023) 052008 [arXiv:2206.07501] [INSPIRE].

[32] CDF collaboration, *Observation of $B_s^0 \to J/\psi K^{*0}(892)$ and $B_s^0 \to J/\psi K_S^0$ decays*, Phys. Rev. D **83** (2011) 052012 [arXiv:1102.1961] [INSPIRE].

[33] R. Fleischer and R. Knegjens, *Effective lifetimes of B_s decays and their constraints on the B_s^0-$\bar{B}_s^0$ mixing parameters*, Eur. Phys. J. C **71** (2011) 1789 [arXiv:1109.5115] [INSPIRE].

[34] Particle Data Group collaboration, *Review of particle physics*, Phys. Rev. D **110** (2024) 030001 [INSPIRE].

[35] CMS collaboration, *Description and performance of track and primary-vertex reconstruction with the CMS tracker*, 2014 JINST **9** P10009 [arXiv:1405.6569] [INSPIRE].

[36] CMS Tracker Group collaboration, *The CMS phase-1 pixel detector upgrade*, 2021 JINST **16** P02027 [arXiv:2012.14304] [INSPIRE].

[37] CMS collaboration, *Track impact parameter resolution for the full pseudo rapidity coverage in the 2017 dataset with the CMS phase-1 pixel detector*, CMS-DP-2020-049, CERN, Geneva, Switzerland (2020).

[38] CMS collaboration, *The CMS experiment at the CERN LHC*, 2008 JINST **3** S08004 [INSPIRE].

[39] CMS collaboration, *Performance of the CMS level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV*, 2020 JINST **15** P10017 [arXiv:2006.10165] [INSPIRE].

[40] CMS collaboration, *The CMS trigger system*, 2017 JINST **12** P01020 [arXiv:1609.02366] [INSPIRE].

[41] CMS collaboration, *Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS*, Eur. Phys. J. C **81** (2021) 800 [arXiv:2104.01927] [INSPIRE].

[42] CMS collaboration, *CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV*, CMS-PAS-LUM-17-004, CERN, Geneva, Switzerland (2018).

[43] CMS collaboration, *CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV*, CMS-PAS-LUM-18-002, CERN, Geneva, Switzerland (2019).

[44] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, Comput. Phys. Commun. **191** (2015) 159 [arXiv:1410.3012] [INSPIRE].

[45] D.J. Lange, *The EvtGen particle decay simulation package*, Nucl. Instrum. Meth. A **462** (2001) 152 [INSPIRE].

[46] E. Barberio and Z. Was, *PHOTOS: a universal Monte Carlo for QED radiative corrections. Version 2.0*, Comput. Phys. Commun. **79** (1994) 291 [INSPIRE].

[47] GEANT4 collaboration, *GEANT4 — a simulation toolkit*, Nucl. Instrum. Meth. A **506** (2003) 250 [INSPIRE].

[48] CMS collaboration, *Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV*, 2018 *JINST* **13** P06015 [arXiv:1804.04528] [INSPIRE].

[49] CMS collaboration, *CMS tracking performance results from early LHC operation*, Eur. Phys. J. C **70** (2010) 1165 [arXiv:1007.1988] [INSPIRE].

[50] R. Fruhwirth, *Application of Kalman filtering to track and vertex fitting*, Nucl. Instrum. Meth. A **262** (1987) 444 [INSPIRE].

[51] J. Podolanski and R. Armenteros, *III. Analysis of V-events*, Philos. Mag. **45** (1954) 13.

[52] J.E. Gaiser, *Charmonium spectroscopy from radiative decays of the J/ψ and ψ'*, Ph.D. thesis, SLAC report SLAC-R-255, Stanford University, Stanford, CA, U.S.A. (1982) [INSPIRE].

[53] N.L. Johnson, *Systems of frequency curves generated by methods of translation*, Biometrika **36** (1949) 149 [INSPIRE].

[54] S. Jackman, *Bayesian analysis for the social sciences*, Wiley, U.S.A. (2009) [DOI:10.1002/9780470686621].

[55] CMS collaboration, *Measurement of the $B^0_s \to J/\psi K^0_S$ effective lifetime from proton-proton collisions at $\sqrt{s} = 13$ TeV*, CMS-BPH-22-001, CERN, Geneva, Switzerland (2024).

The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. Hayrapetyan, A. Tumasyan[1]

Institut für Hochenergiephysik, Vienna, Austria
W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, P.S. Hussain, M. Jeitler[2], N. Krammer, A. Li, D. Liko, I. Mikulec, J. Schieck[2], R. Schöfbeck, D. Schwarz, M. Sonawane, W. Waltenberger, C.-E. Wulz[2]

Universiteit Antwerpen, Antwerpen, Belgium
T. Janssen, T. Van Laer, P. Van Mechelen

Vrije Universiteit Brussel, Brussel, Belgium
N. Breugelmans, J. D'Hondt, S. Dansana, A. De Moor, M. Delcourt, F. Heyen, S. Lowette, I. Makarenko, D. Müller, S. Tavernier, M. Tytgat[3], G.P. Van Onsem, S. Van Putte, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium
B. Bilin, B. Clerbaux, A.K. Das, G. De Lentdecker, H. Evard, L. Favart, P. Gianneios, J. Jaramillo, A. Khalilzadeh, F.A. Khan, K. Lee, M. Mahdavikhorrami, A. Malara, S. Paredes, M.A. Shahzad, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

Ghent University, Ghent, Belgium
M. De Coen, D. Dobur, G. Gokbulut, Y. Hong, J. Knolle, L. Lambrecht, D. Marckx, K. Mota Amarilo, A. Samalan, K. Skovpen, N. Van Den Bossche, J. van der Linden, L. Wezenbeek

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
A. Benecke, A. Bethani, G. Bruno, C. Caputo, J. De Favereau De Jeneret, C. Delaere, I.S. Donertas, A. Giammanco, A.O. Guzel, Sa. Jain, V. Lemaitre, J. Lidrych, P. Mastrapasqua, T.T. Tran, S. Wertz

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, M. Alves Gallo Pereira, E. Coelho, G. Correia Silva, C. Hensel, T. Menezes De Oliveira, C. Mora Herrera[4], A. Moraes, P. Rebello Teles, M. Soeiro, A. Vilela Pereira[4]

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[5], E.M. Da Costa, G.G. Da Silveira[6], D. De Jesus Damiao, S. Fonseca De Souza, R. Gomes De Souza, M. Macedo, J. Martins[7], L. Mundim, H. Nogima, J.P. Pinheiro, A. Santoro, A. Sznajder, M. Thiel

