



# Evidence for $CP$ violation and measurement of $CP$ -violating parameters in $B_s^0 \rightarrow J/\psi \phi(1020)$ decays in $pp$ collisions at $\sqrt{s} = 13$ TeV

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## Abstract

A pioneering machine-learning-based flavor-tagging algorithm combining same-side and opposite-side tagging is used to obtain the equivalent of 27 500 tagged  $B_s^0 \rightarrow J/\psi \phi(1020)$  decays from  $pp$  collisions at  $\sqrt{s} = 13$  TeV, collected by the CMS experiment and corresponding to an integrated luminosity of  $96.5 \text{ fb}^{-1}$ . A time- and flavor-dependent angular analysis of the  $\mu^+ \mu^- K^+ K^-$  final state is used to measure parameters of the  $B_s^0 - \bar{B}_s^0$  system. The weak phase is measured to be  $\phi_s = -73 \pm 23$  (stat)  $\pm 7$  (syst) mrad, which, combined with a  $\sqrt{s} = 8$  TeV CMS result, gives  $\phi_s = -74 \pm 23$  mrad. This value differs from zero by 3.2 standard deviations, providing evidence for  $CP$  violation in  $B_s^0 \rightarrow J/\psi \phi(1020)$  decays. All measured physics parameters are found to agree with standard model predictions where available.

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The decays of  $B_s^0$  mesons provide powerful ways to test the standard model (SM) predictions for  $CP$  violation (CPV) in the quark sector and search for new physics effects. In the SM, the weak phase  $\phi_s$ , which arises from CPV in the interference between decays with and without mixing of  $B_s^0$  mesons to a  $CP$  eigenstate, is related to the elements of the Cabibbo–Kobayashi–Maskawa quark mixing matrix [1, 2] by  $\phi_s \approx -2\beta_s = -2 \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$ , ignoring small contributions from penguin diagrams [3]. Global fits to measurements of b-hadron and kaon decays in the context of the SM predict  $-2\beta_s \approx -37 \pm 1$  mrad [4, 5]. This precise determination makes  $\phi_s$  an excellent probe for beyond-the-SM physics, as its value can be modified by the contribution of new particles to  $B_s^0$  mixing [6–8]. Several experiments have measured  $\phi_s$  via  $b \rightarrow c\bar{c}s$  transitions in  $B_s^0$  decays [9–26], with no evident deviation from SM-based predictions. This Letter presents a study of the  $B_s^0 \rightarrow J/\psi \phi(1020)$  decay to the  $\mu^+\mu^-K^+K^-$  final state using proton-proton collisions collected by the CMS experiment [27, 28] at  $\sqrt{s} = 13$  TeV during 2017–2018, corresponding to an integrated luminosity of  $96.5 \text{ fb}^{-1}$  [29–31]. This analysis introduces a pioneering flavor-tagging algorithm, which combined with the use of additional trigger paths compared to the results in Ref. [15], provides the largest effective number of tagged signal candidates ever used for a single measurement of  $\phi_s$ . A combination of this result with the one obtained by CMS at  $\sqrt{s} = 8$  TeV [14] is also presented. In this Letter, wherever a particle or its decay mode is specified, the charge conjugate is also implied unless otherwise indicated.

The  $B_s^0 \rightarrow J/\psi \phi(1020)$  decay proceeds through a mixture of  $CP$  eigenstates, which requires an amplitude analysis to separate the  $CP$ -odd and  $CP$ -even components. A time-dependent angular analysis is performed in the transversity basis [32] by measuring the decay angles of the final-state particles  $\Theta = (\theta_T, \psi_T, \varphi_T)$  and  $ct$ , which is the proper decay time of the reconstructed  $B_s^0$  meson candidate, as described in Refs. [15, 33]. In the transversity basis, a reference frame is chosen such that the  $x$  axis aligns with the  $\phi(1020)$  momentum, and the  $x$ - $y$  plane is the  $\phi(1020) \rightarrow K^+K^-$  decay plane. The polar and azimuthal angles of the  $\mu^+$  in the  $J/\psi$  rest frame are denoted  $\theta_T$  and  $\varphi_T$ , respectively. The helicity angle  $\psi_T$ , computed in the  $\phi(1020)$  rest frame, is the angle between the  $K^+$  momentum and the direction of negative  $J/\psi$  momentum. The three decay angles are illustrated in Fig. 1 (left). The decay rate formalism used to describe the distribution of final-state particles is the same as in previous CMS results [14, 15]. The CPV in the  $B_s^0 - \bar{B}_s^0$  system is described by the complex parameter  $\lambda = (q/p)(\bar{A}_f/A_f)$ , where  $A_f$  ( $\bar{A}_f$ ) is the decay amplitude of the  $B_s^0$  ( $\bar{B}_s^0$ ) meson to the final state  $f$ , and the parameters  $p$  and  $q$  relate the heavy and light mass eigenstates to the flavor eigenstates through  $B_s^{L(H)} = p|B_s^0\rangle \pm q|\bar{B}_s^0\rangle$  [34]. The parameters of interest (POIs) describing the decay rate are the weak phase  $\phi_s$ ; the decay width and absolute mass differences between the  $B_s^0$  mass eigenstates  $\Delta\Gamma_s$  and  $\Delta m_s$ ; their average decay width  $\Gamma_s$ ; the direct CPV observable  $|\lambda|$ ; the longitudinal, parallel, and perpendicular transversity amplitudes  $A_0$ ,  $A_{\parallel}$ , and  $A_{\perp}$ ; and the corresponding ( $CP$  conserving) strong phases  $\delta_0$ ,  $\delta_{\parallel}$ , and  $\delta_{\perp}$ . Possible contributions from  $B_s^0 \rightarrow J/\psi f_0(980)$  and nonresonant  $B_s^0 \rightarrow J/\psi K^+K^-$  decays are taken into account by including an additional  $S$ -wave term in the decay model, parametrized with amplitude  $A_S$  and phase  $\delta_S$ . An effective coupling factor is required to model the  $S$ - $P$  wave interference due to the lack of a  $m(K^+K^-)$  parametrization in the fit model. Within the  $m(K^+K^-)$  range used in this analysis (1009.5–1039.5 MeV), we calculate this correction to be  $k_{SP} = 0.538 \pm 0.004$  by integrating the mass lineshape interference term. A relativistic Breit–Wigner distribution and a constant distribution are assumed to describe the  $P$ - and  $S$ -wave, respectively, with alternative assumptions used to estimate the  $k_{SP}$  uncertainty. To simplify the decay model, the value of  $\delta_0$  is set to zero, following a general convention [10, 12], and the value of  $\Delta\Gamma_s$  is constrained to be positive, based on Ref. [35]. To reduce correlations,  $\delta_{S\perp} \equiv \delta_S - \delta_{\perp}$  is used instead of  $\delta_S$ , as only phase differences have physical meaning.

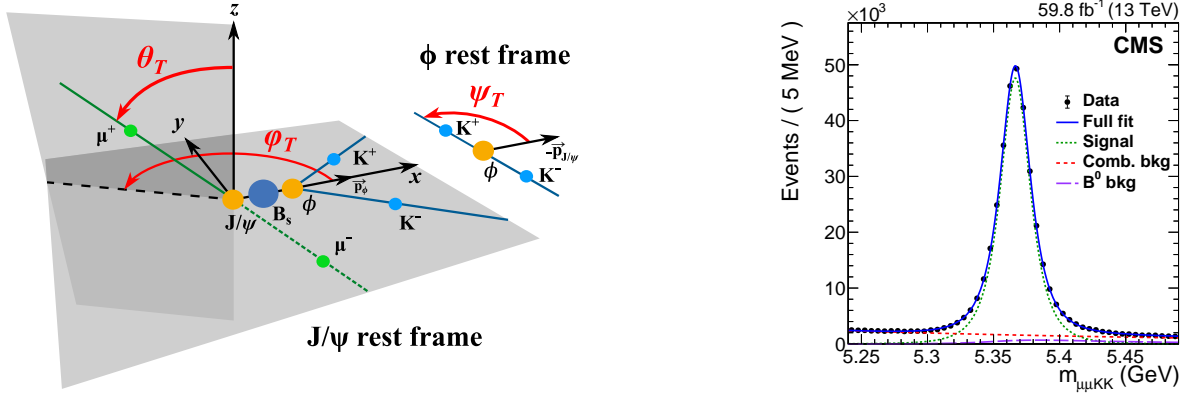


Figure 1: Left: Definition of the three decay angles  $\theta_T$ ,  $\psi_T$ , and  $\phi_T$ . Right: Invariant mass distribution and fit projection of the selected candidates for the ST trigger category (2018 data).

The CMS apparatus is a multipurpose, nearly hermetic detector, designed to perform a wide range of particle physics measurements. The  $B_s^0 \rightarrow J/\psi \phi(1020) \rightarrow \mu^+\mu^- K^+K^-$  data sample (“ $B_s^0$  data sample”) is collected with two independent triggers [36]. The first trigger (“muon-tagging”, MT) requires a  $J/\psi \rightarrow \mu^+\mu^-$  candidate along with an additional muon, potentially usable for flavor tagging [14]. In the second trigger, (“standard”, ST), events with a displaced  $J/\psi \rightarrow \mu^+\mu^-$  candidate in conjunction with a  $\phi(1020) \rightarrow K^+K^-$  vertex are demanded. To avoid double counting, events collected by the MT trigger are not considered in the ST trigger. To improve the signal purity, additional selection requirements are applied, including a requirement of  $ct > 60$  (100)  $\mu\text{m}$  for the MT (ST) triggered events. A total of 67 908 and 555 213 candidates are selected from the MT and ST triggered events, respectively. The distributions for the invariant mass  $m_{\mu\mu KK}$ ,  $ct$ , and its uncertainty  $\sigma_{ct}$  of the selected candidates in the ST trigger category (2018 data) are shown in Figs. 1 (right) and 2 (left and center). Appendices A and B provide a more detailed description of the experimental setup and event reconstruction, while distributions for the other data samples can be found in the Appendix C.

The flavor of the  $B_s^0$  meson candidate, i.e., its particle or antiparticle state at production is determined using a novel flavor-tagging framework developed for this measurement. It consists of four separate tagging algorithms (“taggers”): opposite-side (OS) muon, OS electron, OS jet, and same-side (SS). The OS taggers infer the flavor of the b quark contained in the signal b meson by exploiting the decay products of the other b quark in the event, relying on the fact that b quarks are predominantly produced in  $b\bar{b}$  pairs. The SS tagger takes advantage of the charge correlations between the b quark in the signal b meson and nearby particles produced in its hadronization, which reflect the underlying flavor content. Each tagging algorithm produces a tagging inference  $\zeta_{\text{tag}} = 0, +1, -1$ , indicating whether the event is untagged, tagged as  $B_s^0$  or  $\bar{B}_s^0$ . For tagged events, the algorithm also estimates the mistag probability  $\omega_{\text{tag}}$ . The tagging efficiency ( $\epsilon_{\text{tag}}$ ) represents the fraction of tagged events, while the dilution factor  $\mathcal{D}_{\text{tag}} \equiv 1 - 2\omega_{\text{tag}}$  quantifies the inference purity. The tagging power  $P_{\text{tag}} \equiv \epsilon_{\text{tag}} \mathcal{D}_{\text{tag}}^2$  combines these parameters and reflects the effective number of correctly tagged signal events ( $N_{B_s^0} P_{\text{tag}}$ ), contributing to flavor-sensitive measurements.

