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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

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## 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  $140 \text{ fb}^{-1}$ . 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  $1.59 \pm 0.07$  (stat)  $\pm 0.03$  (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 [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  $\beta$  is one of the angles of the most commonly used unitarity triangle and is most precisely determined by measuring the phase  $\phi_d$  in a time-dependent  $CP$  asymmetry analysis of  $B^0 \rightarrow J/\psi K_S^0$  decays, where  $\phi_d$  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  $B^0 \rightarrow J/\psi K_S^0$  may not exactly equal  $\phi_d$  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  $\phi_d$ . 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) [9–13].

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 [14], 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  $B_s^0 \rightarrow \mu^+ \mu^-$  [15, 16], a  $CP$ -odd final state, as well as other  $B_s^0$  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  $J/\psi K_S^0$  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  $B_s^0$  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

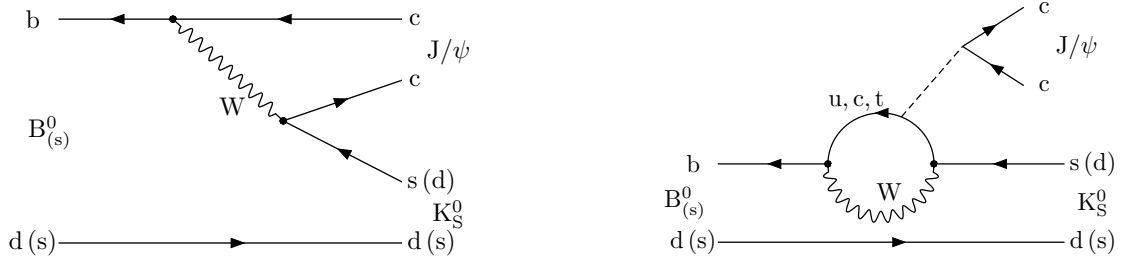


Figure 1: The tree-level (left) and penguin (right) Feynman diagrams for the decays  $B^0 \rightarrow J/\psi K_S^0$  and  $B_s^0 \rightarrow J/\psi K_S^0$ .

as [33]

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

where  $A_{\Delta\Gamma}$  is the mass eigenstate rate asymmetry,  $y_s$  is the normalized decay width difference, defined as  $y_s = \tau_{B_s^0} \Delta\Gamma / 2$ ,  $\Delta\Gamma$  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  $B_s^0 \rightarrow J/\psi K_S^0$  effective lifetime is  $1.62 \pm 0.02$  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)  $\pm 0.07$  (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  $B^0 \rightarrow J/\psi K_S^0$  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)  $\mu\text{m}$  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  $\mu\text{m}$  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  $\mu\text{s}$  [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  $140 \text{ fb}^{-1}$  [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 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  $\chi^2$  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  $p_T > 19.9 \text{ GeV}$  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 [48].

The  $J/\psi K_S^0$  candidates are reconstructed using the  $J/\psi$  meson decay to  $\mu^+\mu^-$  and  $K_S^0$  meson decay to  $\pi^+\pi^-$ . After the standard track selection criteria [49], 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  $\chi^2 < 7$  [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  $\sigma_1$  and  $\sigma_2$  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  $J/\psi$ , 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 [51].

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 [34]. 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  $J/\psi$  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  $\pi^+$ .

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  $\chi^2$  fit probabilities; the  $p_T$  of the  $J/\psi$  and  $K_S^0$  candidates; the  $\eta$  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 calculated uncertainty in the proper decay time ( $\sigma_t$ ) 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  $\varepsilon_{B_s^0}$  and  $\varepsilon_{B^0}$ , respectively. The parameters  $N_{B_s^0}$ ,  $N_{B^0}$ , and  $N_{\text{bkg}}$  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 world-average value for the difference in masses of the  $B_s^0$  and  $B^0$  mesons of  $87.26 \pm 0.24$  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  $B_s^0$  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  $\varepsilon_{B_s^0}(t)$  and  $\varepsilon_{B^0}(t)$ . A sum of two exponential functions is used to model  $T_{\text{bkg}}$ , with all parameters left free in the fit.