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Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
C.A. Bernardes[6], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, I. Maietto Silverio, P.G. Mercadante, S.F. Novaes, B. Orzari, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria
A. Dimitrov, L. Litov, B. Pavlov, P. Petkov, A. Petrov, E. Shumka

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile
S. Keshri, D. Laroze, S. Thakur

Beihang University, Beijing, China
T. Cheng, T. Javaid, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
Z. Hu, Z. Liang, J. Liu, K. Yi[8,9]

Institute of High Energy Physics, Beijing, China
G.M. Chen[10], H.S. Chen[10], M. Chen[10], F. Iemmi, C.H. Jiang, A. Kapoor[11], H. Liao, Z.-A. Liu[12], R. Sharma[13], J.N. Song[12], J. Tao, C. Wang[10], J. Wang, Z. Wang[10], H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ban, S. Deng, B. Guo, C. Jiang, A. Levin, C. Li, Q. Li, Y. Mao, S. Qian, S.J. Qian, X. Qin, X. Sun, D. Wang, H. Yang, L. Zhang, Y. Zhao, C. Zhou

Guangdong Provincial Key Laboratory of Nuclear Science and Guangdong-Hong Kong Joint Laboratory of Quantum Matter, South China Normal University, Guangzhou, China
S. Yang

Sun Yat-Sen University, Guangzhou, China
Z. You

University of Science and Technology of China, Hefei, China
K. Jaffel, N. Lu

Nanjing Normal University, Nanjing, China
G. Bauer[14], B. Li, J. Zhang

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Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) — Fudan University, Shanghai, China
X. Gao[15], Y. Li

Zhejiang University, Hangzhou, Zhejiang, China
Z. Lin, C. Lu, M. Xiao

Universidad de Los Andes, Bogota, Colombia
C. Avila, D.A. Barbosa Trujillo, A. Cabrera, C. Florez, J. Fraga, J.A. Reyes Vega

Universidad de Antioquia, Medellin, Colombia
F. Ramirez, C. Rendón, M. Rodriguez, A.A. Ruales Barbosa, J.D. Ruiz Alvarez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
D. Giljanovic, N. Godinovic, D. Lelas, A. Sculac

University of Split, Faculty of Science, Split, Croatia
M. Kovac, A. Petkovic, T. Sculac

Institute Rudjer Boskovic, Zagreb, Croatia
P. Bargassa, V. Brigljevic, B.K. Chitroda, D. Ferencek, K. Jakovcic, A. Starodumov[16], T. Susa

University of Cyprus, Nicosia, Cyprus
A. Attikis, K. Christoforou, A. Hadjiagapiou, C. Leonidou, J. Mousa, C. Nicolaou, L. Paizanos, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, A. Stepennov

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr., A. Kveton

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
A.A. Abdelalim[17,18], S. Elgammal[19], A. Ellithi Kamel[20]

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
A. Lotfy, M.A. Mahmoud

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
K. Ehataht, M. Kadastik, T. Lange, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
H. Kirschenmann, K. Osterberg, M. Voutilainen

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Helsinki Institute of Physics, Helsinki, Finland
S. Bharthuar, N. Bin Norjoharuddeen, E. Brücken, F. Garcia, P. Inkaew, K.T.S. Kallonen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, L. Martikainen, M. Myllymäki, M.m. Rantanen, H. Siikonen, J. Tuominiemi

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
P. Luukka, H. Petrow

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, M. Kumar, V. Lohezic, J. Malcles, F. Orlandi, L. Portales, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[21], P. Simkina, M. Titov, M. Tornago

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
F. Beaudette, G. Boldrini, P. Busson, A. Cappati, C. Charlot, M. Chiusi, F. Damas, O. Davignon, A. De Wit, I.T. Ehle, B.A. Fontana Santos Alves, S. Ghosh, A. Gilbert, R. Granier de Cassagnac, A. Hakimi, B. Harikrishnan, L. Kalipoliti, G. Liu, M. Nguyen, C. Ochando, R. Salerno, J.B. Sauvan, Y. Sirois, L. Urda Gómez, E. Vernazza, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[22], J. Andrea, D. Apparu, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, S. Falke, U. Goerlach, R. Haeberle, A.-C. Le Bihan, M. Meena, O. Poncet, G. Saha, M.A. Sessini, P. Van Hove, P. Vaucelle

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
A. Di Florio

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
D. Amram, S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, D. Contardo, P. Depasse, C. Dozen[23], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, E. Jourd'huy, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, A. Purohit, M. Vander Donckt, P. Verdier, J. Xiao

Georgian Technical University, Tbilisi, Georgia
D. Chokheli, I. Lomidze, Z. Tsamalaidze[16]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Botta, S. Consuegra Rodríguez, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, D. Pérez Adán, N. Röwert, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, F. Engelke, J. Erdmann, M. Erdmann, P. Fackeldey, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, A. Jung,

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M.y. Lee, F. Mausolf, M. Merschmeyer, A. Meyer, S. Mukherjee, D. Noll, F. Nowotny, A. Pozdnyakov, Y. Rath, W. Redjeb, F. Rehm, H. Reithler, V. Sarkisovi, A. Schmidt, C. Seth, A. Sharma, J.L. Spah, A. Stein, F. Torres Da Silva De Araujo[24], S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
C. Dziwok, G. Flügge, T. Kress, A. Nowack, O. Pooth, A. Stahl, T. Ziemons, A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, Germany
H. Aarup Petersen, M. Aldaya Martin, J. Alimena, S. Amoroso, Y. An, J. Bach, S. Baxter, M. Bayatmakou, H. Becerril Gonzalez, O. Behnke, A. Belvedere, F. Blekman[25], K. Borras[26], A. Campbell, A. Cardini, C. Cheng, F. Colombina, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo[25], A. Geiser, V. Guglielmi, M. Guthoff, A. Hinzmann, L. Jeppe, B. Kaech, M. Kasemann, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka[27], W. Lohmann[28], F. Lorkowski, R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, A.B. Meyer, G. Milella, K. Moral Figueroa, A. Mussgiller, L.P. Nair, J. Niedziela, A. Nürnberg, Y. Otarid, J. Park, E. Ranken, A. Raspereza, D. Rastorguev, J. Rübenach, L. Rygaard, A. Saggio, M. Scham[29,26], S. Schnake[26], P. Schütze, C. Schwanenberger[25], D. Selivanova, K. Sharko, M. Shchedrolosiev, D. Stafford, F. Vazzoler, A. Ventura Barroso, R. Walsh, D. Wang, Q. Wang, Y. Wen, K. Wichmann, L. Wiens[26], C. Wissing, Y. Yang, A. Zimermmane Castro Santos

