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Observation of the decay $B^+ \to \psi(2S)\phi(1020)K^+$ in pp collisions at $\sqrt{s} = 8\,\text{TeV}$

The CMS Collaboration *

CERN, Switzerland

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ABSTRACT

The decay $B^+ \to \psi(2S)\phi(1020)K^+$ is observed for the first time using data collected from pp collisions at $\sqrt{s} = 8\,\text{TeV}$ by the CMS experiment at the LHC, corresponding to an integrated luminosity of $19.6\,\text{fb}^{-1}$. The branching fraction of this decay is measured, using the mode $B^+ \to \psi(2S)K^+$ as normalization, to be $(4.0 \pm 0.4\,(\text{stat}) \pm 0.6\,(\text{syst}) \pm 0.2\,(\mathcal{B})) \times 10^{-6}$, where the third uncertainty is from the measured branching fraction of the normalization channel.

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1. Introduction

The large cross section for b quark production at the CERN LHC and the high luminosity of the accelerator provide the possibility to study rare B meson decays. Recently, several experiments have reported the likely presence of structures in the $J/\psi\phi(1020)$ mass spectrum from $B^\pm \to J/\psi\phi(1020)K^\pm$ decays [1–7]. A natural extension of these results is to study the $\psi(2S)\phi(1020)K^\pm$ and the $\psi(2S)\phi(1020)$ mass spectra. As part of that investigation, we report the first observation of the decay $B^\pm \to \psi(2S)\phi(1020)K^\pm$, with $\psi(2S) \to \mu^+\mu^-$ and $\phi(1020) \to K^+K^-$. We measure the corresponding branching fraction using data collected at the LHC with the CMS detector in proton–proton (pp) collisions at $\sqrt{s} = 8\,\text{TeV}$, corresponding to an integrated luminosity of $19.6\,\text{fb}^{-1}$. Possible contributions from nonresonant K^+K^- and $f_0(980)$ states in the signal are also studied, and an upper limit is determined in the fraction of events that do not correspond to $\phi(1020) \to K^+K^-$ in the $B^\pm \to \psi(2S)K^\pm K^\mp K^\pm$ channel. In what follows, ϕ is used to represent the $\phi(1020)$ meson, and all results are combined in the investigation of the two charge-conjugate states.

2. The CMS detector

The central feature of the CMS apparatus is a 13 m long superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections, reside within the volume of the solenoid. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors.

The main subdetectors used in the present analysis are the silicon tracker and the muon detection system. Muons are identified within the pseudorapidity range $|\eta| < 2.4$, using detection planes based on three technologies: drift tubes, cathode-strip chambers, and resistive-plate chambers. The silicon tracker measures charged particles within the range $|\eta| < 2.5$. It consists of 66 million $100 \times 150\,\mu\text{m}^2$ silicon pixels and more than 9 million silicon strips. For reconstructed particles with transverse momenta $1 < p_T < 10\,\text{GeV}$ and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_T, and the transverse and longitudinal impact parameters are in the respective ranges of 25–90 and 45–150 μm [8].

The first level of the CMS trigger system, constructed from specialized hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events in a time interval of less than 4 μs. The high-level trigger (HLT) processor farm further decreases the event rate from around 100 kHz to less than 1 kHz, before data storage. At the HLT stage, there is full access to all event information, including tracking, and therefore selection criteria similar to those applied offline can be implemented.

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

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A more detailed description of the CMS detector, together with a definition of its coordinate system and relevant kinematic variables, can be found in Ref. [9].

3. Data and event selection

Monte Carlo (MC) simulated events are generated using PYTHIA6.4 [10] for particle production, EVTGEN1.3.0 [11] for particle decays, and GEANT4 [12] for tracing the particles through a detailed model of the CMS detector. These samples are generated using the conditions appropriate for the data analyzed, including the effects of alignment, efficiency, and average number of additional pp collisions and their multiple reconstructed vertices per beam crossing (pileup).

The events in the analysis were collected with a trigger based on the invariant mass and p_T of the dimuon system. The following criteria are applied in the HLT: (i) the dimuon p_T is required to be greater than 4.9 GeV, (ii) the two muons must be oppositely charged, (iii) the dimuon invariant mass is required to be in the range of 3.35–4.05 GeV, and (iv) the dimuon tracks must form a three-dimensional (3D) vertex with a χ^2 probability greater than 0.5%.

The mass of the two muons from the triggered event is required to be within 5 $\sigma_M^{\psi(2S)}$ of the nominal $\psi(2S)$ mass [13], where the standard deviation $\sigma_M^{\psi(2S)}$ is obtained from fits to signal MC events in four bins of dimuon pseudorapidity. The value of $\sigma_M^{\psi(2S)}$ varies from 23 MeV for $|\eta| < 0.6$ to 45 MeV for $|\eta| > 1.8$. The $B^+ \to \psi(2S)\phi K^+$ candidates are reconstructed by combining three additional charged particle tracks consistent with originating from the $\psi(2S)$ vertex, and have a total charge of 1. These tracks are assigned the kaon mass. The B^+ decay vertex is reconstructed using a kinematic fit to a common 3D vertex constraining the invariant mass of the two muons to the nominal $\psi(2S)$ mass. For multiple candidates, the one with the highest B^+ vertex probability is retained. The overall efficiencies in selecting the correct candidate obtained from MC studies are 96.8% and 99.4% for the $B^+ \to \psi(2S)\phi K^+$ and $B^+ \to \psi(2S)K^+$ events, respectively. The p_T of each kaon track is required to be greater than 1 GeV. Only tracks passing the standard CMS high-purity requirements [14] are used. There are two K^+K^- combinations for the three charged kaon tracks, and the combination with invariant mass closest to the nominal ϕ meson mass [13] is used as the ϕ candidate. This selection yields the correct K^+K^- pair (94 ± 1)% of the time, as determined from simulation. The mass of the ϕ candidate is not constrained to its nominal value because the experimental K^+K^- mass resolution (1.3 MeV, obtained from our MC simulation) is less than the natural width of the ϕ meson (4.3 MeV) [13].

