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

The CMS Collaboration*

Abstract

The effective lifetime of the B_s^0 meson in the decay $B_s^0 \rightarrow J/\psi K_S^0$ 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 ± 0.07 (stat) ± 0.03 (syst) ps is the most precise measurement to date and is in good agreement with the expected value.

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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_s^0 mesons provide a valuable tool in the study of CP violation. 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 [1, 2]. 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 common unitarity triangle and is most precisely determined by measuring the phase ϕ_d in a time-dependent CP asymmetry analysis of $B^0 \rightarrow J/\psi K_S^0$ decays, where ϕ_d arises from the interference between the direct decay of B^0 and the decay after oscillating to \bar{B}^0 . In the SM, $\phi_d = 2\beta$. However, the value of the phase measured in $B^0 \rightarrow J/\psi K_S^0$ does not exactly equal ϕ_d since there is a small contribution to the decay from doubly-Cabibbo-suppressed penguin decays, with a different phase [3–6]. Because the value of $\sin(2\beta)$ is now known to better than 2% [7], understanding the penguin contribution is becoming more important in determining ϕ_d . This can be accomplished by studying the decay $B_s^0 \rightarrow J/\psi K_S^0$, where the penguin contribution is much larger, since it is not Cabibbo suppressed relative to the tree diagram, and it is related to the $B^0 \rightarrow J/\psi K_S^0$ decay through the U-spin flavor symmetry of the strong interaction (swapping s and d quarks) [8–12].

In this paper, we measure the effective lifetime of the B_s^0 meson in its decay to $J/\psi K_S^0$. Charge conjugate states and decays are implied unless otherwise indicated. Figure 1 shows the tree-level and penguin Feynman diagrams for the decay modes $B^0 \rightarrow J/\psi K_S^0$ and $B_s^0 \rightarrow J/\psi K_S^0$. The effective lifetime is theoretically defined as the time expectation value of the untagged decay rate [13], where untagged means that no requirements are made that would bias one B_s^0 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 $B_s^0 \rightarrow \mu^+ \mu^-$ [14, 15], a CP -odd final state, as well as other B_s^0 meson decay channels [16]. The ATLAS and LHCb experiments have also measured the effective lifetimes for a variety of decay modes [17–29]. The effective lifetime of a particular decay channel can be experimentally determined by fitting a single exponential function to its untagged rate. The $J/\psi K_S^0$ state can be considered a pure CP -odd state [30], since CP violation in mixing is negligible. This allows us to accurately measure the B_s^0 heavy-state lifetime.

The $B_s^0 \rightarrow J/\psi K_S^0$ effective lifetime is defined as

$$\tau(B_s^0 \rightarrow J/\psi K_S^0) \equiv \frac{\int_0^\infty t \{ \Gamma[B_s^0(t) \rightarrow J/\psi K_S^0] + \Gamma[\bar{B}_s^0(t) \rightarrow J/\psi K_S^0] \} dt}{\int_0^\infty \{ \Gamma[B_s^0(t) \rightarrow J/\psi K_S^0] + \Gamma[\bar{B}_s^0(t) \rightarrow J/\psi K_S^0] \} dt}, \quad (1)$$

where t is the proper decay time of the B_s^0 meson. The effective lifetime can also be expressed

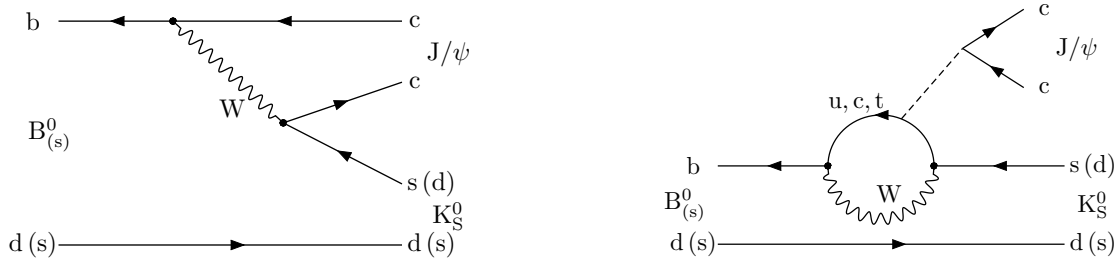


Figure 1: The tree-level (left) and penguin (right) Feynman diagrams for the decays $B^0 \rightarrow J/\psi K_S^0$ and $B_s^0 \rightarrow J/\psi K_S^0$.