University of Hamburg, Hamburg, Germany
A. Albrecht, S. Albrecht, M. Antonello, S. Bein, L. Benato, S. Bollweg, M. Bonanomi, P. Connor, K. El Morabit, Y. Fischer, E. Garutti, A. Grohsjean, J. Haller, H.R. Jabusch, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, C.c. Kuo, V. Kutzner, F. Labe, J. Lange, A. Lobanov, C. Matthies, L. Moureaux, M. Mrowietz, A. Nigamova, Y. Nissan, A. Paasch, K.J. Pena Rodriguez, T. Quadfasel, B. Raciti, M. Rieger, D. Savoiu, J. Schindler, P. Schleper, M. Schröder, J. Schwandt, M. Sommerhalder, H. Stadie, G. Steinbrück, A. Tews, M. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
S. Brommer, M. Burkart, E. Butz, T. Chwalek, A. Dierlamm, A. Droll, U. Elicabuk, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[30], R. Hofsaess, M. Horzela, U. Husemann, J. Kieseler, M. Klute, R. Koppenhöfer, J.M. Lawhorn, M. Link, A. Lintuluoto, S. Maier, S. Mitra, M. Mormile, Th. Müller, M. Neukum, M. Oh, E. Pfeffer, M. Presilla, G. Quast, K. Rabbertz, B. Regnery, N. Shadskiy, I. Shvetsov, H.J. Simonis, L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms, N. Trevisani, R.F. Von Cube, M. Wassmer, S. Wieland, F. Wittig, R. Wolf, X. Zuo

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, A. Kyriakis, A. Papadopoulos[30], A. Stakia

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National and Kapodistrian University of Athens, Athens, Greece
P. Kontaxakis, G. Melachroinos, Z. Painesis, I. Papavergou, I. Paraskevas, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, I. Zisopoulos

National Technical University of Athens, Athens, Greece
G. Bakas, T. Chatzistavrou, G. Karapostoli, K. Kousouris, I. Papakrivopoulos, E. Siamarkou, G. Tsipolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece
K. Adamidis, I. Bestintzanos, I. Evangelou, C. Foudas, C. Kamtsikis, P. Katsoulis, P. Kokkas, P.G. Kosmoglou Kioseoglou, N. Manthos, I. Papadopoulos, J. Strologas

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
C. Hajdu, D. Horvath[31,32], K. Márton, A.J. Rádl[33], F. Sikler, V. Veszpremi

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanád, K. Farkas, A. Fehérkuti[34], M.M.A. Gadallah[35], Á. Kadlecsik, P. Major, G. Pásztor, G.I. Veres

Faculty of Informatics, University of Debrecen, Debrecen, Hungary
B. Ujvari, G. Zilizi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
F. Nemes[34], T. Novak

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[36], A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, K. Sandeep, T. Sheokand, J.B. Singh, A. Singla

University of Delhi, Delhi, India
A. Ahmed, A. Bhardwaj, A. Chhetri, B.C. Choudhary, A. Kumar, A. Kumar, M. Naimuddin, K. Ranjan, M.K. Saini, S. Saumya

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
S. Baradia, S. Barman[37], S. Bhattacharya, S. Das Gupta, S. Dutta, S. Dutta, S. Sarkar

Indian Institute of Technology Madras, Madras, India
M.M. Ameen, P.K. Behera, S.C. Behera, S. Chatterjee, G. Dash, P. Jana, P. Kalbhor, S. Kamble, J.R. Komaragiri[38], D. Kumar[38], P.R. Pujahari, N.R. Saha, A. Sharma, A.K. Sikdar, R.K. Singh, P. Verma, S. Verma, A. Vijay

Tata Institute of Fundamental Research-A, Mumbai, India
S. Dugad, G.B. Mohanty, B. Parida, M. Shelake, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India
A. Bala, S. Banerjee, R.M. Chatterjee, M. Guchait, Sh. Jain, A. Jaiswal, S. Kumar, G. Majumder, K. Mazumdar, S. Parolia, A. Thachayath

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
S. Bahinipati[39], C. Kar, D. Maity[40], P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu[40], K. Naskar[40], A. Nayak[40], S. Nayak, K. Pal, P. Sadangi, S.K. Swain, S. Varghese[40], D. Vats[40]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Acharya[41], A. Alpana, S. Dube, B. Gomber[41], P. Hazarika, B. Kansal, A. Laha, B. Sahu[41], S. Sharma, K.Y. Vaish

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[42], A. Jafari[43], M. Zeinali[44]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Bashiri, S. Chenarani[45], S.M. Etesami, Y. Hosseini, M. Khakzad, E. Khazaie[46], M. Mohammadi Najafabadi, S. Tizchang[47]

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], A. Colaleo[a,b], D. Creanza[a,c], B. D'Anzi[a,b], N. De Filippis[a,c], M. De Palma[a,b], W. Elmetenawee[a,b,17], L. Fiore[a], G. Iaselli[a,c], L. Longo[a], M. Louka[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a], V. Mastrapasqua[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a,b], D. Ramos[a], A. Ranieri[a], L. Silvestris[a], F.M. Simone[a,c], Ü. Sözbilir[a], A. Stamerra[a,b], D. Troiano[a,b], R. Venditti[a,b], P. Verwilligen[a], A. Zaza[a,b]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], P. Capiluppi[a,b], A. Castro[†,a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,48], M. Lorusso[a,b], L. Lunerti[a], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], G. Paggi[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], S. Rossi Tisbeni[a,b], T. Rovelli[a,b], G.P. Siroli[a,b]

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy
S. Costa[a,b,49], A. Di Mattia[a], A. Lapertosa[a], R. Potenza[a,b], A. Tricomi[a,b,49], C. Tuve[a,b]

INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy

P. Assiouras[a], G. Barbagli[a], G. Bardelli[a,b], B. Camaiani[a,b], A. Cassese[a], R. Ceccarelli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], T. Kello[a], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a], M. Meschini[a], S. Paoletti[a], A. Papanastassiou[a,b], G. Sguazzoni[a], L. Viliani[a]

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, S. Meola[50], D. Piccolo

INFN Sezione di Genova[a], Università di Genova[b], Genova, Italy

P. Chatagnon[a], F. Ferro[a], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milano, Italy

A. Benaglia[a], F. Brivio[a], F. Cetorelli[a,b], F. De Guio[a,b], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], R. Gerosa[a,b], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a], M.T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], S. Palluotto[a,b], D. Pedrini[a], A. Perego[a,b], B.S. Pinolini[a], G. Pizzati[a,b], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy; Università della Basilicata[c], Potenza, Italy; Scuola Superiore Meridionale (SSM)[d], Napoli, Italy