Additional requirements are placed on the resulting sample to optimize the sensitivity to the signal mode. The signal region is defined to lie within $\pm 5\ \sigma_M^B$ of the nominal B^+ mass [13], where σ_M^B is determined to be 3 MeV in a fit to simulated signal events using a single Gaussian function. Five quantities are chosen to optimize a 5 standard deviation discovery Punzi figure-of-merit (FOM), defined as $N_S/(5/2 + \sqrt{N_B})$ [15], where N_S is the number of B^+ candidates in the simulated sample, and N_B is the number of background candidates within $\pm 5\ \sigma_M^B$ of the B^+ mass peak. The background contribution is obtained from a fit to the sideband events in the $\psi(2S)\phi K^+$ invariant mass spectrum, where the lower and upper sidebands are defined as 5.220–5.264 and 5.294–5.330 GeV, respectively. The five quantities used to optimize the FOM are as follows: (i) the B^+ vertex probability; (ii) the significance of the transverse displacement, defined as the ratio of the transverse distance L_{xy} of the B^+ secondary vertex relative to the center of the beam spot and its uncertainty $\sigma_{L_{xy}}$, with the latter being the sum in quadrature of the uncertainty in the transverse position of the secondary vertex and the transverse size of the beam spot; (iii) the cosine of the pointing angle θ, defined as the angle between the reconstructed B^+ momentum vector and its flight direction, as determined from the vector connecting the primary vertex [8] to the B^+ secondary vertex, where the primary vertex is chosen so that this angle is closest to zero; (iv) the p_T of the dimuon system; and (v) the ϕ mass window, defined as the difference between the invariant mass of the K^+K^- system and the mass of the ϕ meson [13]. The selection criteria derived from the optimization procedure are shown in Table 1. The overall efficiency of the offline signal selection is $(1.91 \pm 0.01) \times 10^{-3}$.

Table 1
The selection criteria derived from the optimization procedure.

Quantity	Requirement
B vertex probability	>10%
$L_{xy}/\sigma_{L_{xy}}$	>4
$\cos\theta$	>0.99
Dimuon p_T	>7 GeV
ϕ mass window	<8 MeV

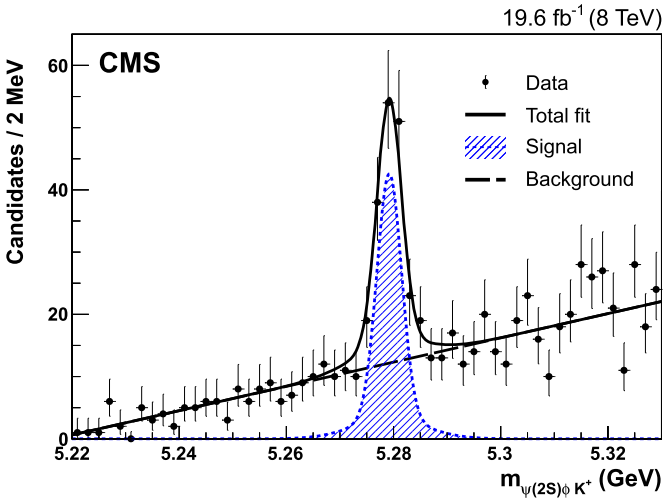

Fig. 1. The $\psi(2S)\phi K^+$ mass distribution after the selection requirements. The solid curve shows the result of fitting this distribution to a signal represented by two Gaussian functions and a first-order polynomial for the background. The shaded area represents the signal component, while the black dashed line shows the fitted background contribution.

4. Observation of $B^+ \to \psi(2S)\phi K^+$ decay

The invariant mass spectrum of the selected $\psi(2S)\phi K^+$ candidates is shown in Fig. 1. An extended unbinned maximum-likelihood estimator from RooFit [16] is used to perform the fit to the data, using two Gaussian functions for the signal and a first-order polynomial for the background. The two Gaussian functions share a common mean fixed to the nominal B^+ mass [13], while their widths and relative fractions are fixed to the values obtained in the MC simulation. The goodness of fit is checked using a χ^2 test, which returns a χ^2 per degree of freedom (dof) of 23.0/24, with a corresponding probability of 52%. The fit gives a B^+ yield of 140 ± 15 events, where the uncertainty is statistical.

The small amount of available phase space, only 80 MeV, in the $B^+ \to \psi(2S)\phi K^+$ decay makes it difficult to model the expected $\psi(2S)\phi$ invariant mass distribution. This, and the limited number of signal events, precludes any search for $\psi(2S)\phi$ resonances in the current data sample.

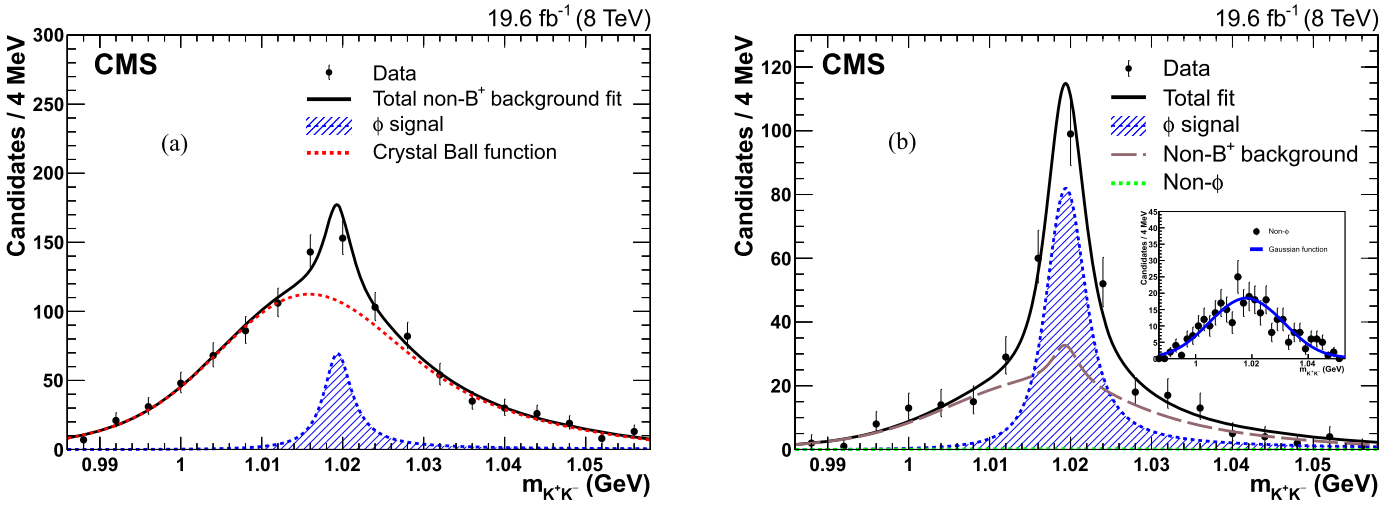

Fig. 2. The distributions of the K^+K^- invariant mass closest to the nominal ϕ mass outside (a) and inside (b) the B^+ mass window. The results show the total fit, as well as (a) the Crystal Ball function component of the non-B^+ background, and in (b) the four components: ϕ signal, non-B^+ background, non-ϕ signal. The non-ϕ component is almost invisible due to its small contribution. The inset shows the non-ϕ distribution modeled by a Gaussian function.

