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Observation of a peaking structure in the $J/\psi\phi$ mass spectrum from $B^{\pm} \to J/\psi\phi K^{\pm}$ decays

CMS Collaboration *

CERN, Switzerland

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ABSTRACT

A peaking structure in the $J/\psi\phi$ mass spectrum near threshold is observed in $B^{\pm} \to J/\psi\phi K^{\pm}$ decays, produced in pp collisions at $\sqrt{s} = 7$ TeV collected with the CMS detector at the LHC. The data sample, selected on the basis of the dimuon decay mode of the J/ψ, corresponds to an integrated luminosity of 5.2 fb^{-1}. Fitting the structure to an S-wave relativistic Breit–Wigner lineshape above a three-body phase-space nonresonant component gives a signal statistical significance exceeding five standard deviations. The fitted mass and width values are $m = 4148.0 \pm 2.4$ (stat.) ± 6.3 (syst.) MeV and $\Gamma = 28^{+15}_{-11}$ (stat.) $\pm$ 19 (syst.) MeV, respectively. Evidence for an additional peaking structure at higher $J/\psi\phi$ mass is also reported.

1. Introduction

The discovery of new charmonium-like states [1–6] over the last decade poses a challenge to the conventional quark model. Many explanations, such as charmed hybrids, tetraquarks, and molecular states, have been proposed for these new entities, but their nature remains a puzzle [7,8]. In 2009, the CDF Collaboration reported evidence for a narrow structure, which they called Y(4140), near the $J/\psi\phi$ threshold in $B^{\pm} \to J/\psi\phi K^{\pm}$ decays [9]. This structure, if confirmed as a new resonance, would be a candidate for an exotic meson [10–18]. The Belle Collaboration searched for the Y(4140) through the same $B^{\pm}$ decay channel [19] and in the two-photon process $\gamma\gamma \to J/\psi\phi$ [20], but did not confirm it. Using the same $B^{\pm}$ decay channel, the LHCb Collaboration recently reported finding no evidence for such a state, in disagreement with the CDF result [21].

In this Letter, a study of the $J/\psi\phi$ mass spectrum from $B^{+} \to J/\psi\phi K^{+}$ decays is reported, where charge conjugate decay modes are implied throughout. The data were collected in 2011 with the Compact Muon Solenoid (CMS) detector from proton–proton collisions at the Large Hadron Collider (LHC) operating at a center-of-mass energy of 7 TeV and corresponding to an integrated luminosity of 5.2 ± 0.1 fb^{-1} [22].

A detailed description of CMS can be found elsewhere [23]. The central feature of the CMS apparatus is a superconducting solenoid, 13 m long with a 6 m internal diameter, which provides an axial magnetic field of 3.8 T. Within the field volume is the silicon tracker, which consists of a pixel-based detector in the inner region and layers of microstrip detectors in the outer region. Charged-particle trajectories are measured with the silicon tracker, covering $0 < \phi \le 2\pi$ in azimuth and $|\eta| < 2.5$, where the pseudorapidity η is defined as $-\ln(\tan[\theta/2])$ and θ is the polar angle of the trajectory of the particle with respect to the counterclockwise-beam direction. Muons are detected in the pseudorapidity range $|\eta| < 2.4$ by three types of gas-ionization detectors embedded in the steel flux-return yoke of the magnet: drift tubes in the barrel, cathode strip chambers in the endcaps, and resistive-plate chambers in both the barrel and endcaps. The strong magnetic field and excellent position resolution of the silicon tracker enable the transverse momentum (p_T) of a muon matched to a reconstructed track to be measured with a resolution of approximately 0.7% for p_T of 1 GeV. The pixel detector, with its excellent spatial resolution and low occupancy, enables the separation of B^{+}-decay vertices from the primary interaction vertex.

Monte Carlo (MC) simulated data were created using PYTHIA6 [24] for the particle production, EVTGEN [25] for the particle decays, and GEANT4 [26] for tracing the particles through a detailed model of the detector. These samples were created with the appropriate conditions for the data analyzed, including the effects of alignment, efficiency, and number of simultaneous pp collisions.