S. Buontempo[a], A. Cagnotta[a,b], F. Carnevali[a,b], N. Cavallo[a,c], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a,b,51], P. Paolucci[a,30], B. Rossi[a]

INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy; Università di Trento[c], Trento, Italy

R. Ardino[a], P. Azzi[a], N. Bacchetta[a,52], P. Bortignon[a], G. Bortolato[a,b], A. Bragagnolo[a,b], A.C.M. Bulla[a], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], F. Gasparini[a,b], U. Gasparini[a,b], S. Giorgetti[a], E. Lusiani[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], M. Migliorini[a,b], J. Pazzini[a,b], P. Ronchese[a,b], R. Rossin[a,b], M. Sgaravatto[a], F. Simonetto[a,b], M. Tosi[a,b], A. Triossi[a,b], S. Ventura[a], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy

C. Aimè[a], A. Braghieri[a], S. Calzaferri[a], D. Fiorina[a], P. Montagna[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy

S. Ajmal[a,b], M.E. Ascioti[a,b], G.M. Bilei[a], C. Carrivale[a,b], D. Ciangottini[a,b], L. Fanò[a,b], M. Magherini[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,53], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

INFN Sezione di Pisa[a], Università di Pisa[b], Scuola Normale Superiore di Pisa[c], Pisa, Italy; Università di Siena[d], Siena, Italy

C.A. Alexe[a,c], P. Asenov[a,b], P. Azzurri[a], G. Bagliesi[a], R. Bhattacharya[a], L. Bianchini[a,b], T. Boccali[a], E. Bossini[a], D. Bruschini[a,c], R. Castaldi[a], M.A. Ciocci[a,b], M. Cipriani[a,b],

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V. D'Amante[a,d], R. Dell'Orso[a], S. Donato[a], A. Giassi[a], F. Ligabue[a,c], A.C. Marini[a], D. Matos Figueiredo[a], A. Messineo[a,b], S. Mishra[a], M. Musich[a,b], F. Palla[a], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a], T. Sarkar[a], A. Scribano[a], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], F. Vaselli[a,c], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma[a], Sapienza Università di Roma[b], Roma, Italy

C. Baldenegro Barrera[a,b], P. Barria[a], C. Basile[a,b], F. Cavallari[a], L. Cunqueiro Mendez[a,b], D. Del Re[a,b], E. Di Marco[a,b], M. Diemoz[a], F. Errico[a,b], E. Longo[a,b], J. Mijuskovic[a,b], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a]

INFN Sezione di Torino[a], Università di Torino[b], Torino, Italy; Università del Piemonte Orientale[c], Novara, Italy

N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], A. Bellora[a,b], C. Biino[a], C. Borca[a,b], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], L. Finco[a], M. Grippo[a,b], B. Kiani[a,b], F. Legger[a], F. Luongo[a,b], C. Mariotti[a], L. Markovic[a,b], S. Maselli[a], A. Mecca[a,b], L. Menzio[a,b], P. Meridiani[a], E. Migliore[a,b], M. Monteno[a], R. Mulargia[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], M. Ruspa[a,c], F. Siviero[a,b], V. Sola[a,b], A. Solano[a,b], A. Staiano[a], C. Tarricone[a,b], D. Trocino[a], G. Umoret[a,b], R. White[a,b]

INFN Sezione di Trieste[a], Università di Trieste[b], Trieste, Italy

J. Babbar[a,b], S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], K. De Leo[a], G. Della Ricca[a,b]

Kyungpook National University, Daegu, Korea

S. Dogra, J. Hong, B. Kim, J. Kim, D. Lee, H. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, M.S. Ryu, S. Sekmen, B. Tae, Y.C. Yang

Department of Mathematics and Physics — GWNU, Gangneung, Korea

M.S. Kim

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

G. Bak, P. Gwak, H. Kim, D.H. Moon

Hanyang University, Seoul, Korea

E. Asilar, J. Choi, D. Kim, T.J. Kim, J.A. Merlin, Y. Ryou

Korea University, Seoul, Korea

S. Choi, S. Han, B. Hong, K. Lee, K.S. Lee, S. Lee, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh, S. Yang

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Sejong University, Seoul, Korea
H. S. Kim, Y. Kim, S. Lee

Seoul National University, Seoul, Korea
J. Almond, J.H. Bhyun, J. Choi, J. Choi, W. Jun, J. Kim, S. Ko, H. Kwon, H. Lee, J. Lee, J. Lee, B.H. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

University of Seoul, Seoul, Korea
W. Jang, D.Y. Kang, Y. Kang, S. Kim, B. Ko, J.S.H. Lee, Y. Lee, I.C. Park, Y. Roh, I.J. Watson

Yonsei University, Department of Physics, Seoul, Korea
S. Ha, H.D. Yoo

Sungkyunkwan University, Suwon, Korea
M. Choi, M.R. Kim, H. Lee, Y. Lee, I. Yu

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
T. Beyrouthy

Kuwait University — College of Science — Department of Physics, Safat, Kuwait
F. Alazemi

Riga Technical University, Riga, Latvia
K. Dreimanis, A. Gaile, C. Munoz Diaz, D. Osite, G. Pikurs, A. Potrebko, M. Seidel, D. Sidiropoulos Kontos

University of Latvia (LU), Riga, Latvia
N.R. Strautnieks

Vilnius University, Vilnius, Lithuania
M. Ambrozas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Yusuff[54], Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello, J.A. Murillo Quijada, A. Sehrawat, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, H. Crotte Ledesma, E. De La Cruz-Burelo, I. Heredia-De La Cruz[55], R. Lopez-Fernandez, J. Mejia Guisao, C.A. Mondragon Herrera, A. Sánchez Hernández

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Universidad Iberoamericana, Mexico City, Mexico
C. Oropeza Barrera, D.L. Ramirez Guadarrama, M. Ramírez García

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Bautista, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

University of Montenegro, Podgorica, Montenegro
I. Bubanja, N. Raicevic

University of Canterbury, Christchurch, New Zealand
P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, H.R. Hoorani, W.A. Khan

AGH University of Krakow, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, M. Górski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, A. Muhammad

Warsaw University of Technology, Warsaw, Poland
K. Pozniak, W. Zabolotny

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, D. Bastos, C. Beirão Da Cruz E Silva, A. Boletti, M. Bozzo, T. Camporesi, G. Da Molin, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, G.B. Marozzo, T. Niknejad, A. Petrilli, M. Pisano, J. Seixas, J. Varela, J.W. Wulff

Faculty of Physics, University of Belgrade, Belgrade, Serbia
P. Adzic, P. Milenovic

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, Cristina F. Bedoya, J.A. Brochero Cifuentes, Oliver M. Carretero, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Martin Viscasillas,