Possible contamination from the decays of the $f_0(980)$ meson and nonresonant K^+K^- is studied through a simultaneous fit of the K^+K^- invariant mass distributions for the combinations closest to the nominal ϕ mass inside and outside of an 18 MeV mass window centered around the nominal B^+ mass, not using the ± 8 MeV ϕ mass window listed in Table 1. The distributions of the nonresonant K^+K^- and f_0 background invariant mass contributions are obtained from dedicated $B^+ \to \psi(2S)K^+K^-K^+$ and $B^+ \to \psi(2S)f_0K^+$ MC simulations generated using EVTGEN [11], which models the f_0 distribution as a coupled-channel Breit–Wigner function [17]. Both the nonresonant K^+K^- and f_0 contributions are distorted through the selection of the K^+K^- pair closest to the nominal ϕ mass. We parametrize these forms using Gaussian functions that are very similar for the two components. Their correlation coefficients show that the two contributions are strongly anticorrelated, and we therefore choose the nonresonant K^+K^- background in the fit to represent both the f_0 and any other K^+K^- components, and label it as the non-ϕ contribution to the signal.

A $3\sigma_M^B$-wide window around the B^+ mass of 5.270–5.288 GeV is chosen, with lower and upper sidebands of 5.220–5.270 and 5.288–5.330 GeV, respectively. Figs. 2(a) and (b) show the distributions of the K^+K^- invariant masses closest to the nominal ϕ mass outside (a) and inside (b) the B^+ window, where Fig. 2(a) thereby provides the non-B^+ background. Both the distributions share the same non-B^+ background function. We find (not displayed) that the non-B^+ contribution within the B^+ mass window is of 194 ± 14 events, obtained from a fit to the $\psi(2S)\phi K^+$ invariant mass spectrum. In the simultaneous fit, we therefore fix this number to 194, while the number of non-B^+ events contributing in the sidebands is allowed to vary.

The ϕ signal component is parametrized by a P-wave relativistic Breit–Wigner function, convolved with a Gaussian resolution function. The standard deviation of the Gaussian function is fixed to 1.3 MeV. The mass and width of the ϕ reflect their nominal values [13]. Since there is a ϕ signal in the non-B^+ events, the non-B^+ ϕ contribution in Fig. 2(a) is parametrized by the sum of a Crystal Ball function [18] and the above-mentioned function that represents the ϕ component.

The data in Fig. 2(a) is fitted using the non-B^+ function, and simultaneously in Fig. 2(b) using the above three functions. The fit returns a yield of 2 ± 20 events for the non-ϕ signal contribution that is too small to be seen in the Fig. 2(b). The systematic uncertainty in this yield is negligible. The fit quality in Fig. 2(b) is checked using a χ^2 test, which returns $\chi^2/\text{dof} = 21.6/16$. We set an upper limit on the fraction of the non-ϕ component in $B^+ \to \psi(2S)K^+K^-K^+$ decays, obtained with the CL_s method [19,20] using an asymptotic approximation [21], of 0.26 at the 95% confidence level.

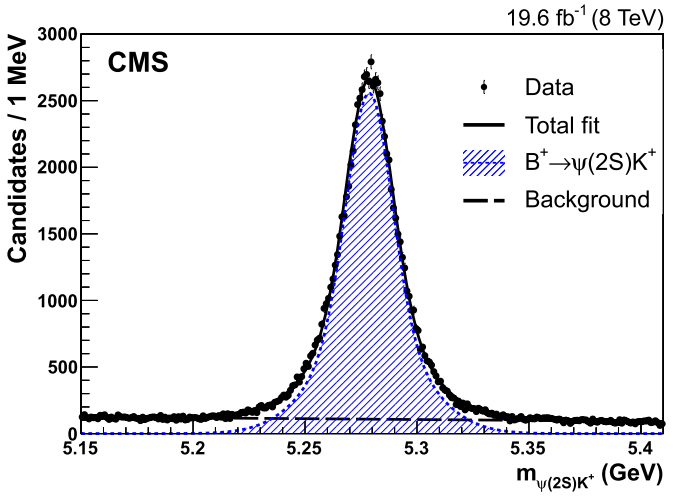

Fig. 3. The $\psi(2S)K^+$ invariant mass distribution after implementing all event selection requirements. The solid curve shows the result of fitting this distribution to a signal corresponding to two Gaussian functions and a first-order polynomial for the background. The shaded area represents the contribution from the $B^+ \to \psi(2S)K^+$ channel, while the black dashed line shows the fitted background contribution.

5. $B^+ \to \psi(2S)K^+$ decay

The $B^+ \to \psi(2S)K^+$ decay is chosen as the normalization channel because its absolute branching fraction is well measured, it is recorded with the same trigger as the signal channel, and it is topologically similar to the signal, so that many systematic uncertainties cancel or are reduced. All applicable selection requirements are kept the same as those for the signal channel. The $\psi(2S)K^+$ invariant mass distribution is shown in Fig. 3. A binned maximum-likelihood fit is used to determine the number of events in this channel. Again, two Gaussian functions are used to model the B^+ signal, and a first-order polynomial to model the back-

Table 2
Relative systematic uncertainties in the measurement of $\mathcal{B}(B^+ \to \psi(2S)\phi K^+)$ in percent. The total systematic uncertainty corresponds to the sum in quadrature of the listed uncertainties.

Source	Uncertainty (%)
B^+ mass shape for signal mode	8.6
Charged particle track reconstruction efficiency	7.8
Modeling of p_T dependence of B^+ efficiency	5.3
ϕ purity	5.0
Mass distribution for the background in the signal	2.9
Uncertainty in relative efficiency of signal and normalization	2.3
Background distribution in the normalization channel	2.2
Angular distributions of K^+K^- systems	1.9
B^+ mass shape for normalization mode	1.0
$\mathcal{B}(\phi \to K^+K^-)$ uncertainty	1.0
Total	15

ground. The large number of events allows a fit with all parameters free to vary and the yield is found to be 87264 ± 363 (stat). The goodness of the fit is checked using a χ^2 test, which returns $\chi^2/\text{dof} = 363/253$.

6. Results and systematic uncertainties

The value of the branching fraction $\mathcal{B}(B^+ \to \psi(2S)\phi K^+)$ is obtained from the ratio:

$$\frac{N_{B^+\to\psi(2S)\phi K^+}\,\mathcal{B}(B^+ \to \psi(2S)K^+)}{N_{B^+\to\psi(2S)K^+}\,\varepsilon_{\text{rel}}\,\mathcal{B}(\phi \to K^+K^-)}, \quad (1)$$

where $N_{B^+\to\psi(2S)\phi K^+}$ and $N_{B^+\to\psi(2S)K^+}$ are the signal and normalization yields extracted from the fit to the invariant mass distributions in the $B^+ \to \psi(2S)\phi K^+$ and $B^+ \to \psi(2S)K^+$ channels, respectively. The relative reconstruction efficiency $\varepsilon_{\text{rel}} = 0.52 \pm 0.01$ is calculated from the ratio of the reconstruction efficiencies in the signal and normalization channels with a statistical uncertainty from the number of MC events. Using the branching fractions $\mathcal{B}(\phi \to K^+K^-) = 0.489 \pm 0.005$ and $\mathcal{B}(B^+ \to \psi(2S)K^+) = (6.26 \pm 0.24) \times 10^{-4}$ [13], the value of $\mathcal{B}(B^+ \to \psi(2S)\phi K^+)$ is determined to be $(4.0 \pm 0.4\,(\text{stat})) \times 10^{-6}$.