2. Event selection

Events are chosen using a two-level trigger system. The first level, composed of custom hardware processors, uses information from the muon detectors to select dimuon candidates. The high-level trigger (HLT) runs a special version of the offline software

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

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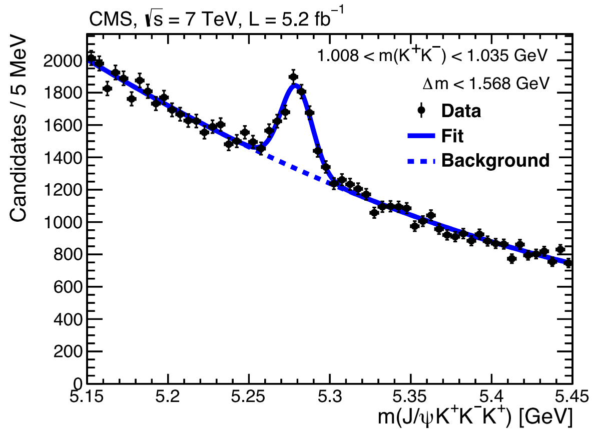

Fig. 1. The $J/\psi\phi K^+$ mass distribution with the standard event selection (left) and the tighter requirements (right). The solid curves show the result of fitting these distributions to a Gaussian signal and a second-degree polynomial background while the dashed curves show the background contribution.

code on a processor farm to select events with nonprompt J/ψ candidates coming from the decays of B mesons.

Events containing J/ψ candidates are selected by the HLT dimuon trigger. Because of the increasing LHC instantaneous luminosity, there are two configurations of the HLT, corresponding to two running periods and two distinct data sets. For both data sets, the following requirements are already applied with the HLT. The dimuon p_T is required to be greater than 6.9 GeV, the two muons must be oppositely charged and form a three-dimensional (3D) vertex with a χ^2 probability greater than 0.5–10%, depending on the running period. The resulting J/ψ vertex must be displaced from the average interaction point (beamspot) in the transverse plane by at least three times its uncertainty, which is the sum in quadrature of the secondary-vertex uncertainty and the beamspot size in the transverse plane. The cosine of the angle between the transverse projections of the line joining the beamspot and dimuon vertex and the dimuon momentum direction must exceed 0.9. For the later data set, there is an additional requirement that the p_T of each muon be greater than 4 GeV. In the final selection of J/ψ candidates, the dimuon p_T is required to be greater than 7 GeV, the χ^2 probability of the dimuon vertex is demanded to be greater than 10%, and the reconstructed dimuon invariant mass must be within 150 MeV of the J/ψ mass [27].

The $B^+ \to J/\psi\phi K^+$ candidates are reconstructed by combining three additional charged-particle tracks that are consistent with originating from the displaced J/ψ vertex and have a total charge of ± 1. These tracks are assigned the kaon mass and this mass is used in accounting for the effects of energy loss and multiple-scattering. We do not apply a mass constraint on the ϕ candidate because our experimental K^+K^- mass resolution (1.3 MeV) is less than the ϕ meson natural width (4.3 MeV). The p_T of all kaon tracks are required to be greater than 1 GeV. Only tracks that pass the standard CMS quality requirements [28] are used. The five tracks, with the $\mu^+\mu^-$ invariant mass constrained to the J/ψ mass, are required to form a good 3D vertex with a χ^2 probability greater than 1%. There are two K^+K^- combinations from the three charged kaon tracks, and we use the lower invariant mass as the ϕ candidate; MC simulations of the B^+ decay predict that the ϕ signal from the other combination is negligible, which is verified in the data. The reconstructed K^+K^- invariant mass must satisfy $1.008\ \text{GeV} < m(K^+K^-) < 1.035\ \text{GeV}$ to be considered as a ϕ candidate. These selection requirements were designed to maintain high efficiency for B^+ decays and were fixed before the $J/\psi\phi$ mass spectrum in data was examined.