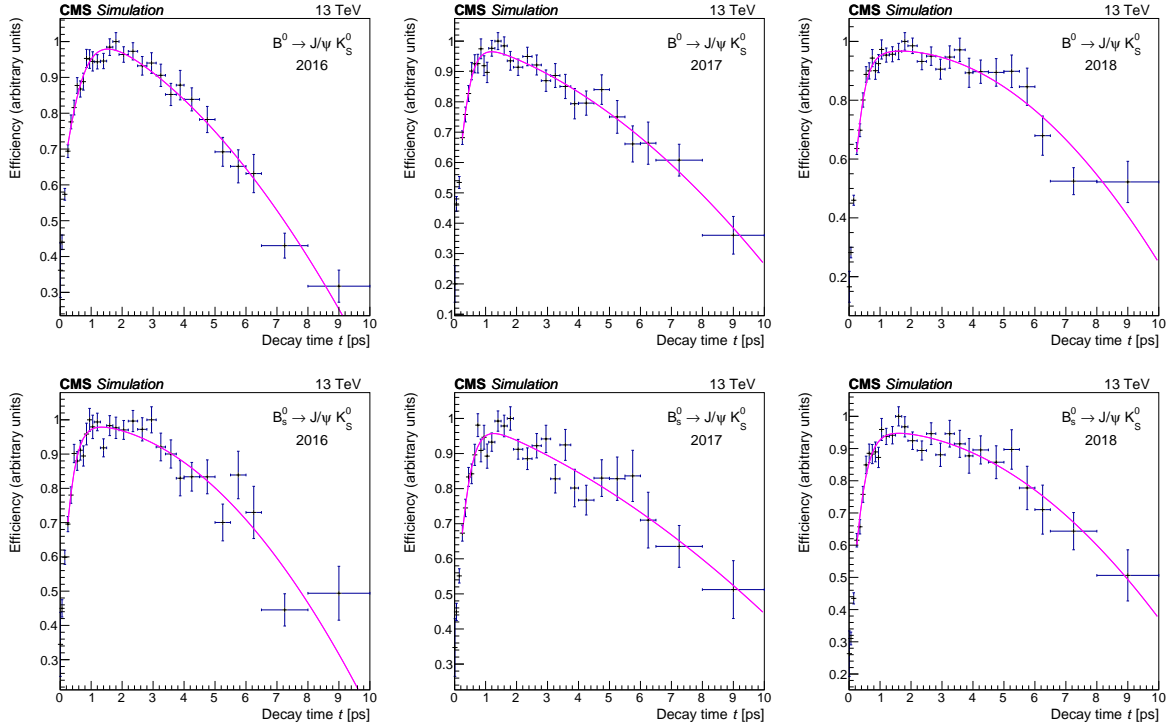


Figure 2: The signal efficiency as a function of the decay time for the  $B^0 \rightarrow J/\psi K_S^0$  (upper) and  $B_s^0 \rightarrow J/\psi K_S^0$  (lower) decays from simulation for each of the three data-taking years. The vertical bars indicate the statistical uncertainty, and the horizontal bars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

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:

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

where  $p_i$  ( $i = 0-4$ ) are free parameters in the fit. The efficiencies, along with the fitted  $\varepsilon$  functions, are shown in Fig. 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 Fig. 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  $\chi^2$  value of 82 with 80 bins, while the decay time projection results in a  $\chi^2$  value of 62 with 49 bins. For a better visualization of the signal component, the proper decay time projection is shown in Fig. 4 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 A, along with the corresponding data results.