Estimates of the contributions to the systematic uncertainty in $\mathcal{B}(B^+ \to \psi(2S)\phi K^+)$ are summarized in Table 2, and described below. The uncertainty from modeling the shape of the B^+ invariant mass distribution is estimated to be 8.6% by allowing the widths of the two Gaussian functions to vary in the fit, with the background function fixed to a first order polynomial. Systematic uncertainties from sources such as muon identification, trigger efficiency, and track reconstruction efficiency for the three common tracks (two muons and a kaon) almost cancel in the measurement of the signal branching fraction. The uncertainty in the charged particle track reconstruction efficiency, obtained in an independent study by comparing two-body and four-body D^0 decays in data and simulated events [8], gives an uncertainty of 3.9% per track and a total uncertainty of 7.8% for the two additional kaon tracks. A mismatch in the p_T distribution between B^+ mesons in MC simulations and in data can lead to an incorrect efficiency. We therefore reweight the signal and normalization events using a weighting function derived from the normalization channel. The ratio of efficiencies from the reweighted MC events is compared to the nominal value to extract a systematic uncertainty of 5.3%.

The choice of the K^+K^- candidate closest to the nominal ϕ mass causes a bias, and, to estimate any systematic contamination of the K^+K^- mass peak from non-ϕ backgrounds, the analysis is repeated after removing the selection on the K^+K^- mass being closest to the mass of the ϕ. This makes the choice of the K^+K^- pair independent of the closest value to the nominal ϕ mass,

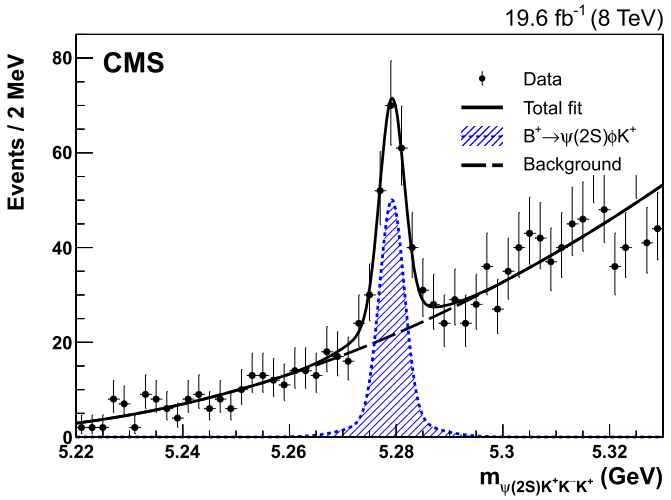

Fig. 4. The $\psi(2S)K^+K^-K^+$ invariant mass distribution with no ϕ mass selection. The solid curve shows the result of fitting this distribution to a signal represented by two Gaussian functions and a second-order polynomial for the background. The shaded area represents the signal component, while the black dashed line shows the fitted background contribution.

and the branching fraction is remeasured by keeping both K^+K^- pair candidate events. The subsequent $B^+ \to \psi(2S)K^+K^-K^+$ invariant mass distribution is shown in Fig. 4. The signal in Fig. 4 is clear, but there is more background relative to the signal mass distribution shown in Fig. 1. There are 165 ± 18 B^+ signal events with two K^+K^- combinations for each event. The efficiency for the $B^+ \to \psi(2S)\phi K^+$ signal after removing the choice of ϕ candidate is $(2.14 \pm 0.02) \times 10^{-3}$, and the redetermined $\mathcal{B}(B^+ \to \psi(2S)\phi K^+)$ is $(4.2 \pm 0.4\,(\text{stat})) \times 10^{-6}$. The 5.0% difference between this and the nominal branching fraction is used as the systematic uncertainty from possible non-ϕ backgrounds.

The uncertainties in modeling the $B^+ \to \psi(2S)\phi K^+$ and the normalization channel backgrounds are estimated to be 2.9% and 2.2%, respectively, by adding polynomials of higher order in the fit to describe the background. The uncertainty from the angular distribution of the K^+K^- system is estimated to be 1.9%, based on the changes induced in the B^+ reconstruction efficiency by weighting the simulated events with different helicity angle distributions. The uncertainty in the B^+ mass shape for the normalization channel is estimated to be 1.0% by adding a third Gaussian function with a common mean and a varying width to the fit, with the background again modeled by a linear function. The uncertainty in $\mathcal{B}(\phi \to K^+K^-)$ is 1% [13].

Possible systematic uncertainties introduced by different trigger and pileup conditions and analysis selections have been investigated by dividing the data into subsets and evaluating the statistical consistency [13] of the independent samples; the resulting variations are found to be within the expected uncertainties.

The overall relative systematic uncertainty in $\mathcal{B}(B^+ \to \psi(2S)\phi K^+)$ is 15% from adding the individual contributions summarized in Table 2 in quadrature. The total uncertainty in $\mathcal{B}(B^+ \to \psi(2S)K^+)$ is 3.8% [13]. Thus, the final measured value of $\mathcal{B}(B^+ \to \psi(2S)\phi K^+)$, including all systematic uncertainties, is: $(4.0 \pm 0.4\,(\text{stat}) \pm 0.6\,(\text{syst}) \pm 0.2\,(\mathcal{B})) \times 10^{-6}$, where the third uncertainty is from the imprecision in $\mathcal{B}(B^+ \to \psi(2S)K^+)$.

7. Summary

The $B^+ \to \psi(2S)\phi K^+$ decay has been observed for the first time by the CMS Collaboration. The result has been achieved using data from pp collisions at $\sqrt{s} = 8$ TeV, corresponding to an in-

tegrated luminosity of 19.6 fb^{-1}. The branching fraction $\mathcal{B}(B^+ \to \psi(2S)\phi K^+)$ is determined to be $(4.0 \pm 0.4(\text{stat}) \pm 0.6(\text{syst}) \pm 0.2(\mathcal{B})) \times 10^{-6}$, where the third uncertainty arises from the imprecision in the value of $\mathcal{B}(B^+ \to \psi(2S)K^+)$. The upper limit on the fraction of $B^+ \to \psi(2S)(\text{non-}\phi)K^+$ decays in $B^+ \to \psi(2S)K^+K^+K^+$ channel is found to be 0.26 at 95% confidence. The observation of $B^+ \to \psi(2S)\phi K^+$ offers future opportunities in searches for resonances in the $\psi(2S)\phi$ mass spectrum.