D. Moran, C. M. Morcillo Perez, Á. Navarro Tobar, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, S. Sánchez Navas, J. Sastre, J. Vazquez Escobar

Universidad Autónoma de Madrid, Madrid, Spain
J.F. de Trocóniz

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, P. Leguina, E. Palencia Cortezon, J. Prado Pico, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, C. Vico Villalba, P. Vischia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
S. Bhowmik, S. Blanco Fernández, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, G. Gomez, C. Lasaosa García, R. Lopez Ruiz, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, E. Navarrete Ramos, J. Piedra Gomez, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
B. Kailasapathy[56], D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna[57], K. Liyanage, N. Perera

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, C. Amendola, E. Auffray, G. Auzinger, J. Baechler, D. Barney, A. Bermúdez Martínez, M. Bianco, A.A. Bin Anuar, A. Bocci, L. Borgonovi, C. Botta, E. Brondolin, C. Caillol, G. Cerminara, N. Chernyavskaya, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, G. Franzoni, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, J. Hegeman, J.K. Heikkilä, B. Huber, V. Innocente, T. James, P. Janot, O. Kaluzinska, O. Karacheban[28], S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, L. Malgeri, M. Mannelli, M. Matthewman, A. Mehta, F. Meijers, S. Mersi, E. Meschi, V. Milosevic, F. Monti, F. Moortgat, M. Mulders, I. Neutelings, S. Orfanelli, F. Pantaleo, G. Petrucciani, A. Pfeiffer, M. Pierini, H. Qu, D. Rabady, B. Ribeiro Lopes, M. Rovere, H. Sakulin, S. Sanchez Cruz, S. Scarfi, C. Schwick, M. Selvaggi, A. Sharma, K. Shchelina, P. Silva, P. Sphicas[58], A.G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, D. Walter, J. Wanczyk[59], J. Wang, K.A. Wozniak[60], S. Wuchterl, P. Zehetner, P. Zejdl, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
T. Bevilacqua[61], L. Caminada[61], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[61], L. Noehte[61], T. Rohe

ETH Zurich — Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

T.K. Aarrestad, K. Androsov[59], M. Backhaus, G. Bonomelli, A. Calandri, C. Cazzaniga, K. Datta, P. De Bryas Dexmiers D'archiac[59], A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, C. Grab, N. Härringer, T.G. Harte, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M. Marchegiani, L. Marchese, C. Martin Perez, A. Mascellani[59], F. Nessi-Tedaldi, F. Pauss, V. Perovic, S. Pigazzini, B. Ristic, F. Riti, R. Seidita, J. Steggemann[59], A. Tarabini, D. Valsecchi, R. Wallny

Universität Zürich, Zurich, Switzerland

C. Amsler[62], P. Bärtschi, M.F. Canelli, K. Cormier, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, F. Meng, U. Molinatti, J. Motta, A. Reimers, P. Robmann, M. Senger, E. Shokr, F. Stäger, R. Tramontano

National Central University, Chung-Li, Taiwan

C. Adloff[63], D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout, P.C. Tiwari[38], S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

L. Ceard, K.F. Chen, P.s. Chen, Z.g. Chen, A. De Iorio, W.-S. Hou, T.h. Hsu, Y.w. Kao, S. Karmakar, G. Kole, Y.y. Li, R.-S. Lu, E. Paganis, X.f. Su, J. Thomas-Wilsker, L.s. Tsai, D. Tsionou, H.y. Wu, E. Yazgan

High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand

C. Asawatangtrakuldee, N. Srimanobhas, V. Wachirapusitanand

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

D. Agyel, F. Boran, F. Dolek, I. Dumanoglu[64], E. Eskut, Y. Guler[65], E. Gurpinar Guler[65], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[66], A. Polatoz, B. Tali[67], U.G. Tok, S. Turkcapar, E. Uslan, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey

G. Sokmen, M. Yalvac[68]

Bogazici University, Istanbul, Turkey

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[69], O. Kaya[70], S. Tekten[71]

Istanbul Technical University, Istanbul, Turkey

A. Cakir, K. Cankocak[64,72], G.G. Dincer[64], Y. Komurcu, S. Sen[73]

Istanbul University, Istanbul, Turkey

O. Aydilek[74], B. Hacisahinoglu, I. Hos[75], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, C. Zorbilmez

Yildiz Technical University, Istanbul, Turkey
S. Cerci[67], B. Isildak[76], D. Sunar Cerci, T. Yetkin

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine
A. Boyaryntsev, B. Grynyov

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
D. Anthony, J.J. Brooke, A. Bundock, F. Bury, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, H.F. Heath, M.-L. Holmberg, L. Kreczko, S. Paramesvaran, L. Robertshaw, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou[77], K. Walkingshaw Pass

Rutherford Appleton Laboratory, Didcot, United Kingdom
A.H. Ball, K.W. Bell, A. Belyaev[78], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, A. Elliot, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, A.R. Sahasransu, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, K.C. Whalen, T. Williams

Imperial College, London, United Kingdom
I. Andreou, R. Bainbridge, P. Bloch, C.E. Brown, O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya, G.S. Chahal[79], D. Colling, J.S. Dancu, I. Das, P. Dauncey, G. Davies, J. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, A. Howard, G. Iles, C.R. Knight, J. Langford, J. León Holgado, L. Lyons, A.-M. Magnan, B. Maier, S. Mallios, M. Mieskolainen, J. Nash[80], M. Pesaresi, P.B. Pradeep, B.C. Radburn-Smith, A. Richards, A. Rose, K. Savva, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, L.H. Vage, T. Virdee[30], M. Vojinovic, N. Wardle, D. Winterbottom

Brunel University, Uxbridge, United Kingdom
K. Coldham, J.E. Cole, A. Khan, P. Kyberd, I.D. Reid

Baylor University, Waco, Texas, U.S.A.
S. Abdullin, A. Brinkerhoff, E. Collins, M.R. Darwish[81], J. Dittmann, K. Hatakeyama, J. Hiltbrand, B. McMaster, J. Samudio, S. Sawant, C. Sutantawibul, J. Wilson

Catholic University of America, Washington, DC, U.S.A.
R. Bartek, A. Dominguez, C. Huerta Escamilla, A.E. Simsek, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, Alabama, U.S.A.
B. Bam, A. Buchot Perraguin, R. Chudasama, S.I. Cooper, C. Crovella, S.V. Gleyzer, E. Pearson, C.U. Perez, P. Rumerio[82], E. Usai, R. Yi