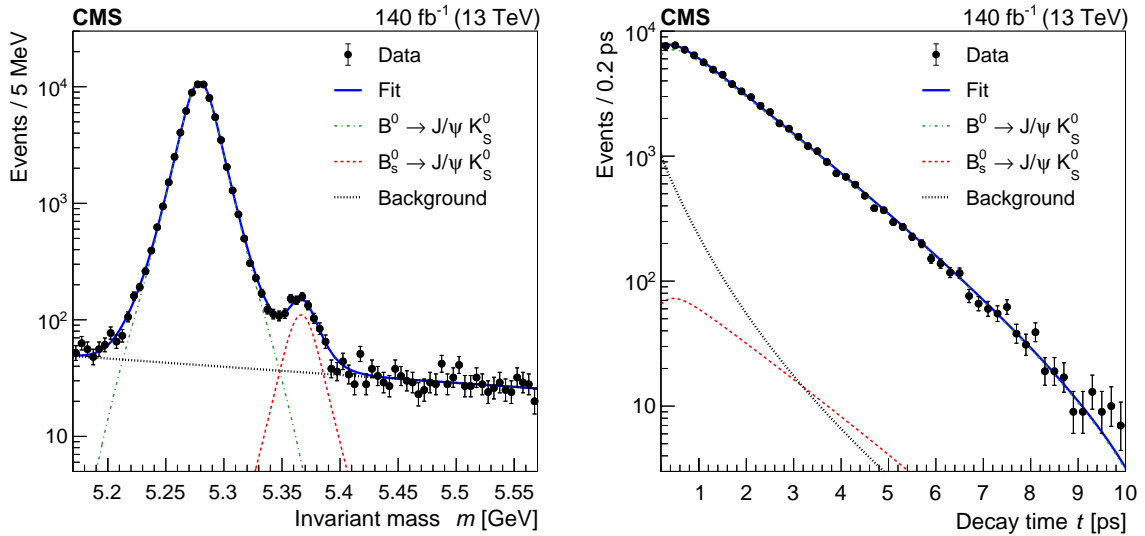


Figure 3: Distributions of the  $J/\psi K_S^0$  invariant mass (left) and proper decay time (right) from data (points) and the results from the 2D UML fit projections (lines) for the 2016–2018 data set. The vertical bars on the data points indicate the statistical uncertainty. The solid, dotted-dashed,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

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 B.

## 6 Systematic uncertainties

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



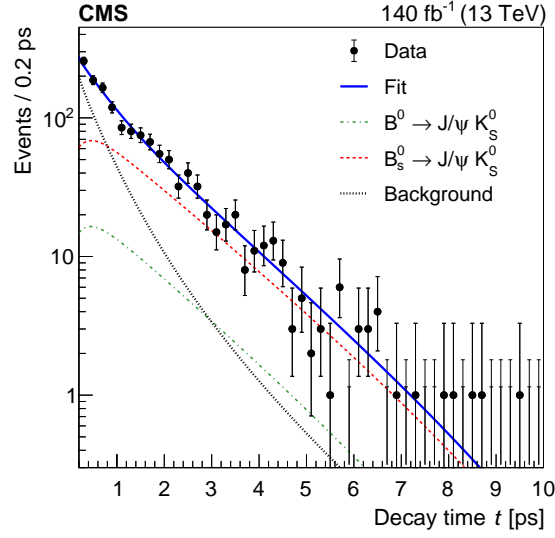


Figure 4: The proper decay time distribution from data (points) for events in the  $B_s^0$  signal region with  $J/\psi K_S^0$  invariant mass in the range 5.34–5.42 GeV and the results from the 2D UML fit projections (lines) for the 2016–2018 data set. The vertical bars on the data points indicate the 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.

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. 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  $B_s^0$ - $B^0$  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  $B_s^0$  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. It is possible that a small number of reconstructed  $B_s^0$  mesons may come from  $B_c^+$  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  $B_c^+$  average lifetime plus the fitted  $B_s^0$  lifetime, and an unconstrained yield. The difference in  $B_s^0$  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  $\sigma_t$  calculation, the values of  $\sigma_t$  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  $B^0 \rightarrow J/\psi K_S^0$  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. As the  $B^0$  meson lifetime extracted in this analysis,  $1.521 \pm 0.007$  (stat) ps, agrees with the world-average value of  $1.517 \pm 0.004$  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.

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
Contribution of $B_s^0$ from $B_c^+$ decays	0.002
Control channel lifetime uncertainty	0.007
Total	0.029

## 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  $727 \pm 35$  and  $68460 \pm 270$ , respectively, where the uncertainties are statistical only. The  $B_s^0 \rightarrow J/\psi K_S^0$  effective lifetime is measured to be:

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

This result is consistent with the expectation from the SM of  $1.62 \pm 0.02$  ps and is twice as

precise as the only previous measurement of  $1.75 \pm 0.12$  (stat)  $\pm 0.07$  (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  $140 \text{ fb}^{-1}$ . 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)  $\pm 0.03$  (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 Projection plots from the 2D UML fits