as [31]

$$\tau(B_s^0 \rightarrow J/\psi K_S^0) = \frac{\tau_{B_s^0}^0}{1 - y_s^2} \left(\frac{1 + 2y_s A_{\Delta\Gamma} + y_s^2}{1 + y_s A_{\Delta\Gamma}} \right), \quad (2)$$

where $A_{\Delta\Gamma}$ is the mass eigenstate rate asymmetry, y_s is the normalized decay width difference, defined as $y_s = \tau_{B_s^0}^0 \Delta\Gamma / 2$, $\Delta\Gamma$ is the decay width difference between the heavy and light B_s^0 mass eigenstates, and $\tau_{B_s^0}^0$ denotes the mean B_s^0 lifetime. Using the most recent measurements [30, 32] of these observables, the SM prediction for the $B_s^0 \rightarrow J/\psi K_S^0$ effective lifetime is 1.62 ± 0.02 ps, where the uncertainty is derived from the uncertainties in the observables in Eq. (2). The only previous measurement of this effective lifetime is from the LHCb Collaboration, which reported $\tau(B_s^0 \rightarrow J/\psi K_S^0) = 1.75 \pm 0.12$ (stat) ± 0.07 (syst) ps from data collected in 2011 [26]. 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 $B^0 \rightarrow J/\psi K_S^0$ 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 [33]. At the start of 2017, a new pixel detector was installed [34]; 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 [35] 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. [36].

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 [37]. 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 [38].

3 Data and simulation samples

Data used in the analysis correspond to an integrated luminosity of 140 fb^{-1} [39–41], 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 [42] and the unstable particle decays are modeled by EVTGEN v1.6.0 [43]. Final-state radiation is included in EVTGEN using PHOTOS v3.61 [44]. The particles are propagated through a detailed model of the CMS detector using GEANT4 [45]. 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 cm of the beamline and the dimuon system was required to have $|\eta| < 2.5$ and $p_T > 19.9 \text{ GeV}$ in 2016 and $p_T > 24.9 \text{ GeV}$ 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 [46].

The $J/\psi K_S^0$ candidates are reconstructed using the J/ψ meson decay to $\mu^+\mu^-$ and K_S^0 meson decay to $\pi^+\pi^-$. After the standard track selection criteria [47], the two daughter tracks assumed to be from the K_S^0 decay are given charged pion mass assignments and fit to a common vertex. The fitted two-track vertex must have a $\chi^2 < 7$ [48] 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_S^0 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_S^0 candidates from $\Lambda \rightarrow p\pi^-$ 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 [49].

The two tracks from the $K_S^0 \rightarrow \pi^+\pi^-$ candidate decay are fit to a common vertex with the invariant mass constrained to the K_S^0 world-average mass value [32]. The B meson candidates are obtained from a vertex fit of $K_S^0 \mu^+\mu^-$, 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 $4.9 < m < 6.0 \text{ GeV}$.

The distance between the B and K_S^0 decay vertices in the transverse plane, referred to as the K_S^0 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_S^0 decays, such as $B^0 \rightarrow J/\psi K^*(892)^0$ where the $K^*(892)^0$ decays to $K^+\pi^-$ 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

$$t = m \frac{\vec{L}_{xy} \cdot \vec{p}_T^B}{(p_T^B)^2}, \quad (3)$$

where m and \vec{p}_T^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}_T^B ; the B and K_S^0 vertex χ^2 fit probabilities; the p_T of the J/ψ and K_S^0 candidates; the η of the B candidate; the angle in the transverse plane between the K_S^0 momentum vector and the line joining the B and 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 $B^0 \rightarrow J/\psi K_S^0$.

5 Effective lifetime measurement

The effective lifetime for the signal B_s^0 meson is extracted using a single two-dimensional unbinned extended maximum likelihood (2D UML) fit to the $J/\psi K_S^0$ invariant mass (m) and the proper decay time (t) distributions, with the 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 $0.2 < t < 10$ ps and $5.17 < m < 5.57$ 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.

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

$$\begin{aligned} \mathcal{L}(m, t; \sigma_t) = & N_{B_s^0} M_{B_s^0}(m) T_{B_s^0}(t; \sigma_t) \varepsilon_{B_s^0}(t) + N_{B^0} M_{B^0}(m) T_{B^0}(t; \sigma_t) \varepsilon_{B^0}(t) \\ & + N_{\text{bkg}} M_{\text{bkg}}(m) T_{\text{bkg}}(t; \sigma_t). \end{aligned} \quad (4)$$

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 B_s^0 , B^0 , and bkg , respectively. The signal and control channel efficiencies are given by $\epsilon_{B_s^0}$ and ϵ_{B^0} , respectively. The parameters $N_{B_s^0}$, N_{B^0} , and N_{bkg} correspond to the signal, control channel, and background yields, respectively.