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Boston University, Boston, Massachusetts, U.S.A.
A. Akpinar, C. Cosby, G. De Castro, Z. Demiragli, C. Erice, C. Fangmeier, C. Fernandez Madrazo, E. Fontanesi, D. Gastler, F. Golf, S. Jeon, J. O'cain, I. Reed, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, A.G. Zecchinelli

Brown University, Providence, Rhode Island, U.S.A.
G. Benelli, D. Cutts, L. Gouskos, M. Hadley, U. Heintz, J.M. Hogan[83], T. Kwon, G. Landsberg, K.T. Lau, D. Li, J. Luo, S. Mondal, N. Pervan, T. Russell, S. Sagir[84], X. Shen, F. Simpson, M. Stamenkovic, N. Venkatasubramanian, X. Yan

University of California, Davis, Davis, California, U.S.A.
S. Abbott, C. Brainerd, R. Breedon, H. Cai, M. Calderon De La Barca Sanchez, M. Chertok, M. Citron, J. Conway, P.T. Cox, R. Erbacher, F. Jensen, O. Kukral, G. Mocellin, M. Mulhearn, S. Ostrom, W. Wei, S. Yoo, F. Zhang

University of California, Los Angeles, California, U.S.A.
M. Bachtis, R. Cousins, A. Datta, G. Flores Avila, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, E. Manca, A. Nunez Del Prado, D. Saltzberg, V. Valuev

University of California, Riverside, Riverside, California, U.S.A.
R. Clare, J.W. Gary, M. Gordon, G. Hanson, W. Si

University of California, San Diego, La Jolla, California, U.S.A.
A. Aportela, A. Arora, J.G. Branson, S. Cittolin, S. Cooperstein, D. Diaz, J. Duarte, L. Giannini, Y. Gu, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, F. Mokhtar, S. Mukherjee, M. Pieri, M. Quinnan, B.V. Sathia Narayanan, V. Sharma, M. Tadel, E. Vourliotis, F. Würthwein, Y. Xiang, A. Yagil

University of California, Santa Barbara — Department of Physics, Santa Barbara, California, U.S.A.
A. Barzdukas, L. Brennan, C. Campagnari, K. Downham, C. Grieco, J. Incandela, J. Kim, A.J. Li, P. Masterson, H. Mei, J. Richman, S.N. Santpur, U. Sarica, R. Schmitz, F. Setti, J. Sheplock, D. Stuart, T.Á. Vámi, S. Wang, D. Zhang

California Institute of Technology, Pasadena, California, U.S.A.
S. Bhattacharya, A. Bornheim, O. Cerri, A. Latorre, J. Mao, H.B. Newman, G. Reales Gutiérrez, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, Pennsylvania, U.S.A.
J. Alison, S. An, P. Bryant, M. Cremonesi, V. Dutta, T. Ferguson, T.A. Gómez Espinosa, A. Harilal, A. Kallil Tharayil, C. Liu, T. Mudholkar, S. Murthy, P. Palit, K. Park, M. Paulini, A. Roberts, A. Sanchez, W. Terrill

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University of Colorado Boulder, Boulder, Colorado, U.S.A.
J.P. Cumalat, W.T. Ford, A. Hart, A. Hassani, G. Karathanasis, N. Manganelli, J. Pearkes, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper, D. Zuolo

Cornell University, Ithaca, New York, U.S.A.
J. Alexander, S. Bright-Thonney, X. Chen, D.J. Cranshaw, J. Fan, X. Fan, S. Hogan, P. Kotamnives, J. Monroy, M. Oshiro, J.R. Patterson, M. Reid, A. Ryd, J. Thom, P. Wittich, R. Zou

Fermi National Accelerator Laboratory, Batavia, Illinois, U.S.A.
M. Albrow, M. Alyari, O. Amram, G. Apollinari, A. Apresyan, L.A.T. Bauerdick, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, G. Cummings, J. Dickinson, I. Dutta, V.D. Elvira, Y. Feng, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, A. Grummer, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, S. Norberg, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[85], F. Ravera, A. Reinsvold Hall[86], L. Ristori, M. Safdari, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, I. Zoi

University of Florida, Gainesville, Florida, U.S.A.
C. Aruta, P. Avery, D. Bourilkov, P. Chang, V. Cherepanov, R.D. Field, C. Huh, E. Koenig, M. Kolosova, J. Konigsberg, A. Korytov, K. Matchev, N. Menendez, G. Mitselmakher, K. Mohrman, A. Muthirakalayil Madhu, N. Rawal, S. Rosenzweig, Y. Takahashi, J. Wang

Florida State University, Tallahassee, Florida, U.S.A.
T. Adams, A. Al Kadhim, A. Askew, S. Bower, V. Hagopian, R. Hashmi, R.S. Kim, S. Kim, T. Kolberg, G. Martinez, H. Prosper, P.R. Prova, M. Wulansatiti, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, Florida, U.S.A.
B. Alsufyani, M.M. Baarmand, S. Butalla, S. Das, T. Elkafrawy[87], M. Hohlmann, E. Yanes

University of Illinois Chicago, Chicago, U.S.A., Chicago, U.S.A.
M.R. Adams, A. Baty, C. Bennett, R. Cavanaugh, R. Escobar Franco, O. Evdokimov, C.E. Gerber, M. Hawksworth, A. Hingrajiya, D.J. Hofman, J.h. Lee, D. S. Lemos, A.H. Merrit, C. Mills, S. Nanda, G. Oh, B. Ozek, D. Pilipovic, R. Pradhan, E. Prifti, T. Roy, S. Rudrabhatla, M.B. Tonjes, N. Varelas, M.A. Wadud, Z. Ye, J. Yoo

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The University of Iowa, Iowa City, Iowa, U.S.A.
M. Alhusseini, D. Blend, K. Dilsiz[88], L. Emediato, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[89], O. Neogi, H. Ogul[90], Y. Onel, A. Penzo, C. Snyder, E. Tiras[91]

Johns Hopkins University, Baltimore, Maryland, U.S.A.
B. Blumenfeld, L. Corcodilos, J. Davis, A.V. Gritsan, L. Kang, S. Kyriacou, P. Maksimovic, M. Roguljic, J. Roskes, S. Sekhar, M. Swartz

The University of Kansas, Lawrence, Kansas, U.S.A.
A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, S. Arteaga Escatel, P. Baringer, A. Bean, Z. Flowers, D. Grove, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, J. Marquez, M. Murray, M. Nickel, M. Pitt, S. Popescu[92], C. Rogan, C. Royon, R. Salvatico, S. Sanders, C. Smith, G. Wilson

Kansas State University, Manhattan, Kansas, U.S.A.
B. Allmond, R. Gujju Gurunadha, A. Ivanov, K. Kaadze, Y. Maravin, J. Natoli, D. Roy, G. Sorrentino