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

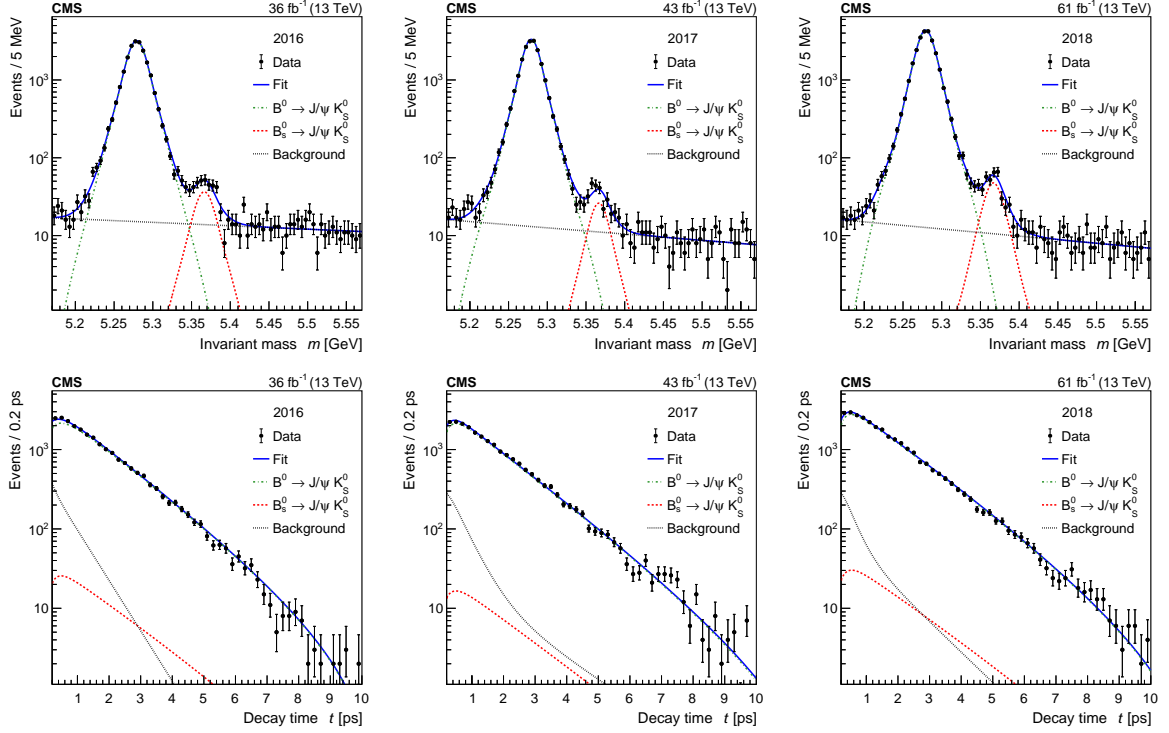


Figure 5: Distributions of the  $J/\psi K_S^0$  invariant mass (upper) and decay time (lower) from data (points), along with the projections from the 2D UML fit for each year of data taking. The vertical bars on the data points indicate the statistical uncertainty. The dashed, dotted-dashed, dotted,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



## B 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. 6 for each of the three data-taking years. The corresponding invariant mass projections for different decay time ranges are shown in Fig. 7.