The invariant mass distribution from simulated $B^0 \rightarrow J/\psi K_S^0$ 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 $B_s^0 \rightarrow J/\psi K_S^0$ events with the yield, mean, and a single scale factor (B_s^0 MC) multiplying each of the widths as the free parameters. In fitting the data, the two invariant mass signal functions for B^0 and B_s^0 have a total of four free parameters: two yields, one mean, and one width scale factor. The means of the two invariant mass Gaussian functions are separated by a fixed value of 87.42 MeV, as the difference in masses of the B_s^0 and B^0 mesons. The width scale factor multiplies all of the width parameters of each function, with the B_s^0 signal function widths also multiplied by the 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 $T_{B_s^0}$ and T_{B^0} are exponential functions convolved with a Gaussian function to account for the detector resolution. These are multiplied by their respective efficiency functions $\epsilon_{B_s^0}(t)$ and $\epsilon_{B^0}(t)$. 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:

$$\epsilon(t; p_0, p_1, p_2, p_3, p_4) = p_0 + p_1 t + p_2 t^2 + \frac{p_3}{1 + \exp(-p_4 t)}, \quad (5)$$

where p_i ($i = 0-4$) are free parameters in the fit. The efficiencies, along with the fitted ϵ functions, are shown in Appendix A for each of the three data-taking years.

The measured m and t distributions are shown in Fig. 2, 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 Fig. 3 for events in the signal invariant mass range $5.34 < m < 5.42$ GeV, along with individual and total pdf components. The measured effective lifetime for the B_s^0 from the simultaneous fit is $\tau(B_s^0 \rightarrow J/\psi K_S^0) = 1.59 \pm 0.07$ (stat) ps. Projections in m and t of this fit are given for each of the three data-taking years in Appendix B, along with the corresponding data results.

Consistency checks are conducted, such as examining the decay time projections in different B_s^0 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 C.

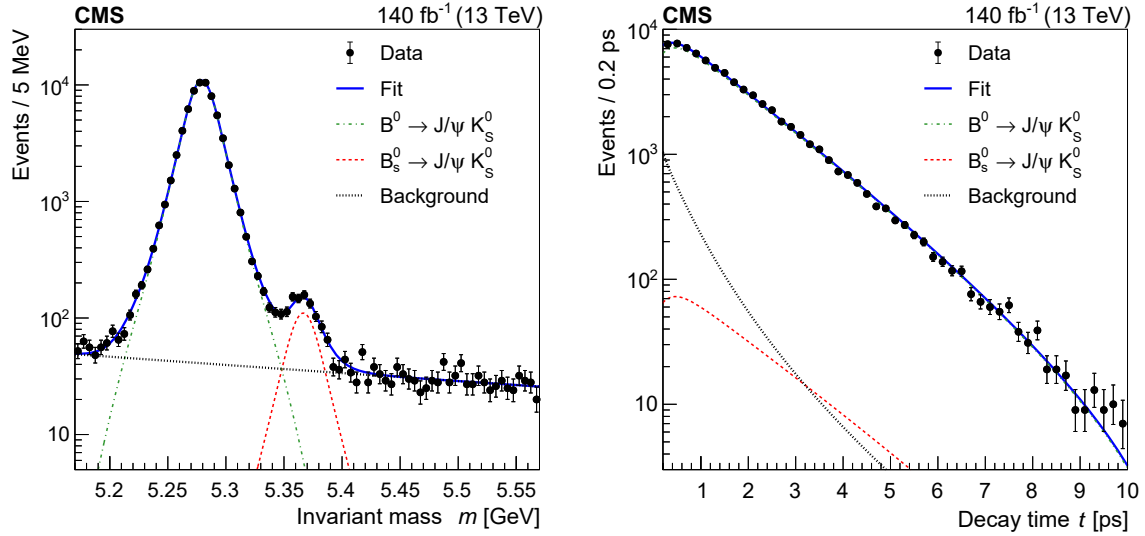


Figure 2: Distributions of the $J/\psi K_S^0$ invariant mass (left) and proper decay time (right) from data (points) and the results from the 2D UML fit projections (lines) for the 2016–2018 data set. The vertical bars on the data points indicate the statistical uncertainty. The solid, dotted-dashed,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