University of Maryland, College Park, Maryland, U.S.A.
A. Baden, A. Belloni, J. Bistany-riebman, Y.M. Chen, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, B. Kronheim, Y. Lai, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer, C. Papageorgakis, M.M. Paranjpe, E. Popova[93], A. Shevelev, L. Wang

Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A.
J. Bendavid, I.A. Cali, P.c. Chou, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, G. Grosso, P. Harris, D. Hoang, D. Kovalskyi, J. Krupa, L. Lavezzo, Y.-J. Lee, K. Long, C. Mcginn, A. Novak, C. Paus, C. Reissel, C. Roland, G. Roland, S. Rothman, G.S.F. Stephans, Z. Wang, B. Wyslouch, T. J. Yang

University of Minnesota, Minneapolis, Minnesota, U.S.A.
B. Crossman, B.M. Joshi, C. Kapsiak, M. Krohn, D. Mahon, J. Mans, B. Marzocchi, M. Revering, R. Rusack, R. Saradhy, N. Strobbe

University of Nebraska-Lincoln, Lincoln, Nebraska, U.S.A.
K. Bloom, D.R. Claes, G. Haza, J. Hossain, C. Joo, I. Kravchenko, J.E. Siado, W. Tabb, A. Vagnerini, A. Wightman, F. Yan, D. Yu

State University of New York at Buffalo, Buffalo, New York, U.S.A.
H. Bandyopadhyay, L. Hay, H.w. Hsia, I. Iashvili, A. Kalogeropoulos, A. Kharchilava, M. Morris, D. Nguyen, J. Pekkanen, S. Rappoccio, H. Rejeb Sfar, A. Williams, P. Young

Northeastern University, Boston, Massachusetts, U.S.A.
G. Alverson, E. Barberis, J. Bonilla, M. Campana, J. Dervan, Y. Haddad, Y. Han, A. Krishna, J. Li, M. Lu, G. Madigan, R. Mccarthy, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, D. Wood

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Northwestern University, Evanston, Illinois, U.S.A.
J. Bueghly, S. Dittmer, K.A. Hahn, Y. Liu, Y. Miao, D.G. Monk, M.H. Schmitt, A. Taliercio, M. Velasco

University of Notre Dame, Notre Dame, Indiana, U.S.A.
G. Agarwal, R. Band, R. Bucci, S. Castells, A. Das, R. Goldouzian, M. Hildreth, K.W. Ho, K. Hurtado Anampa, T. Ivanov, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, C. Moore, Y. Musienko[16], H. Nelson, M. Osherson, A. Piccinelli, R. Ruchti, A. Townsend, Y. Wan, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

The Ohio State University, Columbus, Ohio, U.S.A.
A. Basnet, B. Bylsma, M. Carrigan, L.S. Durkin, C. Hill, M. Joyce, M. Nunez Ornelas, K. Wei, B.L. Winer, B. R. Yates

Princeton University, Princeton, New Jersey, U.S.A.
H. Bouchamaoui, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, K. Kennedy, G. Kopp, S. Kwan, D. Lange, A. Loeliger, D. Marlow, I. Ojalvo, J. Olsen, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, Puerto Rico, U.S.A.
S. Malik

Purdue University, West Lafayette, Indiana, U.S.A.
A.S. Bakshi, S. Chandra, R. Chawla, A. Gu, L. Gutay, M. Jones, A.W. Jung, A.M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, V. Scheurer, J.F. Schulte, M. Stojanovic, J. Thieman, A. K. Virdi, F. Wang, A. Wildridge, W. Xie, Y. Yao

Purdue University Northwest, Hammond, Indiana, U.S.A.
J. Dolen, N. Parashar, A. Pathak

Rice University, Houston, Texas, U.S.A.
D. Acosta, T. Carnahan, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, I. Krommydas, W. Li, J. Lin, O. Miguel Colin, B.P. Padley, R. Redjimi, J. Rotter, E. Yigitbasi, Y. Zhang

University of Rochester, Rochester, New York, U.S.A.
A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, N. Parmar, P. Parygin[93], R. Taus

Rutgers, The State University of New Jersey, Piscataway, New Jersey, U.S.A.
B. Chiarito, J.P. Chou, S.V. Clark, D. Gadkari, Y. Gershtein, E. Halkiadakis, M. Heindl, C. Houghton, D. Jaroslawski, S. Konstantinou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, J. Reichert, H. Routray, P. Saha, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora, H. Wang

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University of Tennessee, Knoxville, Tennessee, U.S.A.

D. Ally, A.G. Delannoy, S. Fiorendi, S. Higginbotham, T. Holmes, A.R. Kanuganti, N. Karunarathna, L. Lee, E. Nibigira, S. Spanier

Texas A&M University, College Station, Texas, U.S.A.

D. Aebi, M. Ahmad, T. Akhter, O. Bouhali[94], R. Eusebi, J. Gilmore, T. Huang, T. Kamon[95], H. Kim, S. Luo, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, Texas, U.S.A.

N. Akchurin, J. Damgov, N. Gogate, V. Hegde, A. Hussain, Y. Kazhykarim, K. Lamichhane, S.W. Lee, A. Mankel, T. Peltola, I. Volobouev

Vanderbilt University, Nashville, Tennessee, U.S.A.

E. Appelt, Y. Chen, S. Greene, A. Gurrola, W. Johns, R. Kunnawalkam Elayavalli, A. Melo, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen

University of Virginia, Charlottesville, Virginia, U.S.A.

B. Cardwell, H. Chung, B. Cox, J. Hakala, R. Hirosky, A. Ledovskoy, C. Neu

Wayne State University, Detroit, Michigan, U.S.A.

S. Bhattacharya, P.E. Karchin

University of Wisconsin — Madison, Madison, Wisconsin, U.S.A.