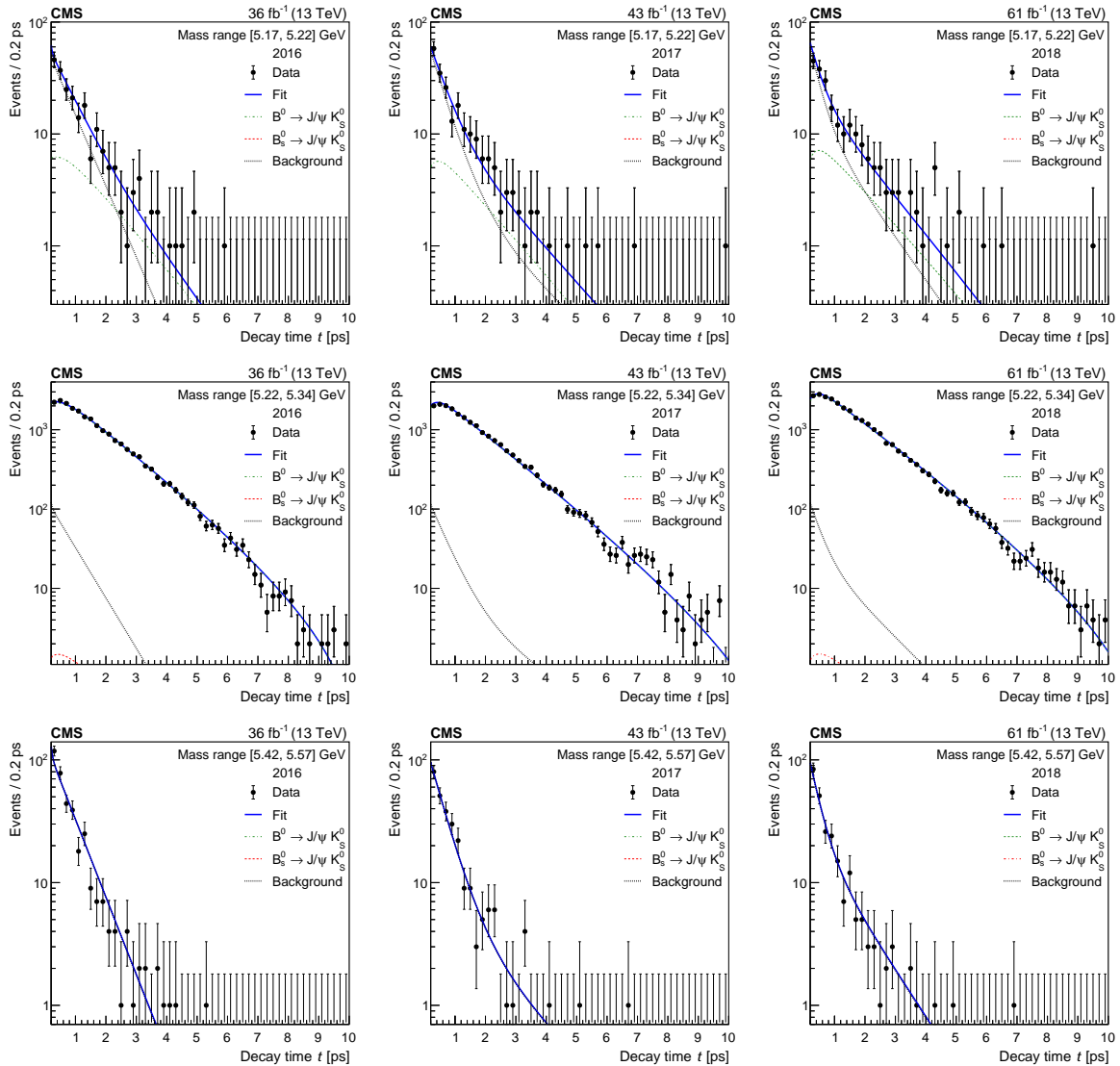


Figure 6: The decay time distribution for events with  $J/\psi K_S^0$  invariant mass in the range  $5.17 < m < 5.22$  (upper),  $5.22 < m < 5.34$  (center), and  $5.42 < m < 5.57$  (lower) GeV and the fit results for the 2016 (left), 2017 (middle), and 2018 (right) data-taking years.