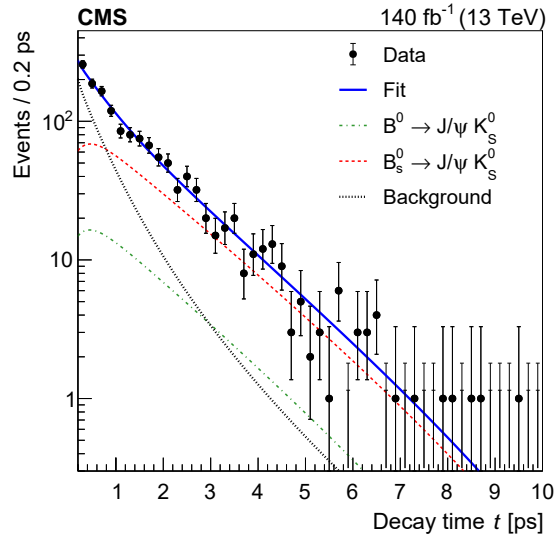


Figure 3: The proper decay time distribution from data (points) for events in the B_s^0 signal region with $J/\psi K_S^0$ invariant mass in the range 5.34–5.42 GeV and the results from the 2D UML fit projections (lines) for the 2016–2018 data set. The vertical bars on the data points indicate the statistical uncertainty. The dashed, dotted-dashed, dotted, and solid lines show the B_s^0 signal, B^0 control channel, background, and total fit contributions, respectively.

6 Systematic uncertainties

Several sources of systematic uncertainty are investigated and their effects on the B_s^0 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)) 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. Two alternative signal functions for the invariant mass, the Johnson S_U function [50] and the Student's t -distribution [51], 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. All combinations of nominal and alternative functions are tried, with the largest variation from the nominal fit of 0.022 ps 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 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 $B_s^0 \rightarrow J/\psi K_S^0$ MC events) and the variation in the B_s^0 effective lifetime is 0.004 ps.

An alternative 2D UML fit is performed in which the ratio of the B_s^0 to 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.

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.

As previously noted, the control channel $B^0 \rightarrow J/\psi K_S^0$ 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. The difference of 0.004 ps between the B^0 meson lifetime extracted in this analysis, 1.521 ± 0.007 (stat) ps, and the world-average value 1.517 ± 0.004 ps [32] is used to assess 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.

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 $B_s^0 \rightarrow J/\psi K_S^0$ effective lifetime is measured to be:

$$\tau(B_s^0 \rightarrow J/\psi K_S^0) = 1.59 \pm 0.07 \text{ (stat)} \pm 0.03 \text{ (syst) ps.} \quad (6)$$

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

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
Deviation in control channel lifetime	0.004
Total	0.028

This result is consistent with the expectation from the SM of 1.62 ± 0.02 ps and is considerably more precise than the only previous measurement of 1.75 ± 0.12 (stat) ± 0.07 (syst) ps, reported by the LHCb Collaboration from data collected in 2011 [26]. Tabulated results for this analysis are provided in the HEPData record [52].

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 $B^0 \rightarrow J/\psi K_S^0$, 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 $\tau(B_s^0 \rightarrow J/\psi K_S^0) = 1.59 \pm 0.07$ (stat) ± 0.03 (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 $B^0 \rightarrow J/\psi K_S^0$ decays.

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A Decay time efficiency plots

The decay time distribution of signal events is distorted due to the impact of the trigger and other selection criteria. The determination of the signal efficiency as a function of the decay time is achieved through simulated samples. Figure A.1 illustrates the B^0 (upper) and B_s^0 (lower) efficiencies as a function of decay time for each of the three data-taking years, along with the results of the fit.