A. Aravind, S. Banerjee, K. Black, T. Bose, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C.K. Koraka, A. Lanaro, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, S. Mondal, G. Parida, L. Pétré, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, H.F. Tsoi, W. Vetens, A. Warden

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN

S. Afanasiev, V. Alexakhin, D. Budkouski, I. Golutvin[†], I. Gorbunov, V. Karjavine, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev[96], V. Palichik, V. Perelygin, M. Savina, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev[97], A. Zarubin, I. Zhizhin, G. Gavrilov, V. Golovtcov, Y. Ivanov, V. Kim[96], P. Levchenko[98], V. Murzin, V. Oreshkin, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev[†], Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, D. Kirpichnikov, M. Kirsanov, N. Krasnikov, I. Tlisova, A. Toropin, T. Aushev, V. Gavrilov, N. Lychkovskaya, A. Nikitenko[99,100], V. Popov, A. Zhokin, R. Chistov[96], M. Danilov[96], S. Polikarpov[96], V. Andreev, M. Azarkin, M. Kirakosyan, A. Terkulov, E. Boos, V. Bunichev, M. Dubinin[85], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova[100], S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, V. Blinov[96], T. Dimova[96], A. Kozyrev[96], O. Radchenko[96], Y. Skovpen[96], V. Kachanov, D. Konstantinov, S. Slabospitskii, A. Uzunian, A. Babaev, V. Borshch, D. Druzhkin[101]

Authors affiliated with an institute formerly covered by a cooperation agreement with CERN

V. Chekhovsky, V. Makarenko

† *Deceased*
1 *Also at Yerevan State University, Yerevan, Armenia*
2 *Also at TU Wien, Vienna, Austria*
3 *Also at Ghent University, Ghent, Belgium*
4 *Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
5 *Also at Universidade Estadual de Campinas, Campinas, Brazil*
6 *Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil*
7 *Also at UFMS, Nova Andradina, Brazil*
8 *Also at Nanjing Normal University, Nanjing, China*
9 *Now at The University of Iowa, Iowa City, Iowa, U.S.A.*
10 *Also at University of Chinese Academy of Sciences, Beijing, China*
11 *Also at China Center of Advanced Science and Technology, Beijing, China*
12 *Also at University of Chinese Academy of Sciences, Beijing, China*
13 *Also at China Spallation Neutron Source, Guangdong, China*
14 *Now at Henan Normal University, Xinxiang, China*
15 *Also at Université Libre de Bruxelles, Bruxelles, Belgium*
16 *Also at an institute or an international laboratory covered by a cooperation agreement with CERN*
17 *Also at Helwan University, Cairo, Egypt*
18 *Now at Zewail City of Science and Technology, Zewail, Egypt*
19 *Now at British University in Egypt, Cairo, Egypt*
20 *Now at Cairo University, Cairo, Egypt*
21 *Also at Purdue University, West Lafayette, Indiana, U.S.A.*
22 *Also at Université de Haute Alsace, Mulhouse, France*
23 *Also at Istinye University, Istanbul, Turkey*
24 *Also at The University of the State of Amazonas, Manaus, Brazil*
25 *Also at University of Hamburg, Hamburg, Germany*
26 *Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
27 *Also at Bergische University Wuppertal (BUW), Wuppertal, Germany*
28 *Also at Brandenburg University of Technology, Cottbus, Germany*
29 *Also at Forschungszentrum Jülich, Juelich, Germany*
30 *Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland*
31 *Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
32 *Now at Universitatea Babes-Bolyai — Facultatea de Fizica, Cluj-Napoca, Romania*
33 *Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*
34 *Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary*
35 *Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt*
36 *Also at Punjab Agricultural University, Ludhiana, India*
37 *Also at University of Visva-Bharati, Santiniketan, India*
38 *Also at Indian Institute of Science (IISc), Bangalore, India*
39 *Also at IIT Bhubaneswar, Bhubaneswar, India*
40 *Also at Institute of Physics, Bhubaneswar, India*
41 *Also at University of Hyderabad, Hyderabad, India*
42 *Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany*
43 *Also at Isfahan University of Technology, Isfahan, Iran*
44 *Also at Sharif University of Technology, Tehran, Iran*
45 *Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran*
46 *Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran*
47 *Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran*

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[48] *Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy*
[49] *Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy*
[50] *Also at Università degli Studi Guglielmo Marconi, Roma, Italy*
[51] *Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy*
[52] *Also at Fermi National Accelerator Laboratory, Batavia, Illinois, U.S.A.*
[53] *Also at Consiglio Nazionale delle Ricerche — Istituto Officina dei Materiali, Perugia, Italy*
[54] *Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia*
[55] *Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico*
[56] *Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka*
[57] *Also at Saegis Campus, Nugegoda, Sri Lanka*
[58] *Also at National and Kapodistrian University of Athens, Athens, Greece*
[59] *Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland*
[60] *Also at University of Vienna, Vienna, Austria*
[61] *Also at Universität Zürich, Zurich, Switzerland*
[62] *Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria*
[63] *Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France*
[64] *Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey*
[65] *Also at Konya Technical University, Konya, Turkey*
[66] *Also at Izmir Bakircay University, Izmir, Turkey*
[67] *Also at Adiyaman University, Adiyaman, Turkey*
[68] *Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey*
[69] *Also at Marmara University, Istanbul, Turkey*
[70] *Also at Milli Savunma University, Istanbul, Turkey*
[71] *Also at Kafkas University, Kars, Turkey*
[72] *Now at Istanbul Okan University, Istanbul, Turkey*
[73] *Also at Hacettepe University, Ankara, Turkey*
[74] *Also at Erzincan Binali Yildirim University, Erzincan, Turkey*
[75] *Also at Istanbul University — Cerrahpasa, Faculty of Engineering, Istanbul, Turkey*
[76] *Also at Yildiz Technical University, Istanbul, Turkey*
[77] *Also at Vrije Universiteit Brussel, Brussel, Belgium*
[78] *Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom*
[79] *Also at IPPP Durham University, Durham, United Kingdom*
[80] *Also at Monash University, Faculty of Science, Clayton, Australia*
[81] *Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt*
[82] *Also at Università di Torino, Torino, Italy*
[83] *Also at Bethel University, St. Paul, Minnesota, U.S.A.*
[84] *Also at Karamanoğlu Mehmetbey University, Karaman, Turkey*
[85] *Also at California Institute of Technology, Pasadena, California, U.S.A.*
[86] *Also at United States Naval Academy, Annapolis, Maryland, U.S.A.*
[87] *Also at Ain Shams University, Cairo, Egypt*
[88] *Also at Bingol University, Bingol, Turkey*
[89] *Also at Georgian Technical University, Tbilisi, Georgia*
[90] *Also at Sinop University, Sinop, Turkey*
[91] *Also at Erciyes University, Kayseri, Turkey*
[92] *Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania*
[93] *Now at another institute or international laboratory covered by a cooperation agreement with CERN*
[94] *Also at Texas A&M University at Qatar, Doha, Qatar*
[95] *Also at Kyungpook National University, Daegu, Korea*
[96] *Also at another institute or international laboratory covered by a cooperation agreement with CERN*

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[97] *Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan*
[98] *Also at Northeastern University, Boston, Massachusetts, U.S.A.*
[99] *Also at Imperial College, London, United Kingdom*
[100] *Now at Yerevan Physics Institute, Yerevan, Armenia*
[101] *Also at Universiteit Antwerpen, Antwerpen, Belgium*

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