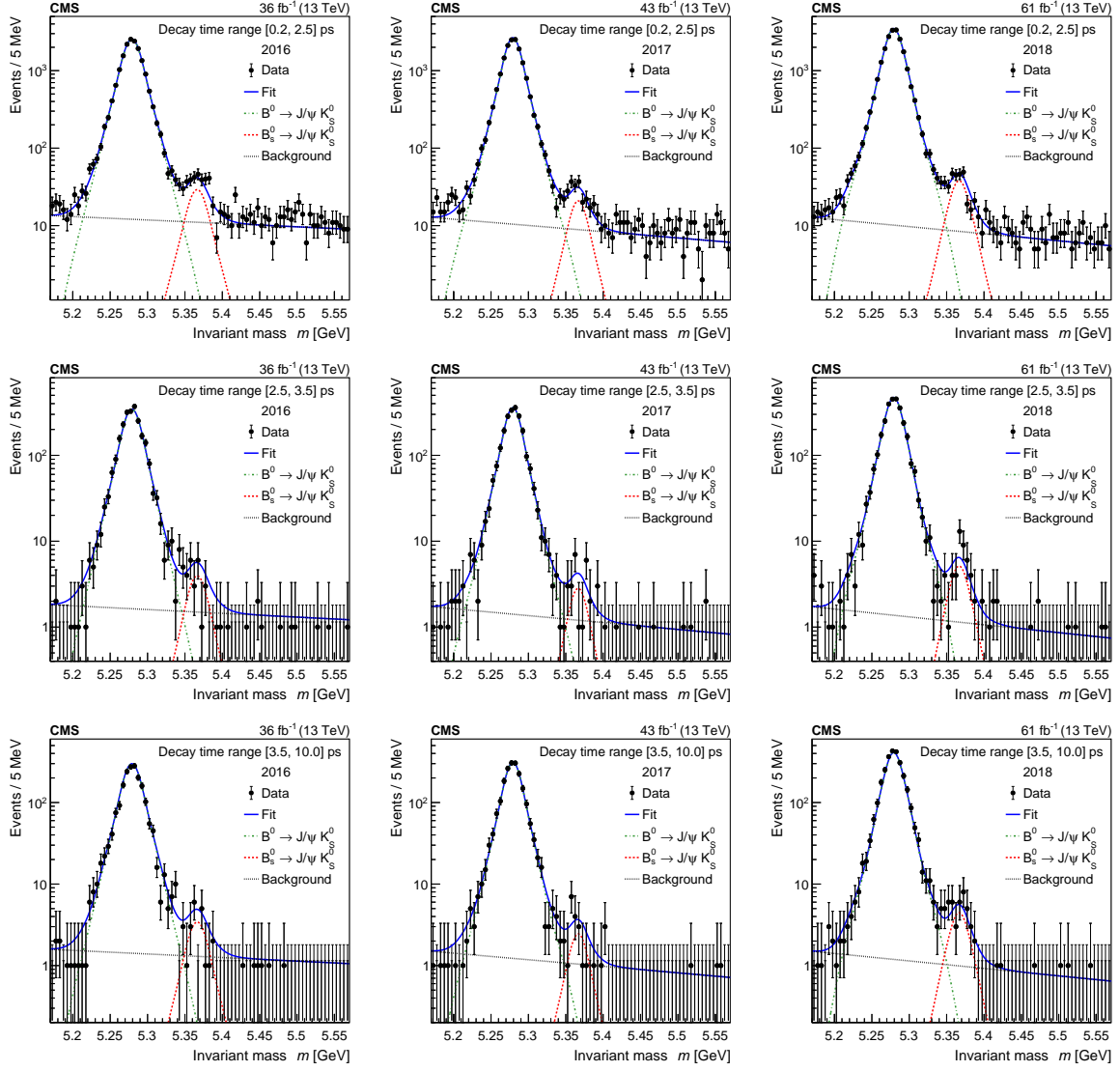




















Figure 7: The invariant mass distribution for events with  $J/\psi K_S^0$  decay time in the range  $0.2 < t < 2.5$  (upper),  $2.5 < t < 3.5$  (center), and  $3.5 < t < 10.0$  (lower) ps and the fit results for the 2016 (left), 2017 (middle), and 2018 (right) data-taking years.

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








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








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





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




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












### 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

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
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S. Keshri , D. Laroze , S. Thakur 













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A. Lotfy , M.A. Mahmoud 
















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H. Kirschenmann , K. Osterberg , M. Voutilainen 



















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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 




























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












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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<sup>21</sup> , P. Simkina , M. Titov , M. Tornago 

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























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




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V. Botta , S. Consuegra Rodríguez , L. Feld , K. Klein , M. Lipinski , D. Meuser , A. Pauls , D. Pérez Adán , N. Röwert , M. Teroerde 











































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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 Araujo<sup>24</sup> , S. Wiedenbeck , S. Zaleski







































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C. Dziwok , G. Flügge , T. Kress , A. Nowack , O. Pooth , A. Stahl , T. Ziemons , A. Zotz 