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CMS Collaboration

V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth [1], V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler [1], A. König, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady, N. Rad, B. Rahbaran, H. Rohringer, J. Schieck [1], J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz [1]

Institut für Hochenergiephysik der OeAW, Wien, Austria

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

National Centre for Particle and High Energy Physics, Minsk, Belarus

S. Alderweireldt, E.A. De Wolf, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Universiteit Antwerpen, Antwerpen, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous, S. Lowette, S. Moortgat, L. Moreels, A. Olbrechts, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Vrije Universiteit Brussel, Brussel, Belgium

H. Brun, C. Caillol, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang [2]

Université Libre de Bruxelles, Bruxelles, Belgium

A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, G. Garcia, M. Gul, D. Poyraz, S. Salva, R. Schöfbeck, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

Ghent University, Ghent, Belgium

H. Bakhshiansohi, C. Beluffi [3], O. Bondu, S. Brochet, G. Bruno, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, L. Forthomme, B. Francois, A. Giammanco, A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, C. Nuttens, K. Piotrzkowski, L. Quertenmont, M. Selvaggi, M. Vidal Marono, S. Wertz

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

N. Beliy

Université de Mons, Mons, Belgium

W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato [4], A. Custódio, E.M. Da Costa, G.G. Da Silveira, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote [4], A. Vilela Pereira

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

S. Ahuja [a], C.A. Bernardes [b], S. Dogra [a], T.R. Fernandez Perez Tomei [a], E.M. Gregores [b], P.G. Mercadante [b], C.S. Moon [a], S.F. Novaes [a], Sandra S. Padula [a], D. Romero Abad [b], J.C. Ruiz Vargas

[a] *Universidade Estadual Paulista, São Paulo, Brazil*
[b] *Universidade Federal do ABC, São Paulo, Brazil*

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

W. Fang [5]

Beihang University, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen [6], T. Cheng, C.H. Jiang, D. Leggat, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, H. Zhang, J. Zhao

Institute of High Energy Physics, Beijing, China

Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, C.F. González Hernández, J.D. Ruiz Alvarez, J.C. Sanabria

Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, S. Micanovic, L. Sudic, T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

University of Cyprus, Nicosia, Cyprus

M. Finger [7], M. Finger Jr. [7]

Charles University, Prague, Czechia

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

E. El-khateeb [8], S. Elgammal [9], A. Mohamed [10]

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

B. Calpas, M. Kadastik, M. Murumaa, L. Perrini, M. Raidal, A. Tiko, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, J. Pekkanen, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

J. Härkönen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Peltola, J. Tuominiemi, E. Tuovinen, L. Wendland

Helsinki Institute of Physics, Helsinki, Finland

J. Talvitie, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, O. Davignon, R. Granier de Cassagnac, M. Jo, S. Lisniak, P. Miné, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3–CNRS, Palaiseau, France

J.-L. Agram [11], J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte [11], X. Coubez, J.-C. Fontaine [11], D. Gelé, U. Goerlach, A.-C. Le Bihan, J.A. Merlin [12], K. Skovpen, P. Van Hove

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, E. Bouvier, C.A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov [13], D. Sabes, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret

Université de Lyon, Université Claude Bernard Lyon 1, CNRS–IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

A. Khvedelidze [7]

Georgian Technical University, Tbilisi, Georgia

Z. Tsamalaidze [7]

Tbilisi State University, Tbilisi, Georgia

C. Autermann, S. Beranek, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, S. Schael, C. Schomakers, J.F. Schulte, J. Schulz, T. Verlage, H. Weber, V. Zhukov [13]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

V. Cherepanov, G. Flügge, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, A. Nehrkorn, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl [12]

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

M. Aldaya Martin, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A.A. Bin Anuar, K. Borras [14], A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Dolinska, G. Eckerlin, D. Eckstein, E. Eren, E. Gallo [15], J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, P. Gunnellini, A. Harb, J. Hauk, M. Hempel [16], H. Jung, A. Kalogeropoulos, O. Karacheban [16], M. Kasemann, J. Keaveney, J. Kieseler, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann [16], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M.Ö. Sahin, P. Saxena,

T. Schoerner-Sadenius, C. Seitz, S. Spannagel, N. Stefaniuk, K.D. Trippkewitz, G.P. Van Onsem, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

V. Blobel, M. Centis Vignali, A.R. Draeger, T. Dreyer, E. Garutti, K. Goebel, D. Gonzalez, J. Haller, M. Hoffmann, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, J. Ott, F. Pantaleo [12], T. Peiffer, A. Perieanu, J. Poehlsen, C. Sander, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

University of Hamburg, Hamburg, Germany

C. Barth, C. Baus, J. Berger, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, S. Fink, R. Friese, M. Giffels, A. Gilbert, P. Goldenzweig, D. Haitz, F. Hartmann [12], S.M. Heindl, U. Husemann, I. Katkov [13], P. Lobelle Pardo, B. Maier, H. Mildner, M.U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

G. Anagnostou, G. Daskalakis, T. Geralis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, I. Topsis-Giotis

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

National and Kapodistrian University of Athens, Athens, Greece

I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Paradas

University of Ioánnina, Ioánnina, Greece

N. Filipovic

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Hungary

G. Bencze, C. Hajdu, P. Hidas, D. Horvath [17], F. Sikler, V. Veszpremi, G. Vesztergombi [18], A.J. Zsigmond

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi [19], A. Makovec, J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

M. Bartók [18], P. Raics, Z.L. Trocsanyi, B. Ujvari

University of Debrecen, Debrecen, Hungary

S. Bahinipati, S. Choudhury [20], P. Mal, K. Mandal, A. Nayak [21], D.K. Sahoo, N. Sahoo, S.K. Swain

National Institute of Science Education and Research, Bhubaneswar, India

S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, U. Bhawandeep, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, A. Mehta, M. Mittal, J.B. Singh, G. Walia

Panjab University, Chandigarh, India

Ashok Kumar, A. Bhardwaj, B.C. Choudhary, R.B. Garg, S. Keshri, S. Malhotra, M. Naimuddin, N. Nishu, K. Ranjan, R. Sharma, V. Sharma

University of Delhi, Delhi, India

R. Bhattacharya, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

Saha Institute of Nuclear Physics, Kolkata, India

P.K. Behera

Indian Institute of Technology Madras, Madras, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty [12], P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Dugad, G. Kole, B. Mahakud, S. Mitra, G.B. Mohanty, B. Parida, N. Sur, B. Sutar

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhowmik [22], R.K. Dewanjee, S. Ganguly, M. Guchait, Sa. Jain, S. Kumar, M. Maity [22], G. Majumder, K. Mazumdar, T. Sarkar [22], N. Wickramage [23]

Tata Institute of Fundamental Research-B, Mumbai, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, A. Rane, S. Sharma

Indian Institute of Science Education and Research (IISER), Pune, India

H. Behnamian, S. Chenarani [24], E. Eskandari Tadavani, S.M. Etesami [24], A. Fahim [25], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh [26], M. Zeinali