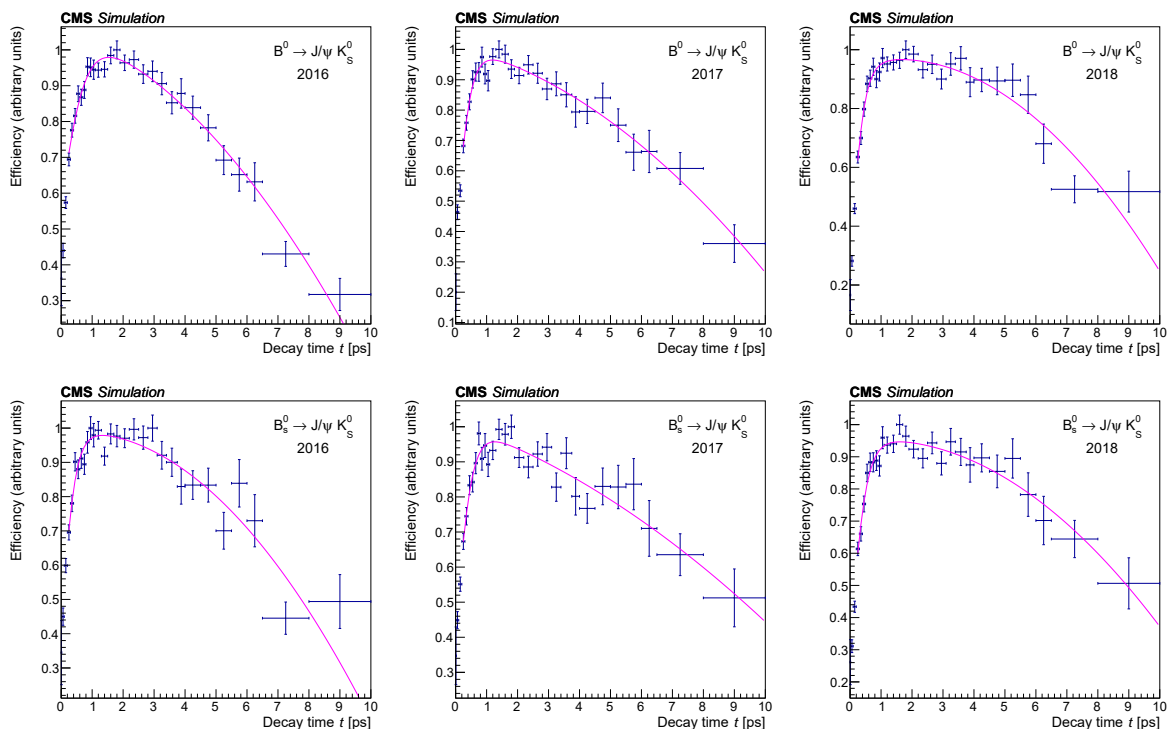


Figure A.1: The signal efficiency as a function of the decay time for the $B^0 \rightarrow J/\psi K_S^0$ (upper) and $B_s^0 \rightarrow J/\psi K_S^0$ (lower) decays from simulation for each of the three data-taking years. The vertical bars indicate the statistical uncertainty, and the horizontal bars give bin widths. The curves show the fit results.

B Projection plots from the 2D UML fits

The invariant mass and decay time projection plots from the 2D UML fit are presented in Fig. B.1. 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.