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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<sup>25</sup> , K. Borras<sup>26</sup> , A. Campbell , A. Cardini , C. Cheng, F. Colombina , G. Eckerlin, D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo<sup>25</sup> , 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<sup>27</sup> , W. Lohmann<sup>28</sup> , 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. Otariid, J. Park , E. Ranken , A. Raspereza , D. Rastorguev , J. Rübenach, L. Rygaard, A. Saggio , M. Scham<sup>29,26</sup> , S. Schnake<sup>26</sup> , P. Schütze , C. Schwanenberger<sup>25</sup> , 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<sup>26</sup> , C. Wissing , Y. Yang , A. Zimmermann Castro Santos 




























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



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












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








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H. Bakhshiansohi<sup>42</sup> , A. Jafari<sup>43</sup> , M. Zeinali<sup>44</sup> 




























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
**University College Dublin, Dublin, Ireland**

M. Felcini , M. Grunewald 






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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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








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















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







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









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<sup>77</sup> , K. Walkingshaw Pass




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





#### **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<sup>79</sup> , 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<sup>80</sup> , 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<sup>30</sup> , M. Vojinovic , N. Wardle , D. Winterbottom 






#### **Brunel University, Uxbridge, United Kingdom**

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











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S. Abdullin , A. Brinkerhoff , E. Collins , M.R. Darwish<sup>81</sup> , J. Dittmann , K. Hatakeyama , J. Hiltbrand , B. McMaster , J. Samudio , S. Sawant , C. Sutantawibul , J. Wilson 



















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R. Bartek , A. Dominguez , C. Huerta Escamilla, A.E. Simsek , R. Uniyal , A.M. Vargas Hernandez 


















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B. Bam , A. Buchot Perraguin , R. Chudasama , S.I. Cooper , C. Crovella , S.V. Gleyzer , E. Pearson, C.U. Perez , P. Rumerio<sup>82</sup> , E. Usai , R. Yi 






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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 

























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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 

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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 
















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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















#### California Institute of Technology, Pasadena, California, USA

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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











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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 
























#### **Florida State University, Tallahassee, Florida, USA**

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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B. Alsufyani, M.M. Baarmand , S. Butalla , S. Das , T. Elkafrawy<sup>87</sup> , M. Hohlmann , E. Yanes












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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 
























#### **The University of Iowa, Iowa City, Iowa, USA**

M. Alhousseini , D. Blend, K. Dilsiz<sup>88</sup> , L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili<sup>89</sup> , O. Neogi, H. Ogul<sup>90</sup> , Y. Onel , A. Penzo , C. Snyder, E. Tiras<sup>91</sup> 









#### **Johns Hopkins University, Baltimore, Maryland, USA**

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. Popescu<sup>92</sup> , 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. Popova<sup>93</sup> , 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 












**University of Minnesota, Minneapolis, Minnesota, USA**

B. Crossman , B.M. Joshi , C. Kapsiak , M. Krohn , D. Mahon , J. Mans ,  
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















**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 








**State University of New York at Buffalo, Buffalo, New York, USA**

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

























**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

















**University of Notre Dame, Notre Dame, Indiana, USA**

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<sup>16</sup> , H. Nelson , M. Osherson , A. Piccinelli , R. Ruchti ,  
A. Townsend , Y. Wan, M. Wayne , H. Yockey, M. Zarucki , L. Zygalá 

**The Ohio State University, Columbus, Ohio, USA**

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, USA**

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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S. Malik 

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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. Viridi , F. Wang ,  
A. Wildridge , W. Xie , Y. Yao 

**Purdue University Northwest, Hammond, Indiana, USA**

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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A. Bodek , P. de Barbaro , R. Demina , J.L. Dulemba , A. Garcia-Bellido , O. Hindrichs , A. Khukhunaishvili , N. Parmar, P. Parygin<sup>93</sup> , R. Taus 















**Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA**

B. Chiarito, J.P. Chou , S.V. Clark , D. Gadkari , Y. Gershtein , E. Halkiadakis , M. Heindl , C. Houghton , D. Jaroslowski , 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 

**University of Tennessee, Knoxville, Tennessee, USA**

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, USA**

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

**Texas Tech University, Lubbock, Texas, USA**

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, USA**

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, USA**

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





























































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













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