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia [a,b], C. Calabria [a,b], C. Caputo [a,b], A. Colaleo [a], D. Creanza [a,c], L. Cristella [a,b], N. De Filippis [a,c], M. De Palma [a,b], L. Fiore [a], G. Iaselli [a,c], G. Maggi [a,c], M. Maggi [a], G. Miniello [a,b], S. My [a,b], S. Nuzzo [a,b], A. Pompili [a,b], G. Pugliese [a,c], R. Radogna [a,b], A. Ranieri [a], G. Selvaggi [a,b], L. Silvestris [a,12], R. Venditti [a,b], P. Verwilligen [a]

[a] *INFN Sezione di Bari, Bari, Italy*
[b] *Università di Bari, Bari, Italy*
[c] *Politecnico di Bari, Bari, Italy*

G. Abbiendi [a], C. Battilana, D. Bonacorsi [a,b], S. Braibant-Giacomelli [a,b], L. Brigliadori [a,b], R. Campanini [a,b], P. Capiluppi [a,b], A. Castro [a,b], F.R. Cavallo [a], S.S. Chhibra [a,b], G. Codispoti [a,b], M. Cuffiani [a,b], G.M. Dallavalle [a], F. Fabbri [a], A. Fanfani [a,b], D. Fasanella [a,b], P. Giacomelli [a], C. Grandi [a], L. Guiducci [a,b], S. Marcellini [a], G. Masetti [a], A. Montanari [a], F.L. Navarria [a,b], A. Perrotta [a], A.M. Rossi [a,b], T. Rovelli [a,b], G.P. Siroli [a,b], N. Tosi [a,b,12]

[a] *INFN Sezione di Bologna, Bologna, Italy*
[b] *Università di Bologna, Bologna, Italy*

S. Albergo [a,b], M. Chiorboli [a,b], S. Costa [a,b], A. Di Mattia [a], F. Giordano [a,b], R. Potenza [a,b], A. Tricomi [a,b], C. Tuve [a,b]

[a] *INFN Sezione di Catania, Catania, Italy*
[b] *Università di Catania, Catania, Italy*

G. Barbagli [a], V. Ciulli [a,b], C. Civinini [a], R. D'Alessandro [a,b], E. Focardi [a,b], V. Gori [a,b], P. Lenzi [a,b], M. Meschini [a], S. Paoletti [a], G. Sguazzoni [a], L. Viliani [a,b,12]

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

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera [12]

INFN Laboratori Nazionali di Frascati, Frascati, Italy

V. Calvelli [a,b], F. Ferro [a], M. Lo Vetere [a,b], M.R. Monge [a,b], E. Robutti [a], S. Tosi [a,b]

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

L. Brianza, M.E. Dinardo [a,b], P. Dini [a], S. Fiorendi [a,b], S. Gennai [a], A. Ghezzi [a,b], P. Govoni [a,b], S. Malvezzi [a], R.A. Manzoni [a,b,12], B. Marzocchi [a,b], D. Menasce [a], M. Paganoni [a,b], D. Pedrini [a], S. Pigazzini, S. Ragazzi [a,b], T. Tabarelli de Fatis [a,b]

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

S. Buontempo [a], N. Cavallo [a,c], G. De Nardo, S. Di Guida [a,d,12], M. Esposito [a,b], F. Fabozzi [a,c], A.O.M. Iorio [a,b], G. Lanza [a], L. Lista [a], S. Meola [a,d,12], P. Paolucci [a,12], C. Sciacca [a,b], F. Thyssen

[a] *INFN Sezione di Napoli, Napoli, Italy*
[b] *Università di Napoli 'Federico II', Napoli, Italy*
[c] *Università della Basilicata, Potenza, Italy*
[d] *Università G. Marconi, Roma, Italy*

P. Azzi [a,12], N. Bacchetta [a], L. Benato [a,b], D. Bisello [a,b], A. Boletti [a,b], R. Carlin [a,b], P. Checchia [a], M. Dall'Osso [a,b], P. De Castro Manzano [a], T. Dorigo [a], U. Dosselli [a], F. Gasparini [a,b], U. Gasparini [a,b], A. Gozzelino [a], S. Lacaprara [a], M. Margoni [a,b], G. Maron [a,27], M. Michelotto [a], J. Pazzini [a,b,12], N. Pozzobon [a,b], P. Ronchese [a,b], F. Simonetto [a,b], S. Ventura [a], M. Zanetti, P. Zotto [a,b], A. Zucchetta [a,b], G. Zumerle [a,b]

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

A. Braghieri [a], A. Magnani [a,b], P. Montagna [a,b], S.P. Ratti [a,b], V. Re [a], C. Riccardi [a,b], P. Salvini [a], I. Vai [a,b], P. Vitulo [a,b]

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

L. Alunni Solestizi [a,b], G.M. Bilei [a], D. Ciangottini [a,b], L. Fanò [a,b], P. Lariccia [a,b], R. Leonardi [a,b], G. Mantovani [a,b], M. Menichelli [a], A. Saha [a], A. Santocchia [a,b]

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

K. Androsov [a,28], P. Azzurri [a,12], G. Bagliesi [a], J. Bernardini [a], T. Boccali [a], R. Castaldi [a], M.A. Ciocci [a,28], R. Dell'Orso [a], S. Donato [a,c], G. Fedi, A. Giassi [a], M.T. Grippo [a,28], F. Ligabue [a,c], T. Lomtadze [a], L. Martini [a,b], A. Messineo [a,b], F. Palla [a], A. Rizzi [a,b], A. Savoy-Navarro [a,29], P. Spagnolo [a], R. Tenchini [a], G. Tonelli [a,b], A. Venturi [a], P.G. Verdini [a]

[a] *INFN Sezione di Pisa, Pisa, Italy*
[b] *Università di Pisa, Pisa, Italy*
[c] *Scuola Normale Superiore di Pisa, Pisa, Italy*

L. Barone [a,b], F. Cavallari [a], M. Cipriani [a,b], G. D'imperio [a,b,12], D. Del Re [a,b,12], M. Diemoz [a], S. Gelli [a,b], C. Jorda [a], E. Longo [a,b], F. Margaroli [a,b], P. Meridiani [a], G. Organtini [a,b], R. Paramatti [a], F. Preiato [a,b], S. Rahatlou [a,b], C. Rovelli [a], F. Santanastasio [a,b]

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

N. Amapane [a,b], R. Arcidiacono [a,c,12], S. Argiro [a,b], M. Arneodo [a,c], N. Bartosik [a], R. Bellan [a,b], C. Biino [a], N. Cartiglia [a], M. Costa [a,b], R. Covarelli [a,b], A. Degano [a,b], G. Dellacasa [a], N. Demaria [a], L. Finco [a,b], B. Kiani [a,b], C. Mariotti [a], S. Maselli [a], G. Mazza [a], E. Migliore [a,b], V. Monaco [a,b], E. Monteil [a,b],

M.M. Obertino [a,b], L. Pacher [a,b], N. Pastrone [a], M. Pelliccioni [a], G.L. Pinna Angioni [a,b], F. Ravera [a,b], A. Romero [a,b], M. Ruspa [a,c], R. Sacchi [a,b], V. Sola [a], A. Solano [a,b], A. Staiano [a], P. Traczyk [a,b]