All four taggers are used for the ST data sets, while only the OS muon algorithm is used in the MT ones. The OS taggers are designed to be orthogonal to each other, meaning only one can provide an inference for each event. To improve performance,  $\omega_{\text{tag}}$  is estimated on a per-event basis by dedicated deep neural networks (DNNs) developed using simulated events and calibrated in data. For the OS-jet and SS taggers, the same DNNs are also used to infer  $\zeta_{\text{tag}}$ .

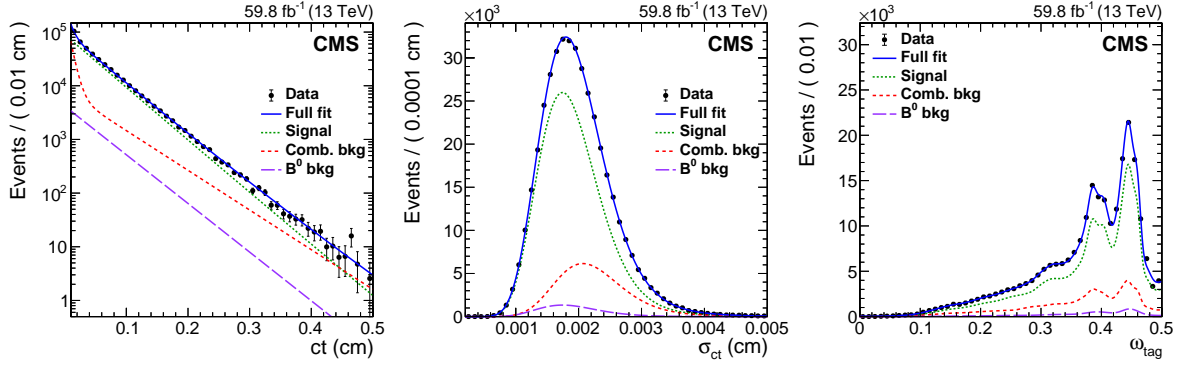


Figure 2: Distributions of the proper decay time  $ct$ , its uncertainty  $\sigma_{ct}$ , and mistag probability  $\omega_{\text{tag}}$  of the selected candidates for the ST trigger category (2018 data). The projections of the fitted model are also shown.

These calibrated DNNs act as probability estimators for the tagging inference. When an OS and the SS algorithm both provide tagging inferences,  $\zeta_{\text{tag}}$  and  $\omega_{\text{tag}}$  are recalculated by combining the available information. B provides more details about the tagging algorithms.

The combined tagging performance for the  $B_s^0$  data sample is  $\varepsilon_{\text{tag}} \approx 56\%$  and  $P_{\text{tag}} \approx 5.6\%$ . The performance breakdown in each mutually exclusive tagging category is reported in Table 3. The mistag probability distribution of the selected candidates for the ST trigger category (2018 data) is shown in Fig. 2 (right).

The flavor-tagging is validated with extensive studies on simulated data and  $B^0 \rightarrow J/\psi K^*(892)^0 \rightarrow \mu^+\mu^- K^+\pi^-$  events (“ $B^0$  control data sample”). Several measurements are performed on this sample to ensure that the tagging inference is reliable and free from significant bias. To test the robustness of the tagging framework in mixing scenarios,  $B^0$  flavor oscillations are analyzed. Using the tagging framework, the fitted value of the oscillation frequency is  $\Delta m_d = 0.5081 \pm 0.0046$  (stat)  $\hbar\text{ps}^{-1}$ , which is in excellent agreement with the world-average value of  $0.5069 \pm 0.0019 \hbar\text{ps}^{-1}$  [33]. The time-integrated mixing asymmetry in the  $B^0$  control data sample is also examined, to investigate possible issues with the overall tagging calibration scale of the SS tagger. This is done by comparing the relationship between the measured mixing asymmetry and the estimated tagging dilution. The observed experimental dilution is found to be consistent with the estimated value. All validation studies are conducted using each tagger independently and in each tagging category, as well as using the tagging inference from the overall framework. Moreover, the CPV measurement in the  $B_s^0 \rightarrow J/\psi \phi(1020)$  channel is repeated four additional times, each using only one of the four tagging algorithms, and the obtained results are compared. No evidence of bias has been found in any of the studies.

The  $B_s^0$  data are divided into four main data sets according to the two trigger categories and two data taking years, and further divided into a total of 12 data sets based on the three possible values of  $\zeta_{\text{tag}}$ . The POIs:  $\phi_s$ ,  $\Delta\Gamma_s$ ,  $\Gamma_s$ ,  $\Delta m_s$ ,  $|\lambda|$ ,  $|A_0|^2$ ,  $|A_\perp|^2$ ,  $|A_S|^2$ ,  $\delta_\parallel$ ,  $\delta_\perp$ , and  $\delta_{S\perp}$ , are extracted with a simultaneous unbinned multidimensional extended maximum likelihood fit to the  $B_s^0$  data sets using seven observables as input:  $m_{\mu\mu KK}$ ,  $ct$ ,  $\sigma_{ct}$ ,  $\cos\theta_T$ ,  $\cos\psi_T$ ,  $\varphi_T$ , and  $\omega_{\text{tag}}$ . The  $B_s^0 \rightarrow J/\psi \phi(1020)$  amplitudes are normalized to unity with the constraint  $|A_\parallel|^2 \equiv 1 - |A_\perp|^2 - |A_0|^2$ . The likelihood function is composed of probability density functions (pdfs) describing the  $B_s^0 \rightarrow J/\psi \phi(1020)$  signal, the combinatorial background, and the background from  $B^0 \rightarrow J/\psi K^*(892)^0 \rightarrow \mu^+\mu^- K^+\pi^-$  where the pion is misidentified as a kaon (“ $B^0$  background”). For each component, the pdf is the product of functions that model the distributions of the seven observables of the reconstructed candidates. Correlations between the input observables

have been studied in data and simulation and found to have a negligible effect. The  $B_s^0 \rightarrow J/\psi \phi(1020)$  differential decay rate model utilized in the fit includes the flavor inference  $\zeta_{\text{tag}}$  and the dilution term  $\mathcal{D}_{\text{tag}}$ . Unless specified otherwise, all pdf parameters are left free in the final fit. The fit model also includes the angular efficiency and time resolution functions. These functions are computed separately for each main data set.

The event reconstruction and selection efficiency as a function of  $ct$ ,  $\varepsilon(ct)$ , is determined from data utilizing the  $B^0$  control data sample, which exhibits a similar topology to the  $B_s^0 \rightarrow J/\psi \phi(1020)$  signal. The efficiency is parametrized using Bernstein polynomials to model the ratio between the observed  $ct$  distribution for the signal and the expected distribution convolved with the time resolution. The expected distribution is an exponential characterized by the  $B^0$  lifetime  $\tau_{B^0}^{\text{PDG}} = 1.517$  ps [33]. Residual efficiency differences between the control and measurement samples are corrected using simulation. In the fit, each event in the  $B_s^0$  data sample is weighted by  $1/\varepsilon(ct)$ . Since no dependence of the time resolution on  $ct$  is observed in simulation, the  $ct$  uncertainty is calibrated for each main data set in bins of  $\sigma_{ct}$  in a data sample of prompt events obtained by removing the displacement requirement from the MT trigger category. Most of these events consist of prompt  $J/\psi \rightarrow \mu^+ \mu^-$  decays accompanied by two tracks and are not anticipated to have a substantial lifetime. The long-lived components are properly accounted for. The negative portion of the  $ct$  distribution in this sample arises from resolution effects and is used to calibrate  $\sigma_{ct}$ . The  $ct$  uncertainty matches the experimental time resolution well, with only a uniform correction of  $+1.5 \mu\text{m}$  being needed. The calibrated  $\sigma_{ct}$  average value for signal candidates is  $\approx 20 \mu\text{m}$ . The angular efficiency functions  $\varepsilon(\Theta)$  are derived from  $B_s^0 \rightarrow J/\psi \phi(1020)$  simulated events in which  $\Delta\Gamma_s$  is set to zero to disentangle the angular and time components. These simulated samples are corrected to better match the observed data, taking into account the kinematic properties of the final-state particles and the relevant physical parameters. The angular efficiency is modeled using the Kernel Density Estimation (KDE) method [38, 39] from the reconstructed and generated angular distributions, and is incorporated in the signal pdf as a 3D histogram. All parameters describing the efficiency and time resolution calibration are fixed in the final fit.

The mass shapes for the signal and the  $B^0$  background are described by Johnson  $S_U$  distributions [40], while an exponential distribution is used for the combinatorial background. The  $\omega_{\text{tag}}$  distribution is modeled for each component using KDE distributions. For the  $B^0$  and combinatorial backgrounds, the  $ct$  component is modeled with one and two exponential distributions, respectively. The angular variables are described with Bernstein polynomials. The pdfs describing  $\sigma_{ct}$  are modeled for each component by the sum of two Gamma distributions, with their parameters fixed in the final fit based on what is obtained from a series of pre-fits. The shape of the  $B^0$  background shape is modeled in simulated  $B^0 \rightarrow J/\psi K^*(892)^0$  events reconstructed as  $B_s^0 \rightarrow J/\psi \phi(1020)$ , while the yield is measured directly in the  $B_s^0$  data sample with a simultaneous fit to the invariant mass distributions in the  $B_s^0 \rightarrow J/\psi \phi(1020)$  and  $B^0 \rightarrow J/\psi K^*(892)^0$  reconstruction hypotheses. The time resolution for the  $B^0$  background is assumed to be the same as for the  $B_s^0$  signal. All parameters related to the  $B^0$  background are fixed in the final fit. The fit model is duplicated for the four main data sets, with the individual log-likelihoods summed to obtain the full log-likelihood.

The fit model is validated with simulation, fits to individual data categories, and the parametric bootstrap method [41]; the bootstrap method is also used to assess the statistical uncertainties. This involves generating 1300 pseudo-experiments by repeatedly sampling from the fitted model. Each of these pseudo-experiments is fitted with the reference fit model, producing a set of POI values. The collection of these results forms the “bootstrap distributions”, which represent the range of possible outcomes that could be observed given the uncertainties in the

Table 1: Summary of the systematic and statistical uncertainties. The symbol (—) indicates an uncertainty that is negligible or not evaluated. The combined systematic uncertainty is the sum in quadrature of the individual uncertainties.