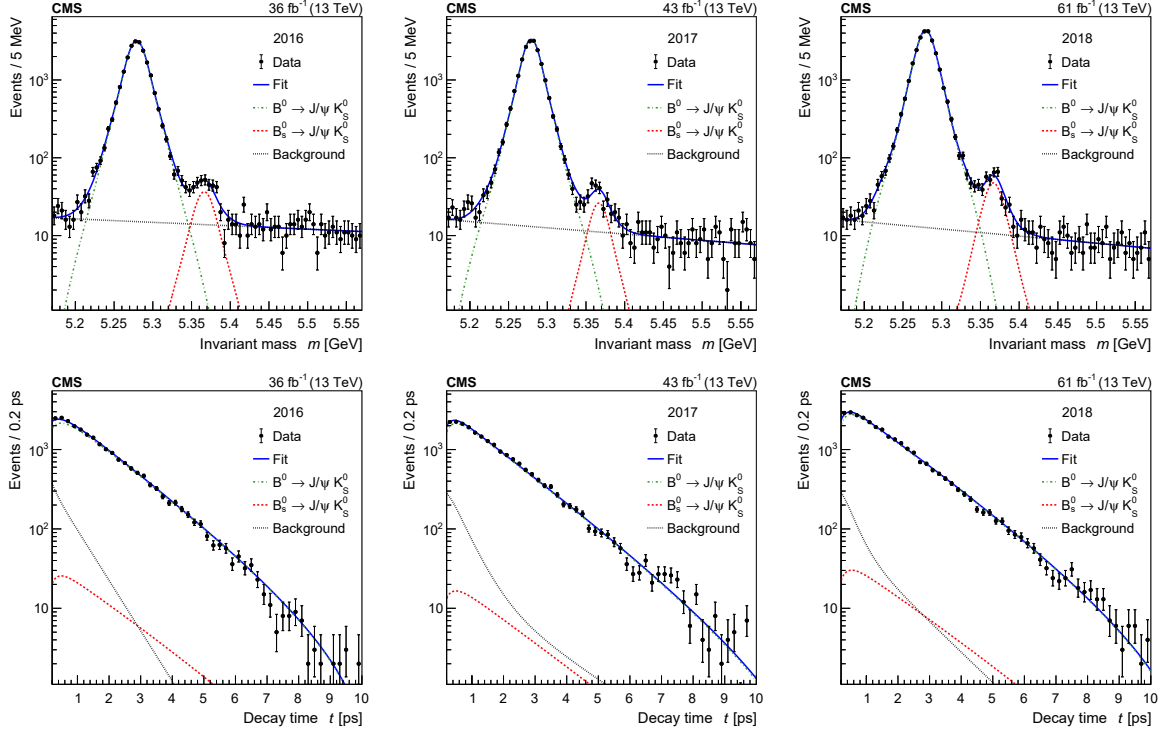


Figure B.1: Distributions of the $J/\psi K_S^0$ invariant mass (upper) and decay time (lower) from data (points), along with the projections from the 2D UML fit for each year of data taking. The vertical bars on the data points indicate the statistical uncertainty. The dashed, dotted-dashed, dotted, and solid lines represent the signal, control channel, background, and total fit contributions, respectively.

C Subrange projection plots

Projections of the decay time distributions for three different $J/\psi K_S^0$ invariant mass ranges and the results of the 2D UML fits are presented in Fig. C.1 for each of the three data-taking years. The corresponding invariant mass projections for different decay time ranges are shown in Fig. C.2.