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

S. Belforte [a], M. Casarsa [a], F. Cossutti [a], G. Della Ricca [a,b], C. La Licata [a,b], A. Schizzi [a,b], A. Zanetti [a]

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

D.H. Kim, G.N. Kim, M.S. Kim, S. Lee, S.W. Lee, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

Kyungpook National University, Daegu, Republic of Korea

A. Lee

Chonbuk National University, Jeonju, Republic of Korea

J.A. Brochero Cifuentes, T.J. Kim

Hanyang University, Seoul, Republic of Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, Y. Kim, B. Lee, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Korea University, Seoul, Republic of Korea

J. Almond, J. Kim, S.B. Oh, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

Seoul National University, Seoul, Republic of Korea

M. Choi, H. Kim, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu, M.S. Ryu

University of Seoul, Seoul, Republic of Korea

Y. Choi, J. Goh, C. Hwang, J. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

V. Dudenas, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali [30], F. Mohamad Idris [31], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz [32], A. Hernandez-Almada, R. Lopez-Fernandez, R. Magaña Villalba, J. Mejia Guisao, A. Sanchez-Hernandez

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

S. Carpinteyro, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

D. Krofcheck

University of Auckland, Auckland, New Zealand

P.H. Butler

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, A. Byszuk [33], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadruccio, J. Varela, P. Vischia

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev [34,35], P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

L. Chtchipounov, V. Golovtsov, Y. Ivanov, V. Kim [36], E. Kuznetsova [37], V. Murzin, V. Oreshkin, V. Sulimov, A. Vorobyev

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, M. Toms, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

A. Bylinkin [35]

MIPT, Russia

R. Chistov [38], M. Danilov [38], V. Rusinov

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

V. Andreev, M. Azarkin [35], I. Dremin [35], M. Kirakosyan, A. Leonidov [35], S.V. Rusakov, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, M. Dubinin [39], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

V. Blinov [40], Y. Skovpen [40]

Novosibirsk State University (NSU), Novosibirsk, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

P. Adzic [41], P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

J. Alcaraz Maestre, M. Barrio Luna, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad Autónoma de Madrid, Madrid, Spain

J. Cuevas, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, I. Suárez Andrés, J.M. Vizan Garcia

Universidad de Oviedo, Oviedo, Spain

I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, E. Curras, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, P. Bloch, A. Bocci, A. Bonato, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, F. De Guio, A. De Roeck, E. Di Marco [42], M. Dobson, B. Dorney, T. du Pree, D. Duggan, M. Dünser, N. Dupont, A. Elliott-Peisert, S. Fartoukh, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, M. Girone, F. Glege, D. Gulhan, S. Gundacker, M. Guthoff, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, H. Kirschenmann, V. Knünz, A. Kornmayer [12], M.J. Kortelainen, K. Kousouris, M. Krammer [1], P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi [43], M. Rovere, M. Ruan, H. Sakulin, J.B. Sauvan, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, M. Simon, P. Sphicas [44], J. Steggemann, M. Stoye, Y. Takahashi, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns [45], G.I. Veres [18], N. Wardle, A. Zagozdzinska [33], W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, P. Lecomte [†], W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, M.T. Meinhard, D. Meister, F. Micheli, P. Musella,

F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Rossini, M. Schönenberger, A. Starodumov [46], V.R. Tavolaro, K. Theofilatos, R. Wallny

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler [47], L. Caminada, M.F. Canelli, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, Y. Yang

Universität Zürich, Zurich, Switzerland

V. Candelise, T.H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, A. Pozdnyakov, S.S. Yu

National Central University, Chung-Li, Taiwan

Arun Kumar, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, F. Fiori, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Paganis, A. Psallidas, J.f. Tsai, Y.M. Tzeng

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, G. Singh, N. Srimanobhas, N. Suwonjandee

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

A. Adiguzel, M.N. Bakirci [48], S. Damarseckin, Z.S. Demiroglu, C. Dozen, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal [49], O. Kara, U. Kiminsu, M. Oglakci, G. Onengut [50], K. Ozdemir [51], S. Ozturk [48], A. Polatoz, D. Sunar Cerci [52], S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Cukurova University, Adana, Turkey

B. Bilin, S. Bilmis, B. Isildak [53], G. Karapinar [54], M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, M. Kaya [55], O. Kaya [56], E.A. Yetkin [57], T. Yetkin [58]

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak, S. Sen [59]

Istanbul Technical University, Istanbul, Turkey

B. Grynyov

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

L. Levchuk, P. Sorokin

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, D.M. Newbold [60], S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev [61], C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, P. Dunne, A. Elwood, D. Futyan, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, R. Lucas [60], L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo,

J. Nash, A. Nikitenko [46], J. Pela, B. Penning, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, C. Seez, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta [62], T. Virdee [12], J. Wright, S.C. Zenz

Imperial College, London, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leslie, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Brunel University, Uxbridge, United Kingdom

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika

Baylor University, Waco, USA

O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

The University of Alabama, Tuscaloosa, USA

D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Boston University, Boston, USA

G. Benelli, E. Berry, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J.M. Hogan, O. Jesus, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, E. Spencer, R. Syarif

Brown University, Providence, USA

R. Breedon, G. Breto, D. Burns, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Davis, Davis, USA

R. Cousins, P. Everaerts, A. Florent, J. Hauser, M. Ignatenko, D. Saltzberg, E. Takasugi, V. Valuev, M. Weber

University of California, Los Angeles, USA

K. Burt, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, M. Malberti, M. Olmedo Negrete, M.I. Paneva, A. Shrinivas, H. Wei, S. Wimpenny, B.R. Yates

University of California, Riverside, Riverside, USA

J.G. Branson, G.B. Cerati, S. Cittolin, M. Derdzinski, R. Gerosa, A. Holzner, D. Klein, V. Krutelyov, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech [63], C. Welke, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, N. Mccoll, S.D. Mullin, A. Ovcharova, J. Richman, D. Stuart, I. Suarez, C. West, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA

D. Anderson, A. Apresyan, J. Bendavid, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, J.M. Lawhorn, A. Mott, H.B. Newman, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

California Institute of Technology, Pasadena, USA

M.B. Andrews, V. Azzolini, B. Carlson, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, K. Stenson, S.R. Wagner

University of Colorado Boulder, Boulder, USA

J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Cornell University, Ithaca, USA

D. Winn

Fairfield University, Fairfield, USA

S. Abdullin, M. Albrow, G. Apollinari, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, M. Cremonesi, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, D. Hare, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, C. Newman-Holmes [†], V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, S. Das, R.D. Field, I.K. Furic, J. Konigsberg, A. Korytov, P. Ma, K. Matchev, H. Mei, P. Milenovic [64], G. Mitselmakher, D. Rank, L. Shchutska, D. Sperka, L. Thomas, J. Wang, S. Wang, J. Yelton