	$\phi_s$ [mrad]	$\Delta\Gamma_s$ [ps <sup>-1</sup> ]	$\Gamma_s$ [ps <sup>-1</sup> ]	$\Delta m_s$ [ $\hbar$ ps <sup>-1</sup> ]	$ \lambda $	$ A_0 ^2$	$ A_\perp ^2$	$ A_S ^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	$\delta_{S\perp}$ [rad]
Statistical uncertainty	23	0.0043	0.0015	0.035	0.014	0.0016	0.0021	0.0033	0.074	0.089	0.15
Fit bias	4	0.0011	0.0002	0.004	0.006	0.0012	0.0022	0.0006	0.015	0.017	0.03
Flavor tagging	4	$<10^{-4}$	0.0005	0.007	0.002	$<10^{-4}$	$<10^{-4}$	0.0006	0.012	0.016	0.03
Angular efficiency	4	0.0002	$<10^{-4}$	0.015	0.011	0.0042	0.0019	0.0001	0.017	0.044	0.02
Time efficiency	$<1$	0.0014	0.0026	$<10^{-3}$	$<10^{-3}$	0.0004	0.0005	$<10^{-4}$	0.001	0.002	$<10^{-2}$
Time resolution	$<1$	$<10^{-4}$	$<10^{-4}$	$<10^{-3}$	$<10^{-3}$	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	$<10^{-3}$	0.001	$<10^{-3}$
Model assumptions	—	0.0005	0.0006	—	—	—	—	—	—	—	—
B <sup>0</sup> background	$<1$	0.0002	0.0003	$<10^{-3}$	$<10^{-3}$	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	$<10^{-3}$	$<10^{-3}$	$<10^{-2}$
$\Lambda_b^0$ background	—	—	0.0004	—	—	0.0004	0.0003	—	—	—	—
S-P wave interference	$<1$	$<10^{-4}$	$<10^{-4}$	$<10^{-3}$	$<10^{-3}$	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	$<10^{-3}$	$<10^{-3}$	$<10^{-2}$
$P(\sigma_{ct})$ uncertainty	$<1$	0.0002	0.0003	$<10^{-3}$	$<10^{-3}$	0.0001	0.0001	$<10^{-4}$	$<10^{-3}$	$<10^{-3}$	$<10^{-2}$
Total systematic uncertainty	7	0.0019	0.0028	0.017	0.012	0.0044	0.0030	0.0009	0.025	0.050	0.05

data. The statistical uncertainty is defined as the 68.3% confidence level (CL) interval centered around the mean of the bootstrap distribution of interest. Importantly, this method helps identify any potential bias in the nominal fit (“fit bias”), which is the difference between the central value of the bootstrap distribution and the expected true value. In line with standard practices in the field [15, 20, 26], this bias is removed from the statistical uncertainty evaluation and is treated as a systematic uncertainty. The measured number of  $B_s^0 \rightarrow J/\psi \phi(1020)$  signal events from the fit is  $491\,270 \pm 950$ , corresponding to an effective number of tagged signal candidates of  $N_{B_s^0} P_{\text{tag}} = 27\,500 \pm 100$ .

The systematic uncertainties potentially impacting the POIs are categorized into two groups. Type-I uncertainties stem from the finite number of events in the simulated samples and from uncertainties related to the parameters of the efficiency and calibration functions. These uncertainties are evaluated by either sampling the function parameters based on their uncertainties or, in the case of nonparametric functions, by resampling the simulated samples. The systematic uncertainties are then quantified as the root-mean-square of the resulting POI distributions. Type-II uncertainties account for potential biases resulting from the assumptions made in the fit model and analysis methods. For each tested assumption, an alternative model choice is selected, and the fit to the data is repeated. A deviation  $\Delta_{\text{syst}}$  from the reference results is significant if it exceeds 20% of the statistical uncertainty associated with a parameter. In such cases, a double-sided systematic uncertainty of  $0.5 \Delta_{\text{syst}}$  is assigned, assuming a uniform distribution for the true bias between 0 and  $\Delta_{\text{syst}}$ . The fit bias does not fall into either of these two categories and is assessed as the mean of the bootstrap distributions with respect to the nominal results. The systematic uncertainties are summarized in Table 1.

Type-I uncertainties are evaluated for the B<sup>0</sup> background yield, the values of  $k_{SP}$  and  $\tau_{B^0}^{\text{PDG}}$ , and the parameters of the time resolution and flavor tagging calibration functions. Similarly, uncertainties arising from the fixed  $\sigma_{ct}$  pdfs in the final fit are also evaluated. Statistical uncertainties associated with the B<sup>0</sup> control data sample and  $B_s^0 \rightarrow J/\psi \phi(1020)$  simulated events, which are employed to determine the efficiency functions, are estimated using resampling techniques.

Type-II uncertainties are assigned by conducting extensive investigations and cross-verification processes to validate the model assumptions. We explore alternative hypotheses regarding the pdf shapes of the mass,  $ct$ , and angular variable distributions for both the signal and background components. Additionally, we examine alternative models for the efficiency functions to identify potential sources of bias. The impact of neglecting background from

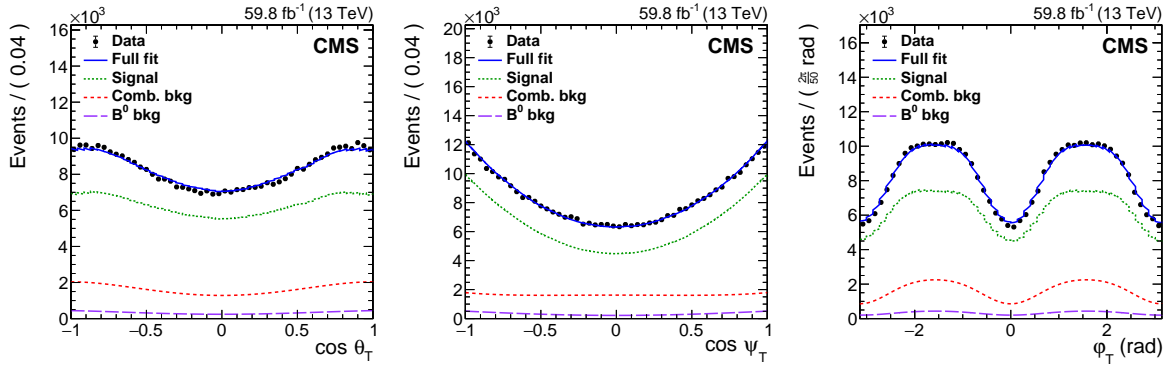


Figure 3: Angular observables distributions of the selected candidates and fit projection for the ST trigger category (2018 data). The projections of the fitted model are also shown.

Table 2: Measured values and uncertainties of the main parameters of interest.

Parameter	Fit value	Stat. unc.	Syst. unc.
$\phi_s$ [mrad]	$-73$	$\pm 23$	$\pm 7$
$\Delta\Gamma_s$ [ $\text{ps}^{-1}$ ]	$0.0761$	$\pm 0.0043$	$\pm 0.0019$
$\Gamma_s$ [ $\text{ps}^{-1}$ ]	$0.6613$	$\pm 0.0015$	$\pm 0.0028$
$\Delta m_s$ [ $\hbar \text{ps}^{-1}$ ]	$17.757$	$\pm 0.035$	$\pm 0.017$
$ \lambda $	$1.011$	$\pm 0.014$	$\pm 0.012$
$ A_0 ^2$	$0.5300$	$^{+0.0016}_{-0.0014}$	$\pm 0.0044$
$ A_{\perp} ^2$	$0.2409$	$\pm 0.0021$	$\pm 0.0030$
$ A_S ^2$	$0.0067$	$\pm 0.0033$	$\pm 0.0009$
$\delta_{\parallel}$ [rad]	$3.145$	$\pm 0.089$	$\pm 0.025$
$\delta_{\perp}$ [rad]	$2.931$	$\pm 0.089$	$\pm 0.050$
$\delta_{S\perp}$ [rad]	$0.48$	$\pm 0.15$	$\pm 0.05$

$\Lambda_b^0 \rightarrow J/\psi p K^- \rightarrow \mu^+ \mu^- p K^-$  is assessed by incorporating a dedicated component into the fit model, following an approach similar to the one for the  $B^0$  background, and repeating the fit to the  $B_s^0$  data sample. Various validation studies are carried out on the correction procedure applied to the simulated samples used to evaluate the angular efficiency. The calibration procedure for the OS tagging algorithms is evaluated using results from simulation to correct for differences between  $B_s^0 \rightarrow J/\psi \phi(1020)$  and  $B^+ \rightarrow J/\psi K^+$  decays. The calibration for the SS tagger already accounts for these differences. We investigate its calibration strategy by removing these corrections, which introduce a significant perturbation of approximately 10% to the calibration parameters, and testing the stability of the physics results in response to these changes.

The fit results, along with the associated statistical and systematic uncertainties, are provided in Table 2. The projection of the fit onto each of the seven fitted distributions for the ST trigger category (2018 data) is shown in Figs. 1, 2, and 3. The results are found to be consistent with SM-based predictions [4, 5, 42] and the latest world-average values [33]. The weak CPV phase is measured to be  $\phi_s = -73 \pm 23$  (stat)  $\pm 7$  (syst) mrad, which is within 1.5 standard deviations of the SM-based prediction. The measured value of  $|\lambda|$  is consistent with no direct CPV ( $|\lambda| = 1$ ). These results are comparable in precision to the world's most precise single measurement [20] and supersede the previous results in Ref. [15]. The results are combined with those obtained by CMS at  $\sqrt{s} = 8$  TeV [14] using the BLUE method [43, 44] to obtain  $\phi_s = -74 \pm 23$  mrad and  $\Delta\Gamma_s = 0.0780 \pm 0.0045 \text{ ps}^{-1}$ , which are both compatible with SM-based predictions. The



uncertainties include both statistical and systematic components. The full set of combined results is reported in Appendix C. Figure 4 shows the two-dimensional  $\phi_s$  vs.  $\Delta\Gamma_s$  contour at 68% CL for the combined results, alongside the SM-based prediction and the latest results from other LHC experiments. Tabulated results are provided in the HEPData record for this analysis [45]. The combined  $\phi_s$  value exhibits a deviation from zero of 3.2 standard deviations, providing the first evidence for CPV in  $B_s^0 \rightarrow J/\psi \phi(1020)$  decays.

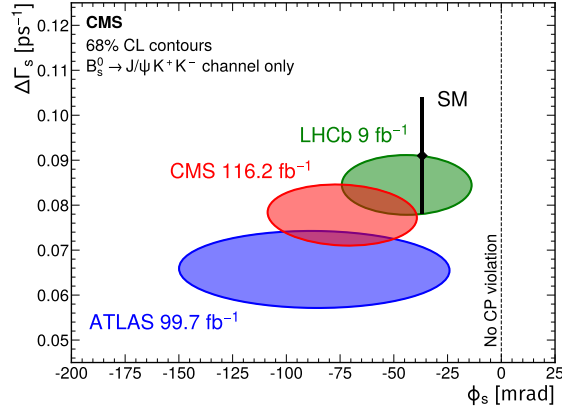


Figure 4: The two-dimensional 68% CL contours in the  $\phi_s$ - $\Delta\Gamma_s$  plane for the combined CMS (red), ATLAS (blue) [26], and LHCb (green) [20] results. Results refer only to  $B_s^0 \rightarrow J/\psi K^+ K^-$  measurements. The contours account for both statistical and systematic uncertainties. The SM prediction neglects possible contributions from higher-order penguin diagrams and is represented by the thin black band, with the central value indicated with the black diamond [4, 5, 42].

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## A The CMS detector, simulated samples, and event reconstruction

The CMS apparatus is a multipurpose, nearly hermetic detector, designed to trigger on [36, 46] and identify electrons, muons, photons, and hadrons [47–49]. A global event description algorithm [50] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon inner tracker and by the crystal electromagnetic, and a brass and scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. Simulated events are employed to determine the angular efficiency and to train the various machine-learning models. These samples are generated with the software described in Refs. [51–56] and validated via comparison with background-subtracted data in several control distributions.