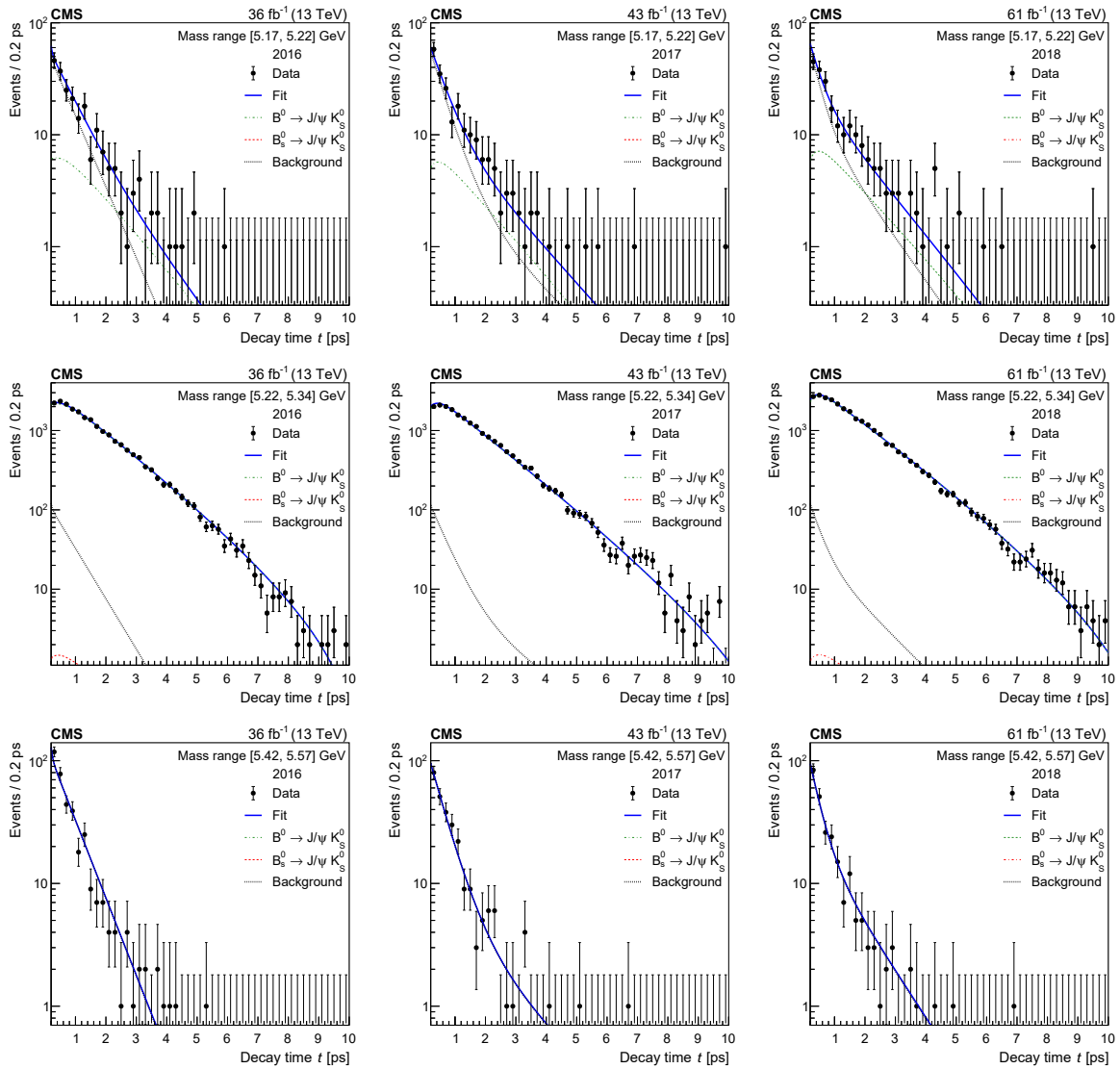


Figure C.1: The decay time distribution for events with $J/\psi K_S^0$ invariant mass in the range $5.17 < m < 5.22$ (upper), $5.22 < m < 5.34$ (center), and $5.42 < m < 5.57$ (lower) GeV and the fit results for the 2016 (left), 2017 (middle), and 2018 (right) data-taking years.

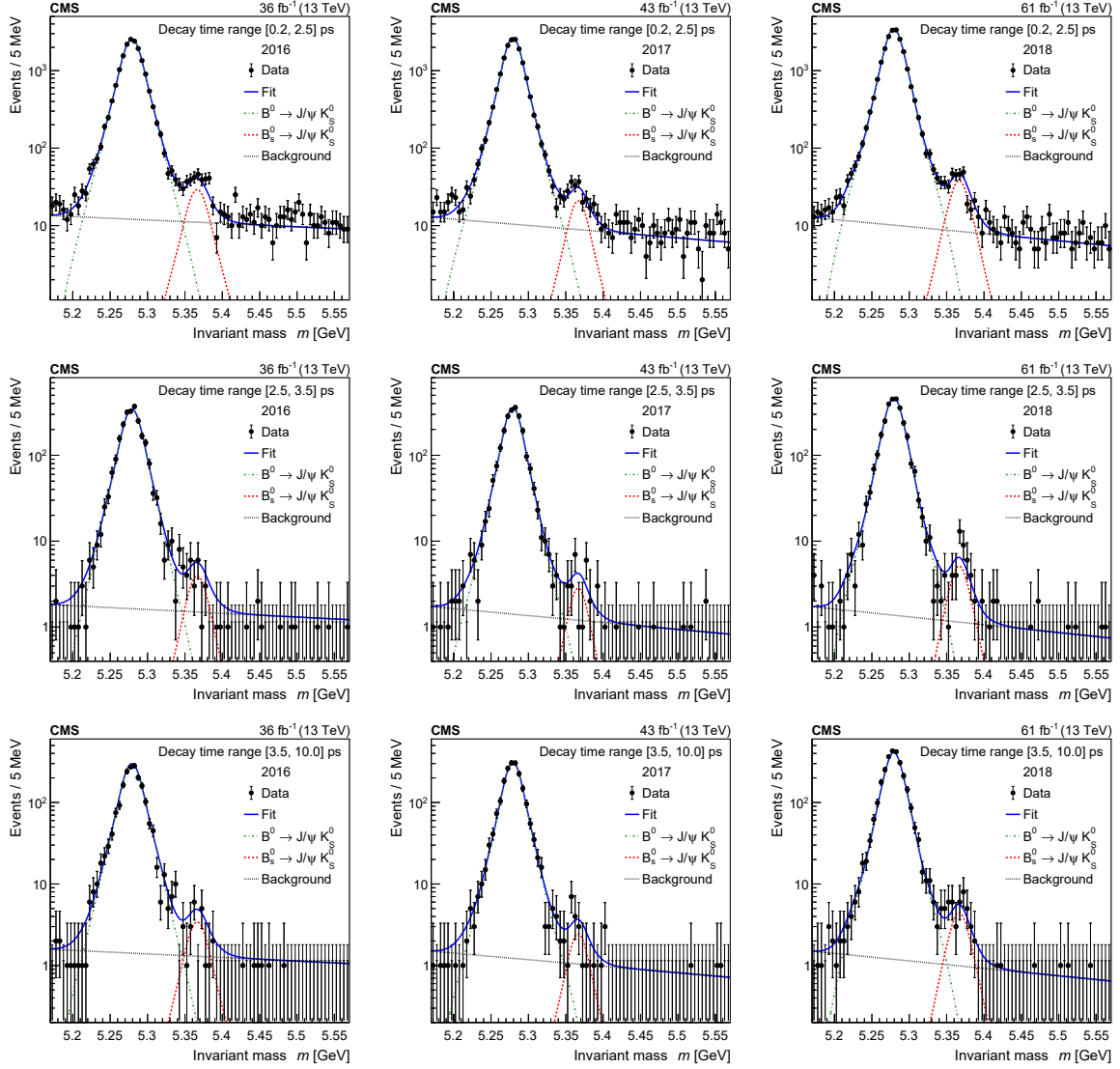




















Figure C.2: The invariant mass distribution for events with $J/\psi K_S^0$ decay time in the range $0.2 < t < 2.5$ (upper), $2.5 < t < 3.5$ (center), and $3.5 < t < 10.0$ (lower) ps and the fit results for the 2016 (left), 2017 (middle), and 2018 (right) data-taking years.