University of Florida, Gainesville, USA

S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida International University, Miami, USA

A. Ackert, J.R. Adams, T. Adams, A. Askew, S. Bein, B. Diamond, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, A. Santra, M. Weinberg

Florida State University, Tallahassee, USA

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi [65], M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, P. Kurt, C. O'Brien, I.D. Sandoval Gonzalez, P. Turner, N. Varelas, H. Wang, Z. Wu, M. Zakaria, J. Zhang

University of Illinois at Chicago (UIC), Chicago, USA

B. Bilki [66], W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya [67], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok [68], A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

The University of Iowa, Iowa City, USA

I. Anderson, B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, M. Osherson, J. Roskes, U. Sarica, M. Swartz, M. Xiao, Y. Xin, C. You

Johns Hopkins University, Baltimore, USA

A. Al-bataineh, P. Baringer, A. Bean, J. Bowen, C. Bruner, J. Castle, R.P. Kenny III, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, S. Sanders, R. Stringer, J.D. Tapia Takaki, Q. Wang

The University of Kansas, Lawrence, USA

A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Kansas State University, Manhattan, USA

D. Lange, F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A.C. Mignerey, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

University of Maryland, College Park, USA

D. Abercrombie, B. Allen, A. Apyan, R. Barbieri, A. Baty, R. Bi, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, K. Krajczar, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Sumorok, K. Tatar, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

Massachusetts Institute of Technology, Cambridge, USA

A.C. Benvenuti, R.M. Chatterjee, A. Evans, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

E. Avdeeva, R. Bartek, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, D. Knowlton, I. Kravchenko, A. Malta Rodrigues, F. Meier, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

University of Nebraska-Lincoln, Lincoln, USA

M. Alyari, J. Dolen, J. George, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, A. Parker, S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, D. Baumgartel, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood

Northeastern University, Boston, USA

S. Bhattacharya, K.A. Hahn, A. Kubik, A. Kumar, J.F. Low, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

Northwestern University, Evanston, USA

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Marinelli, F. Meng, C. Mueller, Y. Musienko[34], M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, N. Valls, M. Wayne, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

J. Alimena, L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, R. Hughes, W. Ji, B. Liu, W. Luo, D. Puigh, B.L. Winer, H.W. Wulsin

The Ohio State University, Columbus, USA

S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, J. Luo, D. Marlow, T. Medvedeva, K. Mei, M. Mooney, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully, A. Zuranski

Princeton University, Princeton, USA

S. Malik

University of Puerto Rico, Mayaguez, USA

A. Barker, V.E. Barnes, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, K. Jung, D.H. Miller, N. Neumeister, B.C. Radburn-Smith, X. Shi, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu

Purdue University, West Lafayette, USA

N. Parashar, J. Stupak

Purdue University Calumet, Hammond, USA

A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, Z. Tu, J. Zabel

Rice University, Houston, USA

B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

University of Rochester, Rochester, USA

J.P. Chou, E. Contreras-Campana, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, K. Nash, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

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

M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

University of Tennessee, Knoxville, USA

O. Bouhali [69], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, E. Juska, T. Kamon [70], R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer

Texas A&M University, College Station, USA

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Dudero, J. Faulkner, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, S. Undleeb, I. Volobouev, Z. Wang

Texas Tech University, Lubbock, USA

A.G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

Vanderbilt University, Nashville, USA

M.W. Arenton, P. Barria, B. Cox, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA

C. Clarke, R. Harr, P.E. Karchin, P. Lamichhane, J. Sturdy

Wayne State University, Detroit, USA

D.A. Belknap, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, T. Ruggles, A. Savin, A. Sharma, N. Smith, W.H. Smith, D. Taylor, N. Woods

University of Wisconsin – Madison, Madison, WI, USA

† Deceased.
[1] Also at Vienna University of Technology, Vienna, Austria.
[2] Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.
[3] Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.
[4] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[5] Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[6] Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
[7] Also at Joint Institute for Nuclear Research, Dubna, Russia.
[8] Also at Ain Shams University, Cairo, Egypt.
[9] Now at British University in Egypt, Cairo, Egypt.
[10] Also at Zewail City of Science and Technology, Zewail, Egypt.
[11] Also at Université de Haute Alsace, Mulhouse, France.
[12] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[13] Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
[14] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[15] Also at University of Hamburg, Hamburg, Germany.
[16] Also at Brandenburg University of Technology, Cottbus, Germany.
[17] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[18] Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[19] Also at University of Debrecen, Debrecen, Hungary.
[20] Also at Indian Institute of Science Education and Research, Bhopal, India.
[21] Also at Institute of Physics, Bhubaneswar, India.
[22] Also at University of Visva-Bharati, Santiniketan, India.
[23] Also at University of Ruhuna, Matara, Sri Lanka.
[24] Also at Isfahan University of Technology, Isfahan, Iran.
[25] Also at University of Tehran, Department of Engineering Science, Tehran, Iran.
[26] Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[27] Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy.
[28] Also at Università degli Studi di Siena, Siena, Italy.
[29] Also at Purdue University, West Lafayette, USA.
[30] Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
[31] Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
[32] Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
[33] Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
[34] Also at Institute for Nuclear Research, Moscow, Russia.
[35] Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
[36] Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[37] Also at University of Florida, Gainesville, USA.
[38] Also at P.N. Lebedev Physical Institute, Moscow, Russia.
[39] Also at California Institute of Technology, Pasadena, USA.
[40] Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
[41] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[42] Also at INFN Sezione di Roma; Università di Roma, Roma, Italy.
[43] Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[44] Also at National and Kapodistrian University of Athens, Athens, Greece.
[45] Also at Riga Technical University, Riga, Latvia.
[46] Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[47] Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
[48] Also at Gaziosmanpasa University, Tokat, Turkey.
[49] Also at Mersin University, Mersin, Turkey.
[50] Also at Cag University, Mersin, Turkey.
[51] Also at Piri Reis University, Istanbul, Turkey.
[52] Also at Adiyaman University, Adiyaman, Turkey.
[53] Also at Ozyegin University, Istanbul, Turkey.
[54] Also at Izmir Institute of Technology, Izmir, Turkey.
[55] Also at Marmara University, Istanbul, Turkey.
[56] Also at Kafkas University, Kars, Turkey.
[57] Also at Istanbul Bilgi University, Istanbul, Turkey.

[58] Also at Yildiz Technical University, Istanbul, Turkey.
[59] Also at Hacettepe University, Ankara, Turkey.
[60] Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[61] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[62] Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
[63] Also at Utah Valley University, Orem, USA.
[64] Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[65] Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
[66] Also at Argonne National Laboratory, Argonne, USA.
[67] Also at Erzincan University, Erzincan, Turkey.
[68] Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[69] Also at Texas A&M University at Qatar, Doha, Qatar.
[70] Also at Kyungpook National University, Daegu, Republic of Korea.