To improve the purity of the signal, additional requirements are imposed on events selected by the trigger system. Muons and kaons must have pseudorapidity  $|\eta| < 2.4$  and  $|\eta| < 2.5$ , respectively. For the MT (ST) trigger category, muons are required to have transverse momentum  $p_T > 3.5$  (4.0) GeV, while tracks are required to have  $p_T > 1.15$  (0.90) GeV. The opposite-charge muons forming the  $J/\psi$  candidate are then constrained to a common vertex, obtained via a Kalman fit [57], with an invariant mass within 150 MeV of the world-average mass of the  $J/\psi$  meson [33]. The  $\phi(1020)$  meson candidates are retained only if their invariant mass, assuming both oppositely charged particles to be kaons, lies within 10 MeV of the world-average mass of the  $\phi(1020)$  meson [33]. Finally, the  $J/\psi$  and  $\phi(1020)$  mesons candidates are combined to create  $B_s^0$  meson candidates through a kinematic fitting process involving the four tracks, where the dimuon mass is constrained to the world-average  $J/\psi$  meson mass [33]. The  $B_s^0$  meson candidates are accepted if their  $p_T > 9.5$  GeV, their invariant mass is in the 5.24–5.49 GeV range, and the vertex fit  $\chi^2$  probability exceeds 2%. The primary vertex (PV) is chosen as the vertex closest to the line passing through the  $B_s^0$  decay vertex and parallel to its momentum. The  $ct$  is measured as  $ct = c m_{B_s^0}^{\text{PDG}} \vec{L}_{xy} \cdot \vec{p}_T / p_T^2$ , where  $m_{B_s^0}^{\text{PDG}}$  is the world-average  $B_s^0$  mass [33] and  $\vec{L}_{xy}$  is the vector from the PV to the  $B_s^0$  vertex in the transverse plane. The  $ct$  uncertainty  $\sigma_{ct}$  is obtained by propagating the uncertainties in  $L_{xy}$  and  $p_T$  of the  $B_s^0$  meson candidate to  $ct$ . It is required that  $ct \geq 60$  (100)  $\mu\text{m}$  for the MT (ST) trigger category, with  $\sigma_{ct} < 50 \mu\text{m}$ . Additionally, events in the ST trigger category need to satisfy  $ct/\sigma_{ct} > 3$ . In approximately 2% of the events, multiple  $B_s^0$  meson candidates are reconstructed, and in these cases the candidate with the highest vertex-fit probability is chosen.

## B Flavor tagging

The OS muon and OS electron taggers follow the same strategy. They search for semileptonic  $b \rightarrow \ell^- + X$  decays of the OS  $b$  quark, using the lepton charge as the tagging variable and subsequently employing DNNs to estimate  $\omega_{\text{tag}}$ . For each event, we search for a candidate OS lepton consistent with being produced by the OS  $b$  hadron. To reduce contamination from background sources, loose kinematic requirements are imposed on the candidates, and DNN discriminators are used to reduce contributions from hadrons and photons misreconstructed as muons and electrons, respectively. To avoid overlaps, an OS electron is searched only if no OS muon is found. In both algorithms, conditions are introduced to separate the OS lepton from the  $B_s^0$  meson candidate. An ensemble of DNNs is used to discriminate the right- and wrong-tag leptons, as well as to estimate the event mistag probability. The DNNs have been developed using simulated  $B_s^0 \rightarrow J/\psi \phi(1020)$  events and calibrated with self-tagging  $B^+ \rightarrow J/\psi K^+$  data

samples, as described below. The input features of the lepton tagging DNNs consist of variables extracted from the kinematic properties of the lepton candidate and the surrounding activity. The structure of all DNN models has been optimized to maximize the tagging power. The architecture is purposefully designed so that its output score “ $s_{\text{DNN}}$ ” corresponds directly to the probability of correctly tagging an event.

The OS jet tagger is based on DNNs, referred to collectively as “DeepJetCharge” (DJC), derived from the DEEPSETS architecture [58] and exploits charge asymmetries in OS  $b$  jets to predict the probability of being produced by  $b$  versus  $\bar{b}$  quarks. The resulting probability serves as the basis for determining both  $\zeta_{\text{tag}}$  and  $\omega_{\text{tag}}$ . An OS jet candidate is selected if it passes loose kinematic requirements, does not contain tracks from the signal  $B_s^0$ , the probability  $P_b$  of originating from a bottom or anti-bottom quark, as estimated by DEEPJET [59] exceeds 20%, and contains at least two tracks from the PV. To ensure the OS algorithms are orthogonal to each other, an OS jet is searched for only if no OS muon or OS electron is found. Features used by DJC include  $p_T$  and  $\eta$  of the  $B_s^0$  meson,  $p_T$ ,  $\eta$ , and  $P_b$  of the jet, and the angular distances  $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$  and  $\Delta\phi$  between the direction of the jet and that of the  $B_s^0$ . Features from at most 15 charged particles (ordered by the longitudinal impact parameter relative to the PV,  $IP_z$ ) are also included: charge,  $p_T$ ,  $\eta$ ,  $\Delta R$  and  $\Delta\phi$  relative to the  $B_s^0$  momentum, impact parameters with respect to the PV, and their uncertainties. Besides the jet constituents, other tracks in a  $\Delta R < 0.5$  cone around the jet axis are used to recover tracks not found by the jet reconstruction. The DJC is trained on simulated  $B_s^0 \rightarrow J/\psi \phi(1020)$  events of the ST trigger category and its structure is composed of four blocks. First, three dense layers act on every input feature except track charge, making this block explicitly flavor invariant. Then, the charge information is added and two more dense layers are executed. Subsequently, all the hidden features are summed across all tracks, flattening the track vector to a single dimension. Finally, four interlaced dense and dropout layers convert the feature vector to a probability, which is the model output. All dense layers use an exponential linear unit activation function [60]. To preserve symmetry between the two classes, that is  $b$  and  $\bar{b}$  jets, the algorithm is constructed as flavor invariant, that is the probabilities for the  $b$  hypothesis are identical to those of the  $\bar{b}$  hypothesis when inverting all the charges. This is achieved by explicitly symmetrizing the output as  $s_{\text{DJC}}(x) = [s_{\text{DJC}}(x) + (1 - s_{\text{DJC}}(\bar{x}))]/2$ , where  $x$  is the model input and  $\bar{x}$  is the input with all the track charges reversed. The output of DJC coincides with the probability of the OS jet being produced by a bottom quark, which can be straightforwardly used to perform the tagging inference and  $\omega_{\text{tag}}$  estimation.

The SS tagger, referred to as “DeepSameSide” (DSS), exploits the correlation between the quark content of the  $B_s^0$  meson at production time and the charges of the fragmentation particles surrounding it. Consequently, it is independent of the OS tag, is not diluted by mixing in the other  $b$  quark, and does not depend on the presence of its decay products from the other  $b$  quark, such as leptons or jets, within the acceptance of the CMS detector. The architecture of DSS is modeled on that of DJC (including output symmetrization), exploiting the features from the  $B_s^0$  meson candidate and all the tracks, other than its constituents, in a  $\Delta R = 0.8$  cone around its direction (care is taken to avoid geometrical overlap with the OS methods). Up to 20 tracks, ordered by  $IP_z$ , are considered; in contrast to DJC, no jet features are used. The DSS is trained on a sample of  $B_s^0$  and  $B^+$  simulated events to compute the probability of having a bottom quark at production time. The  $B^+$  events are used to render the algorithm invariant for  $B_s^0 \leftrightarrow B^-$  and  $\bar{B}_s^0 \leftrightarrow B^+$  transformation and allow the calibration in data with  $B^+ \rightarrow J/\psi K^+$  decays. The DSS exploits the charge of the particles produced in the hadronization for the discrimination, which depends on the light quark in the meson. The DSS is trained to produce the probability of an initial signal  $B_s^0$  meson, from which the tagging inference and  $\omega_{\text{tag}}$  estimation can be then



performed.

The event mistag probability, as estimated by the tagging algorithms, undergoes calibration utilizing a self-tagging data sample of  $B^+ \rightarrow J/\psi K^+$  events, where the kaon's charge corresponds to the  $B^+$  meson flavor. The calibration procedure is executed separately for each data set, by comparing the measured mistag fraction ( $\omega_{\text{meas}}$ ) with the  $\omega_{\text{tag}}$  predicted by the taggers. The  $B^+$  events are divided into bins in  $\omega_{\text{tag}}$ , and, within each bin, the count of right- and wrong-tag events is computed independently on the  $J/\psi K^+$  invariant mass distribution to derive the corresponding  $\omega_{\text{meas}}$  value. The  $(\omega_{\text{tag}}, \omega_{\text{meas}})$  pairs are then used to refine the DNNs' predictions through the Platt scaling method [61]. This method fits a linear function to the model's output before the final sigmoid layer, effectively calibrating the predicted probabilities to the measured outcomes. In the case of the OS lepton taggers, both parameters of the linear function are left free to float, while for the OS jet and SS tagger, the constant term is set to zero to preserve symmetry between the two flavor hypotheses. The calibration of DSS is further corrected to account for potential differences between  $B_s^0$  and  $B^+$  mesons by using the calibrations obtained in simulated  $B_s^0 \rightarrow J/\psi \phi(1020)$  and  $B^+ \rightarrow J/\psi K^+$  events. The size of this correction is found to be of the order of 10%. For the OS-jet and SS tagger, events with  $\omega_{\text{tag}} > 0.48$  and  $\omega_{\text{tag}} > 0.46$ , respectively, are classified as untagged. These events contribute minimally to the performance, and their removal enhances the calibration reliability.

All tagging DNNs are developed in simulated events and employ the cross-entropy loss function combined with the Adam optimizer [62]. Input features are preprocessed so that the mean and variance for each of the input variables are, respectively, zero and one. The four tracks forming the  $B_s^0$  meson candidate are explicitly excluded from consideration by the taggers and precautions are taken to reduce the effect of multiple collisions in the same or neighboring bunch crossings.

The combined performance of the tagging framework yields a tagging power of  $P_{\text{tag}} = (5.59 \pm 0.02)\%$ . The tagging efficiency, tagging power, and effective dilution for each exclusive tagging category are presented in Table 3.

Table 3: Calibrated flavor tagging performance as measured in the  $B_s^0$  data sample in the various mutually exclusive categories. The effective dilution  $\mathcal{D}_{\text{tag,eff}}^2$  is obtained from the measured tagging efficiency  $\varepsilon_{\text{tag}}$  and tagging power  $P_{\text{tag}}$ . The uncertainties are statistical only.