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







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






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









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






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










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









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














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
















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

























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
















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












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


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




























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






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






































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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 , 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 Araujo²⁴ , S. Wiedenbeck , S. Zaleski







































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


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








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



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












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








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



























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
























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












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
















































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


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









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






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

























D. Abbaneo , C. Amendola , E. Auffray , G. Auzinger , J. Baechler, D. Barney , A. Bermúdez Martínez , M. Bianco , A.A. Bin Anuar , A. Bocci , L. Boronovi , 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. Karacheban²⁸ , 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. Rabadý , B. Ribeiro Lopes , M. Rovere , H. Sakulin , S. Sanchez Cruz , S. Scarfi , C. Schwick, M. Selvaggi , A. Sharma , K. Shchelina , P. Silva , P. Sphicas⁵⁸ , A.G. Stahl Leitner , A. Steen , S. Summers , D. Treille , P. Tropea , D. Walter , J. Wanczyk⁵⁹ , J. Wang, K.A. Wozniak⁶⁰ , S. Wuchterl , P. Zehetner , P. Zejdl , W.D. Zeuner

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
T. Bevilacqua⁶¹ , L. Caminada⁶¹ , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli⁶¹ , L. Noehte⁶¹ 

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











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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. Tsiou, H.y. Wu, E. Yazgan 

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








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





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






















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



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
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K. Coldham, J.E. Cole , A. Khan, P. Kyberd , I.D. Reid 











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



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
















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












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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. Vami , S. Wang , D. Zhang















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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, USA

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 




































































University of Colorado Boulder, Boulder, Colorado, USA







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 

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












J. Alexander , S. Bright-Thonney , X. Chen , D.J. Cranshaw , J. Fan , X. Fan , S. Hogan , P. Kotamvives, J. Monroy , M. Oshiro , J.R. Patterson , M. Reid , A. Ryd , J. Thom , P. Wittich , R. Zou 

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











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. Klijsma , 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. Pena⁸⁵ , F. Ravera , A. Reinsvold Hall⁸⁶ , 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 






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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 
























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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











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






















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M. Alhousseini , D. Blend, K. Dilsiz⁸⁸ , L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili⁸⁹ , O. Neogi, H. Ogul⁹⁰ , Y. Onel , A. Penzo , C. Snyder, E. Tiras⁹¹ 









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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, USA

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. Popescu⁹² , C. Rogan , C. Royon , R. Salvatico , S. Sanders , C. Smith , G. Wilson 





















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B. Allmond , R. Gujju Gurunadha , A. Ivanov , K. Kaadze , Y. Maravin , J. Natoli , D. Roy , G. Sorrentino 

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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. Popova⁹³ , A. Shevelev , L. Wang 

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA













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. Kovalskiy , 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 












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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, USA

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 








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H. Bandyopadhyay , L. Hay , H.w. Hsia, I. Iashvili , A. Kalogeropoulos ,
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A. Williams , P. Young 



























Northeastern University, Boston, Massachusetts, USA

G. Alverson , E. Barberis , J. Bonilla , M. Campana , J. Dervan, Y. Haddad , Y. Han ,
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


Northwestern University, Evanston, Illinois, USA

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

















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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. Musienko¹⁶ , H. Nelson , M. Osherson , A. Piccinelli , R. Ruchti ,
A. Townsend , Y. Wan, M. Wayne , H. Yockey, M. Zarucki , L. Zygalá 

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A. Basnet , B. Bylsma, M. Carrigan , L.S. Durkin , C. Hill , M. Joyce , M. Nunez Ornelas ,
K. Wei, B.L. Winer , B. R. Yates 




















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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 




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A.M. Koshy, M. Liu , G. Negro , N. Neumeister , G. Paspalaki , S. Piperov ,
V. Scheurer, J.F. Schulte , M. Stojanovic , J. Thieman , A. K. Viridi , F. Wang ,
A. Wildridge , W. Xie , Y. Yao 

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J. Dolen , N. Parashar , A. Pathak 

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
















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 











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












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

























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













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