Category	$\varepsilon_{\text{tag}}$ [%]	$\mathcal{D}_{\text{tag,eff}}^2$	$P_{\text{tag}}$ [%]
Only OS muon	$6.07 \pm 0.05$	0.212	$1.29 \pm 0.07$
Only OS electron	$2.72 \pm 0.02$	0.079	$0.214 \pm 0.004$
Only OS jet	$5.16 \pm 0.03$	0.045	$0.235 \pm 0.003$
Only SS	$33.12 \pm 0.07$	0.080	$2.64 \pm 0.01$
SS + OS muon	$0.62 \pm 0.01$	0.202	$0.125 \pm 0.003$
SS + OS electron	$2.77 \pm 0.02$	0.150	$0.416 \pm 0.005$
SS + OS jet	$5.40 \pm 0.03$	0.124	$0.671 \pm 0.006$
Combined	$55.9 \pm 0.1$	0.100	$5.59 \pm 0.02$





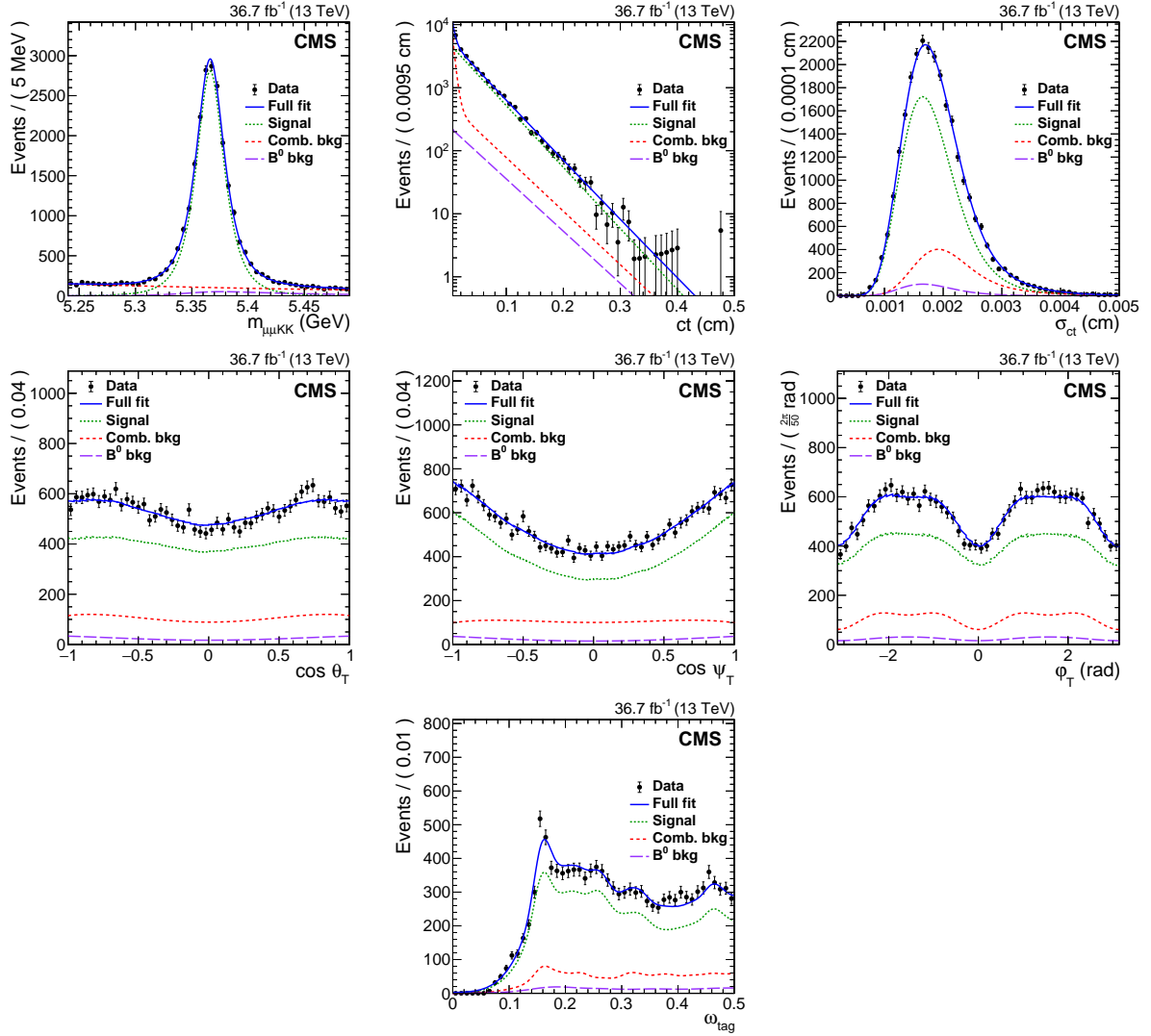


Figure C.1: The distributions for the input observables of the selected candidates and the projections from the fit for the MT trigger category (2017 data).

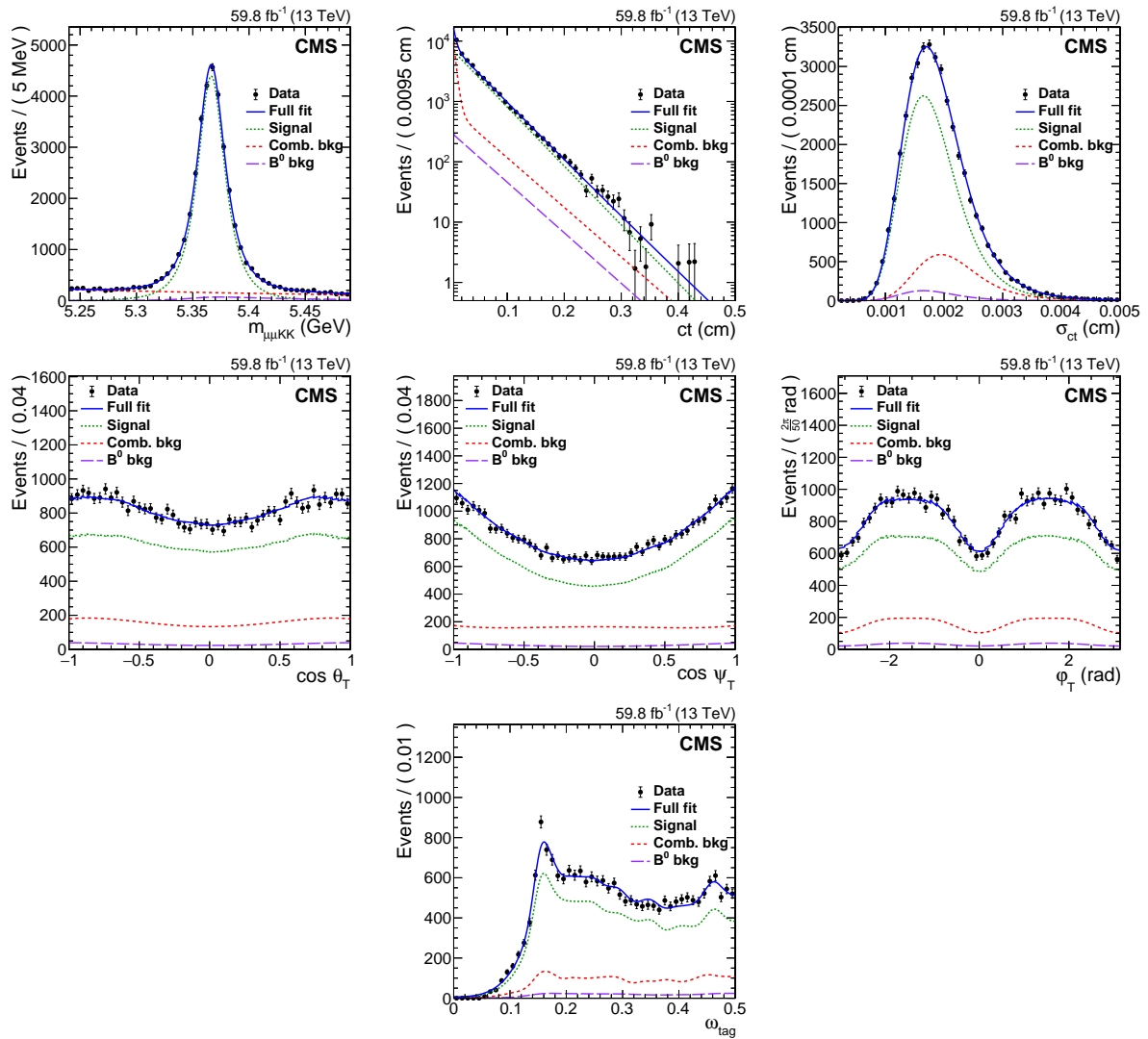


Figure C.2: The distributions for the input observables of the selected candidates and the projections from the fit for the MT trigger category (2018 data).

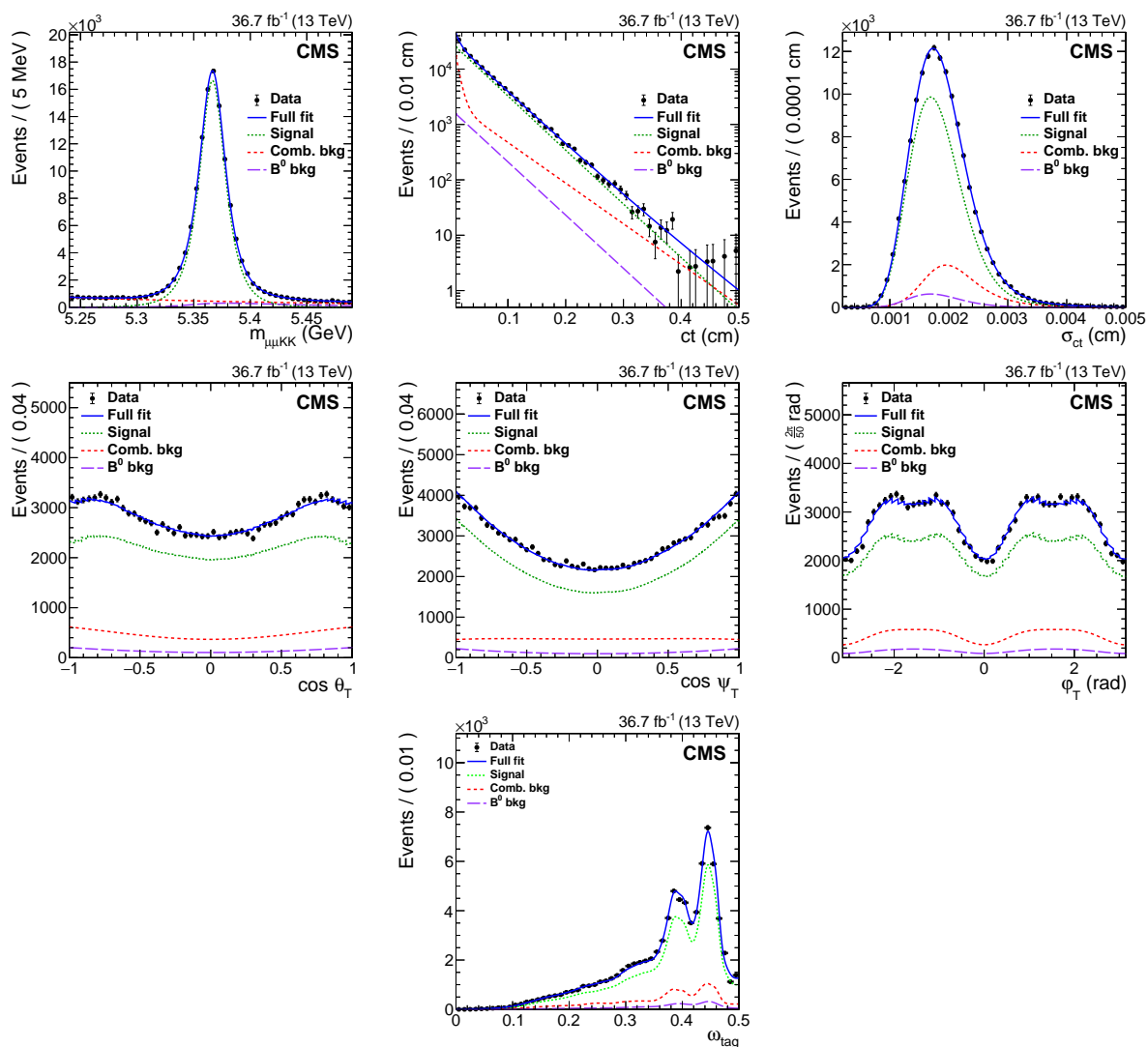


Figure C.3: The distributions for the input observables of the selected candidates and the projections from the fit for the ST trigger category (2017 data).

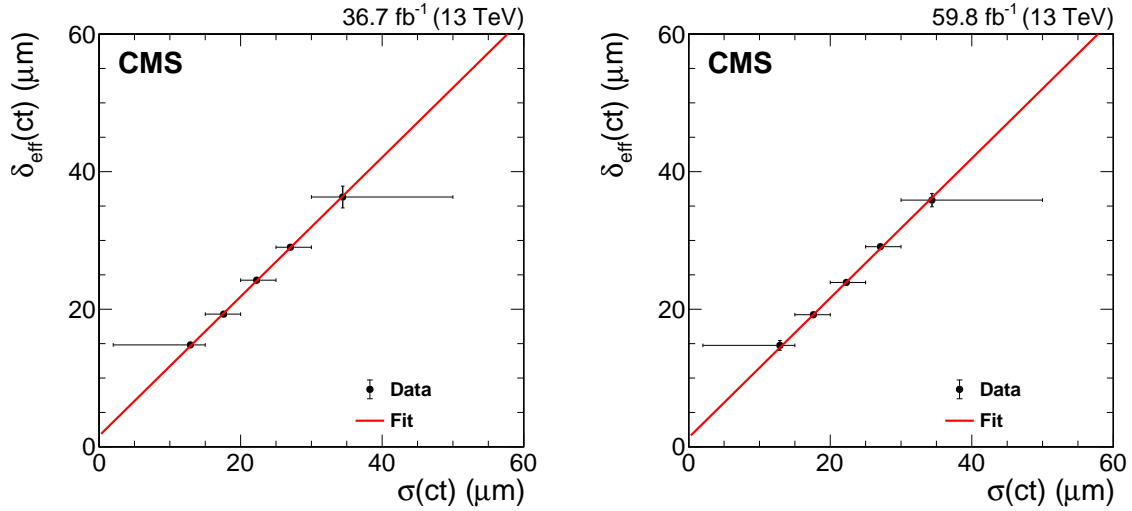


Figure C.4: The  $ct$  uncertainty calibration fits for the 2017 (left) and 2018 (right) data samples. The measured effective  $ct$  resolution is plotted versus the average (calculated) value of  $\sigma_{ct}$  in bins of  $\sigma_{ct}$ . The results of a fit to a line are shown with a solid red line. The horizontal error bars indicate the bins' edges and are not used in the fit.

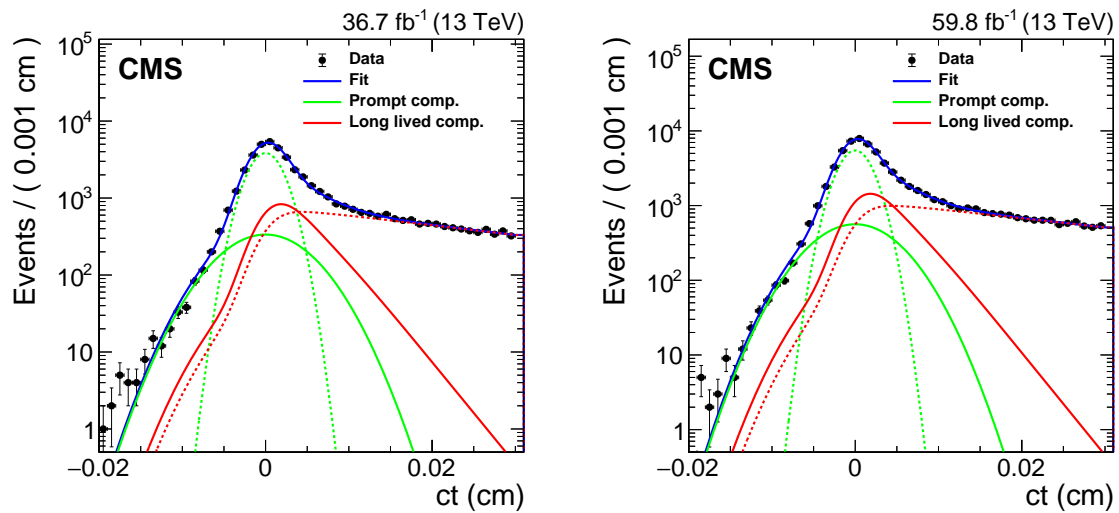


Figure C.5: Proper decay time distribution of prompt events in the MT trigger category for 2017 (left) and 2018 (right) data. The two components of the resolution function are modeled with Gaussian distributions and shown in green. The resolution function is the model for the prompt component, and the long lived components, shown in red, are modeled as two exponential distributions convoluted with the resolution function.

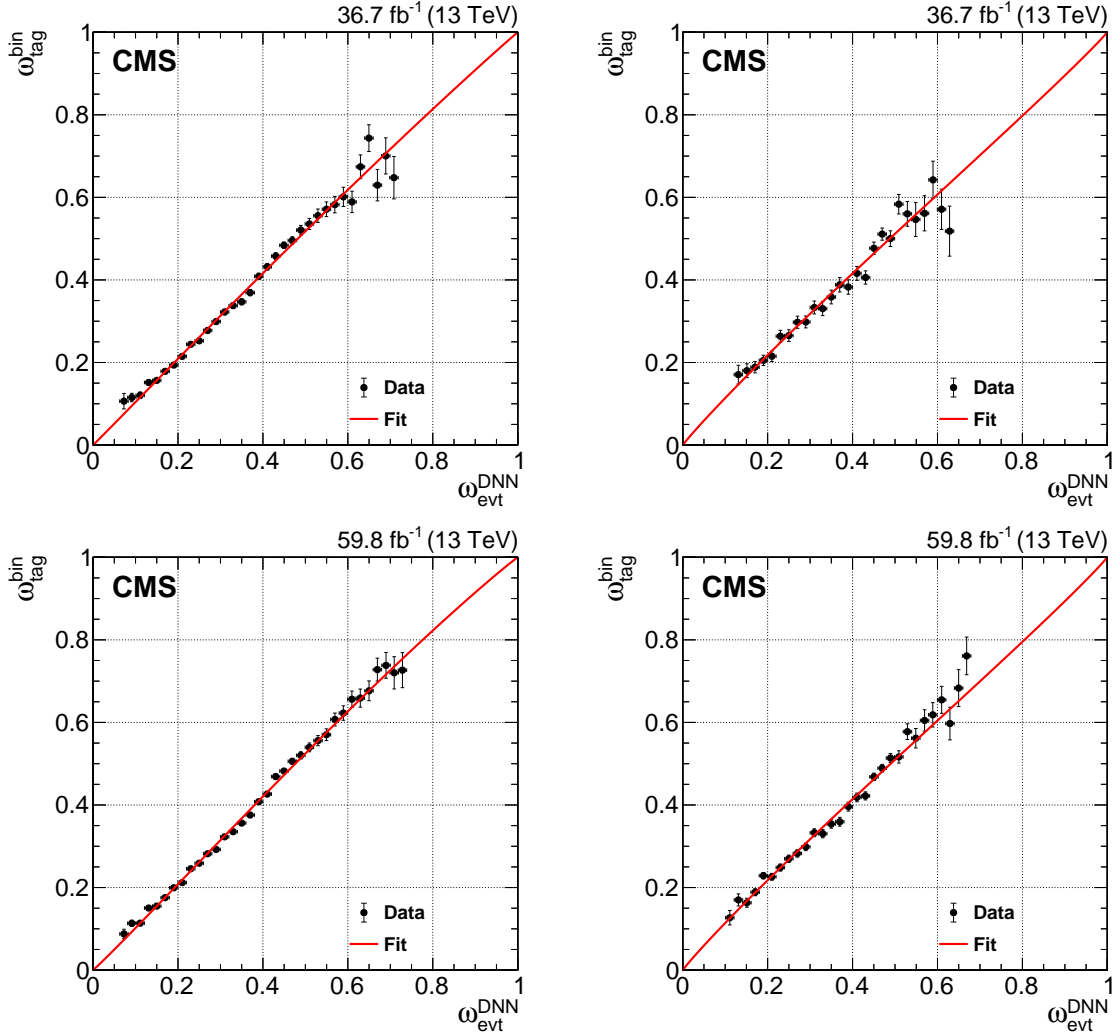


Figure C.6: Results of the mistag probability calibration fit for the OS-muon tagger on  $B^+ \rightarrow J/\psi K^+$  decays for 2017 (top row) and 2018 (bottom row) data. The measured mistag probability is plotted versus the value predicted by the tagging algorithm. The solid red line shows the results of the Platt scaling calibration fit to data. The calibration model is a linear function applied to the tagger DNN's output before the final sigmoid layer. The plots in the left column refer to the MT trigger category, while the ones in the right column to the ST trigger category.



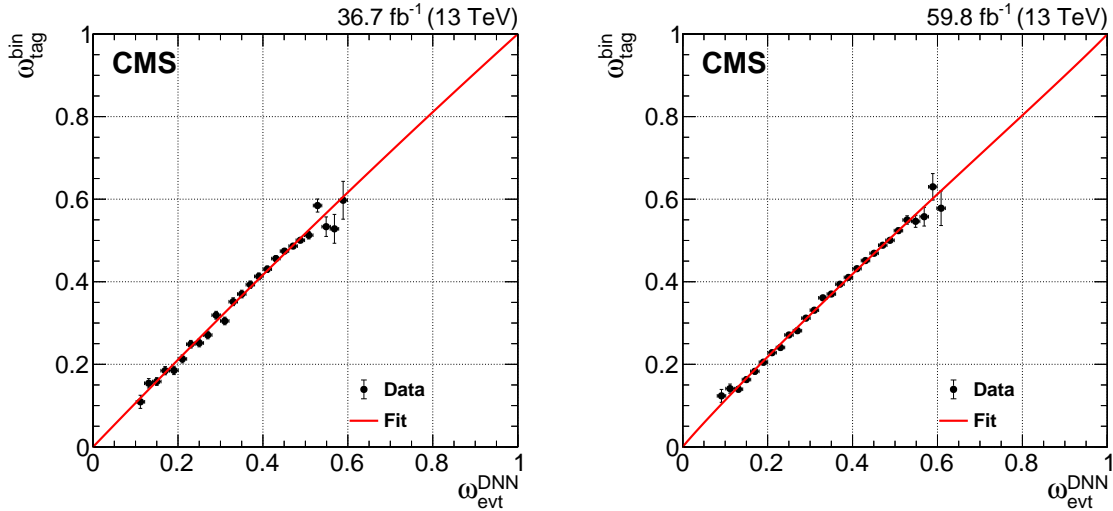


Figure C.7: Results of the mistag probability calibration fit for the OS-electron tagger on  $B^+ \rightarrow J/\psi K^+$  decays for 2017 (left) and 2018 (right) data. The measured mistag probability is plotted versus the value predicted by the tagging algorithm. The solid red line shows the results of the Platt scaling calibration fit to data. The calibration model is a linear function applied to the tagger DNN's output before the final sigmoid layer.

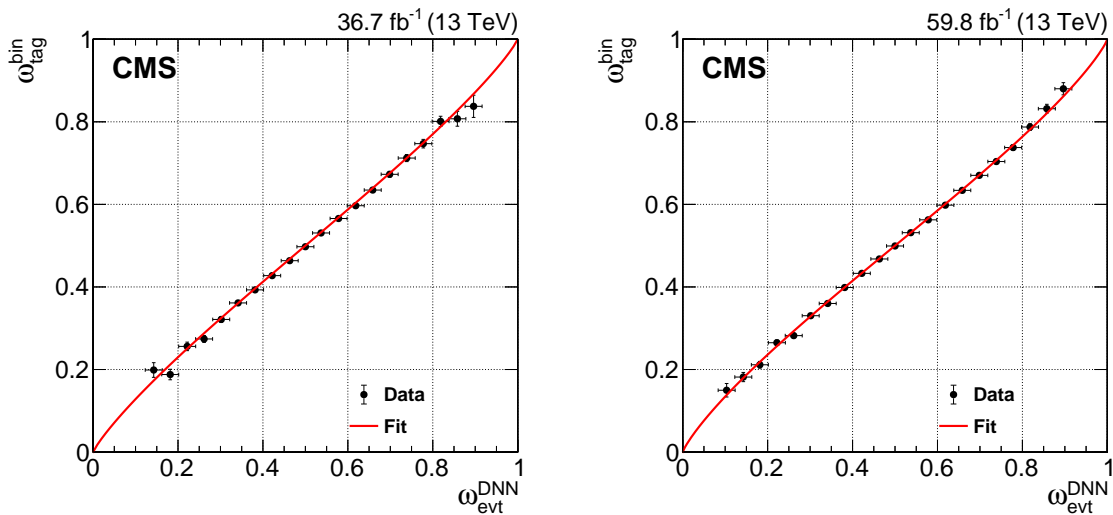


Figure C.8: Results of the mistag probability calibration fit for the OS-jet tagger on  $B^+ \rightarrow J/\psi K^+$  decays for 2017 (left) and 2018 (right) data. The measured mistag probability is plotted versus the value predicted by the tagging algorithm. The solid red line shows the results of the Platt scaling calibration fit to data. The calibration model is a linear function with the intercept fixed to 0 applied to the tagger DNN's output before the final sigmoid layer.

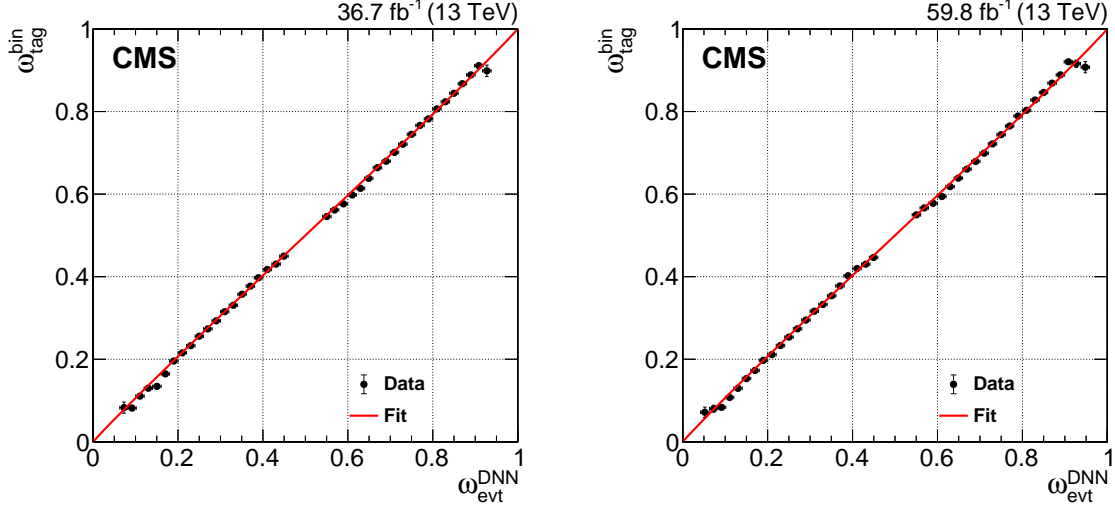


Figure C.9: Results of the mistag probability calibration fit for the SS tagger on  $B^+ \rightarrow J/\psi K^+$  decays for 2017 (left) and 2018 (right) data. The measured mistag probability is plotted versus the value predicted by the tagging algorithm. The solid red line shows the results of the Platt scaling calibration fit to data. The calibration model is a linear function with the intercept fixed to 0 applied to the tagger DNN's output before the final sigmoid layer.

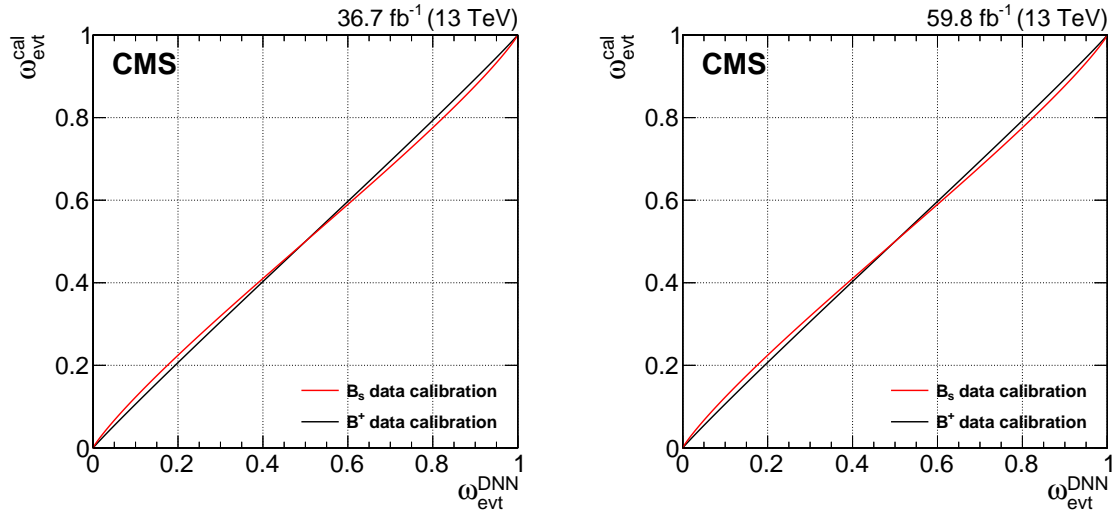


Figure C.10: Comparison of the calibration curves before (black,  $B^+$ ) and after (red,  $B_s^0$ ) the application of the corrections from simulation to the calibration obtained in  $B^+ \rightarrow J/\psi K^+$  decays. The left plot refers to 2017 data, while the right one to 2018 data. The red function is the one used as calibration for the CPV measurement.

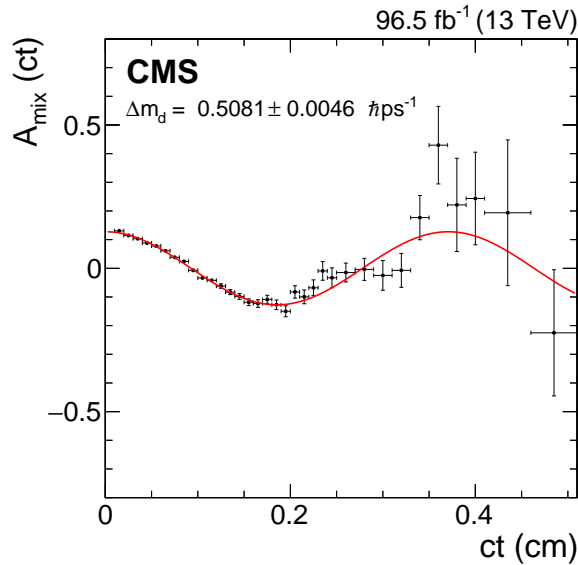


Figure C.11: The  $B^0$  mixing asymmetry as a function of the proper decay time as measured in the  $B^0 \rightarrow J/\psi K^*(892)^0$  control data sample as a validation to the tagging framework. The measured oscillation frequency is consistent with the world-average value  $\Delta m_d^{\text{PDG}} = 0.5069 \pm 0.0019 \text{ } \hbar \text{ps}^{-1}$  [33].

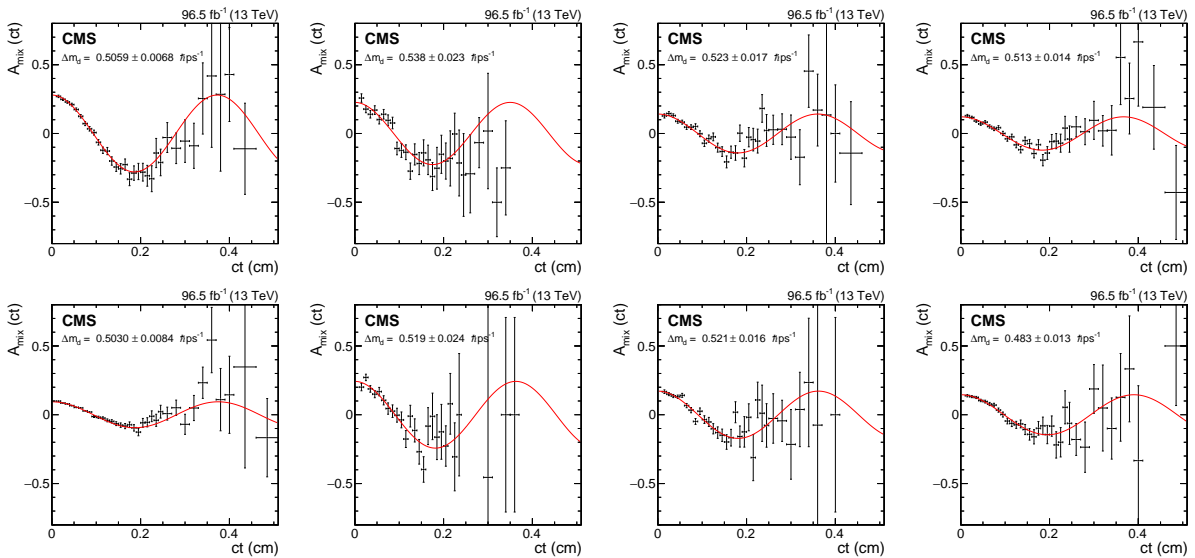


Figure C.12: The  $B^0$  mixing asymmetry as a function of the proper decay time as measured in the  $B^0 \rightarrow J/\psi K^*(892)^0$  control data sample in the different tagging categories. The reported uncertainties for the  $\Delta m_d$  fitted value are statistical only. This study was conducted to validate the tagging framework and assess the consistency of information provided by various tagging techniques. Top row, from left to right: only OS muon (MT trigger category), only OS muon (ST trigger category), only OS electron, and only OS jet. Bottom row, from left to right: only SS, SS + OS muon, SS + OS electron, and SS + OS jet. All tagging categories are mutually exclusive. The oscillation frequencies measured in each category are consistent with one another and with the world-average value  $\Delta m_d^{\text{PDG}} = 0.5069 \pm 0.0019 \text{ } \hbar \text{ps}^{-1}$  [33].

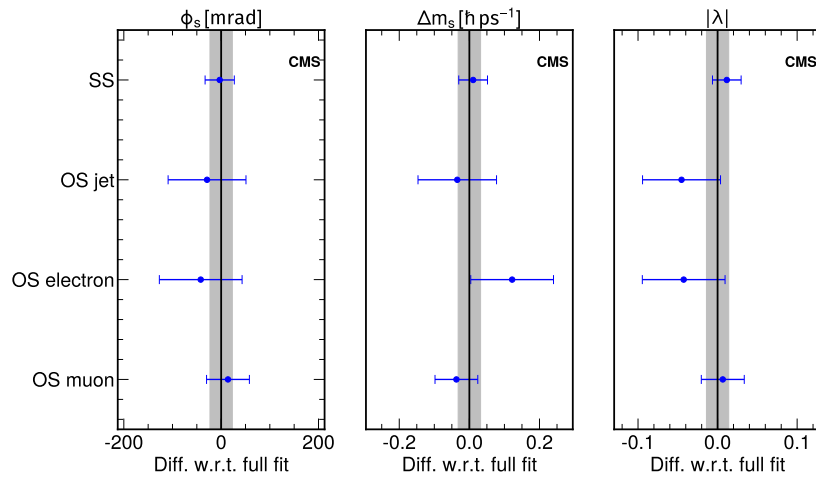




















Figure C.13: Comparison of CPV fit results obtained using each of the four individual flavor tagging algorithms versus the reference fit, which combines all four taggers. Only flavor-sensitive parameters are shown, and only statistical uncertainties are considered. The grey band represents the statistical uncertainty of the reference fit.

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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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C. Greenberg , G. Grenier , B. Ille , E. Jourd'huy, I.B. Laktineh, M. Lethuillier ,  
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



























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

























































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































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


















H. Aarup Petersen , M. Aldaya Martin , J. Alimena , S. Amoroso, Y. An , J. Bach ,  
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





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



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


























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S. Bashiri, S. Chenarani<sup>44</sup> , S.M. Etesami , Y. Hosseini , M. Khakzad , E. Khazaie ,  
M. Mohammadi Najafabadi , S. Tizchang<sup>45</sup> 





























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M. Felcini , M. Grunewald 







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M. De Palma<sup>a,b</sup> , W. Elmetenawee<sup>a,b,46</sup> , N. Ferrara<sup>a,b</sup> , L. Fiore<sup>a</sup> , G. Iaselli<sup>a,c</sup> ,  
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Ü. Sözbilir<sup>a</sup> , A. Stamerra<sup>a,b</sup> , D. Troiano<sup>a,b</sup> , R. Venditti<sup>a,b</sup> , P. Verwilligen<sup>a</sup> ,  
A. Zaza<sup>a,b</sup> 

















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G. Abbiendi<sup>a</sup> , C. Battilana<sup>a,b</sup> , D. Bonacorsi<sup>a,b</sup> , P. Capiluppi<sup>a,b</sup> , A. Castro<sup>+a,b</sup> ,  
F.R. Cavallo<sup>a</sup> , M. Cuffiani<sup>a,b</sup> , G.M. Dallavalle<sup>a</sup> , T. Diotallevi<sup>a,b</sup> , F. Fabbri<sup>a</sup> ,  
A. Fanfani<sup>a,b</sup> , D. Fasanella<sup>a</sup> , P. Giacomelli<sup>a</sup> , L. Giommi<sup>a,b</sup> , C. Grandi<sup>a</sup> ,  
L. Guiducci<sup>a,b</sup> , S. Lo Meo<sup>a,47</sup> , M. Lorusso<sup>a,b</sup> , L. Lunerti<sup>a</sup> , S. Marcellini<sup>a</sup> ,  
G. Masetti<sup>a</sup> , F.L. Navarra<sup>a,b</sup> , G. Paggi<sup>a,b</sup> , A. Perrotta<sup>a</sup> , F. Primavera<sup>a,b</sup> ,  
A.M. Rossi<sup>a,b</sup> , S. Rossi Tisbeni<sup>a,b</sup> , T. Rovelli<sup>a,b</sup> , G.P. Siroli<sup>a,b</sup> 

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R. Ceccarelli<sup>a</sup> , V. Ciulli<sup>a,b</sup> , C. Civinini<sup>a</sup> , R. D'Alessandro<sup>a,b</sup> , E. Focardi<sup>a,b</sup> ,  
T. Kello<sup>a</sup> , G. Latino<sup>a,b</sup> , P. Lenzi<sup>a,b</sup> , M. Lizzo<sup>a</sup> , M. Meschini<sup>a</sup> , S. Paoletti<sup>a</sup> 

A. Papanastassiou<sup>a,b</sup>, G. Sguazzoni<sup>a</sup> , L. Vilianni<sup>a</sup> 










**INFN Laboratori Nazionali di Frascati, Frascati, Italy**

L. Benussi , S. Bianco , S. Meola<sup>49</sup> , D. Piccolo 




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M. Alves Gallo Pereira<sup>a</sup> , F. Ferro<sup>a</sup> , E. Robutti<sup>a</sup> , S. Tosi<sup>a,b</sup> 










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










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






**INFN Sezione di Padova<sup>a</sup>, Università di Padova<sup>b</sup>, Padova, Italy; Università di Trento<sup>c</sup>, Trento, Italy**

R. Ardino<sup>a</sup> , P. Azzi<sup>a</sup> , N. Bacchetta<sup>a,51</sup> , D. Bisello<sup>a,b</sup> , P. Bortignon<sup>a</sup> , G. Bortolato<sup>a,b</sup>, A. Bragagnolo<sup>a,b</sup> , A.C.M. Bulla<sup>a</sup> , R. Carlin<sup>a,b</sup> , P. Checchia<sup>a</sup> , T. Dorigo<sup>a,52</sup> , S. Fantinel<sup>a</sup> , F. Fanzago<sup>a</sup>, U. Gasparini<sup>a,b</sup> , S. Giorgetti<sup>a</sup>, E. Lusiani<sup>a</sup> , M. Margoni<sup>a,b</sup> , M. Migliorini<sup>a,b</sup> , J. Pazzini<sup>a,b</sup> , P. Ronchese<sup>a,b</sup> , R. Rossin<sup>a,b</sup> , F. Simonetto<sup>a,b</sup> , M. Tosi<sup>a,b</sup> , A. Triossi<sup>a,b</sup> , S. Ventura<sup>a</sup> , M. Zanetti<sup>a,b</sup> , P. Zotto<sup>a,b</sup> , A. Zucchetta<sup>a,b</sup> , G. Zumerle<sup>a,b</sup> 










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








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





























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J. Goh , S. Yang 








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

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

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

**Yonsei University, Department of Physics, Seoul, Korea**










































S. Ha , K. Hwang , H.D. Yoo 




















































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M. Choi , M.R. Kim , H. Lee, Y. Lee , I. Yu 













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

T. Beyrouthy , Y. Gharbia 



































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T. Rohe , A. Samalan




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T.K. Aarrestad , M. Backhaus , G. Bonomelli , A. Calandri , C. Cazzaniga ,  
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






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A. Jofrehei , B. Kilminster , S. Leontsinis , S.P. Liehti , A. Macchiolo , P. Meiring ,  
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


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

















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H. Sert , C. Simsek , C. Zorbilmez 

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S. Cerci , B. Isildak<sup>77</sup> , D. Sunar Cerci , T. Yetkin 

**Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv,**














**Ukraine**

A. Boyaryntsev , B. Grynyov 




















**National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine**

L. Levchuk 





































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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, V.J. Smith , K. Walkingshaw Pass


**Rutherford Appleton Laboratory, Didcot, United Kingdom**

A.H. Ball, K.W. Bell , A. Belyaev<sup>78</sup> , C. Brew , R.M. Brown , D.J.A. Cockerill ,  
C. Cooke , A. Elliot , K.V. Ellis, K. Harder , S. Harper , J. Linacre , K. Manolopoulos,  
D.M. Newbold , E. Olaiya, D. Petyt , T. Reis , A.R. Sahasransu , G. Salvi , T. Schuh,  
C.H. Shepherd-Themistocleous , I.R. Tomalin , K.C. Whalen , T. Williams 













**Imperial College, London, United Kingdom**

I. Andreou , R. Bainbridge , P. Bloch , C.E. Brown , O. Buchmuller, C.A. Carrillo Montoya , G.S. Chahal<sup>79</sup> , D. Colling , J.S. Dancu, I. Das , P. Dauncey , G. Davies ,  
M. Della Negra , S. Fayer, G. Fedi , G. Hall , A. Howard, G. Iles , C.R. Knight ,  
P. Krueper, J. Langford , K.H. Law , 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 , T. Virdee<sup>28</sup> , M. Vojinovic , N. Wardle ,  
D. Winterbottom 

**Brunel University, Uxbridge, United Kingdom**

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

**Baylor University, Waco, Texas, USA**

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



















**Catholic University of America, Washington, DC, USA**

R. Bartek , A. Dominguez , A.E. Simsek , S.S. Yu 



















**The University of Alabama, Tuscaloosa, Alabama, USA**

B. Bam , A. Buchot Perraguin , R. Chudasama , S.I. Cooper , C. Crovella ,  
S.V. Gleyzer , E. Pearson, C.U. Perez , P. Rumerio<sup>81</sup> , E. Usai , R. Yi 

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

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







G. Barone , G. Benelli , D. Cutts , L. Gouskos , M. Hadley , U. Heintz ,  
J.M. Hogan<sup>82</sup> , T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , S. Mondal ,  
T. Russell, S. Sagir<sup>83</sup> , X. Shen , F. Simpson , M. Stamenkovic , N. Venkatasubramanian,  
X. Yan 

**University of California, Davis, Davis, California, USA**






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

























#### University of California, Los Angeles, California, USA

K. Adamidis, M. Bachtis , D. Campos, R. Cousins , A. Datta , G. Flores Avila , J. Hauser , M. Ignatenko , M.A. Iqbal , T. Lam , Y.f. Lo, E. Manca , A. Nunez Del Prado, D. Saltzberg , V. Valuev 


#### University of California, Riverside, Riverside, California, USA

R. Clare , J.W. Gary , G. Hanson 




#### University of California, San Diego, La Jolla, California, USA

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
















#### University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA

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















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

#### Cornell University, Ithaca, New York, USA




















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

#### Fermi National Accelerator Laboratory, Batavia, Illinois, USA












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 , C. Lee , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel 

S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , S. Norberg, V. Papadimitriou , N. Pastika , K. Pedro , C. Pena<sup>84</sup> , F. Ravera , A. Reinsvold Hall<sup>85</sup> , L. Ristori , M. Safdari , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , I. Zoi 

#### University of Florida, Gainesville, Florida, USA

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 , R. Hashmi , R.S. Kim , S. Kim , T. Kolberg , G. Martinez, H. Prosper , P.R. Prova, M. Wulansatiti , R. Yohay , J. Zhang











#### Florida Institute of Technology, Melbourne, Florida, USA

B. Alsufyani , M.M. Baarmand , S. Butalla , S. Das , T. Elkafrawy<sup>17</sup> , M. Hohmann , E. Yanes












#### University of Illinois Chicago, Chicago, Illinois, USA

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 , N. Singh, 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>86</sup> , L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili<sup>87</sup> , O. Neogi, H. Ogul<sup>88</sup> , Y. Onel , A. Penzo , C. Snyder, E. Tiras<sup>89</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>90</sup> , C. Rogan , C. Royon , 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>91</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 , M.I. Park , 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 , 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 

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

H. Bandyopadhyay , L. Hay , H.w. Hsia, I. Iashvili , A. Kalogeropoulos , A. Kharchilava , M. Morris , D. Nguyen , S. Rappoccio , H. Rejeb Sfar, A. Williams , P. Young 



























#### **Northeastern University, Boston, Massachusetts, USA**

G. Alverson , E. Barberis , J. Bonilla , B. Bylsma, M. Campana , J. Dervan , Y. Haddad , Y. Han , I. Israr , A. Krishna , J. Li , M. Lu , G. Madigan , R. Mccarthy , D.M. Morse , V. Nguyen , T. Orimoto , A. Parker , L. Skinnari , D. Wood 









#### **Northwestern University, Evanston, Illinois, USA**

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

















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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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