3. Results

The invariant-mass spectrum of the selected $J/\psi\phi K^+$ candidates is shown in the left plot of Fig. 1 for a mass difference $\Delta m \equiv m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-) < 1.568$ GeV. We only investigate candidates with $\Delta m < 1.568$ GeV because of possible background from $B_s^0 \to \psi(2S)\phi \to J/\psi\pi^+\pi^-\phi$ at higher values, as discussed below. The invariant-mass spectrum is fit with a Gaussian signal function and a second-degree polynomial background function. The fit returns a B^+ mass of 5.2796 ± 0.0006 (stat.) GeV, which agrees with the nominal value [27], and a Gaussian width of 9.6 ± 0.7 (stat.) MeV, which is consistent with the prediction from the MC simulation. The B^+ yield is 2480 ± 160 (stat.) events, which is the world's largest $B^+ \to J/\psi\phi K^+$ sample. The combined B^+ yield is 2340 ± 120 (stat.) events when each data set is fit with two Gaussian signal functions and the width of each function is fixed to the prediction from MC simulation. Approximately 5% of the selected events have more than one B^+ candidate within 1.5 times our mass resolution (σ) of the B^+ mass; all candidates are kept.

The right plot in Fig. 1 displays the $J/\psi K^+K^-K^+$ invariant-mass distribution after making the following tighter requirements: the p_T of the kaons must be greater than 1.5 GeV, the B^+ vertex probability must be greater than 10%, the B^+ vertex must be displaced from the primary vertex in the transverse plane by at least seven times its uncertainty, and $m(K^+K^-)$ must be within 7 MeV of the ϕ meson mass [27]. With these requirements, 40% of the B^+ candidates are retained, while the background is reduced by more than a factor of ten. This sample of cleaner signal candidates is used as a cross-check of the results obtained by employing the background-corrected $J/\psi\phi$ mass spectrum, as described below. With the exception of this cross-check, all results are obtained with the less-restrictive criteria.

Fig. 2 shows the K^+K^- invariant-mass distribution for $J/\psi K^+K^-K^+$ candidates that have an invariant mass within $\pm 3\sigma$ of the B^+ mass. We define events in the range $[-12, -6]\sigma$ and $[6, 12]\sigma$ of the B^+ mass as sidebands. The ϕ mass restriction has been removed and a sideband subtraction has been performed in Fig. 2. We fit this distribution to a P-wave relativistic Breit–Wigner (BW) function convolved with a Gaussian resolution function. The width of the Gaussian is fixed to 1.3 MeV, obtained from MC simulation. The fit has a χ^2 probability of 23% and returns a mass of 1019.4 ± 0.1 MeV and a width of 4.7 ± 0.4 MeV, consistent with the ϕ meson [27]. The good fit to only a ϕ component in Fig. 2 indicates that after the J/ψ and ϕ mass requirements are made and the combinatorial background is subtracted, the

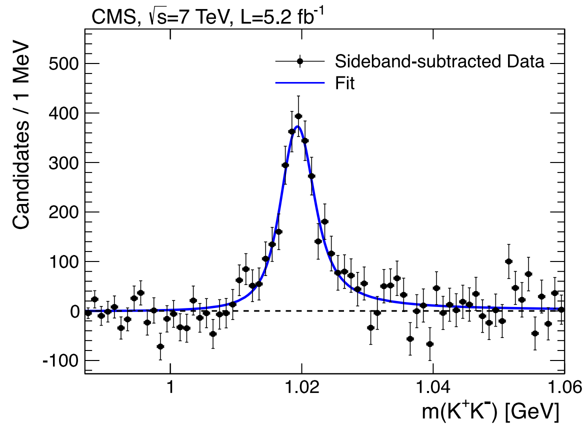

Fig. 2. The B^+ sideband-subtracted K^+K^- invariant-mass distribution for $J/\psi K^+K^-K^+$ candidates within $\pm 3\sigma$ of the nominal B^+ mass. The solid curve is the result of the fit described in the text. The dashed line shows the zero-candidate baseline.

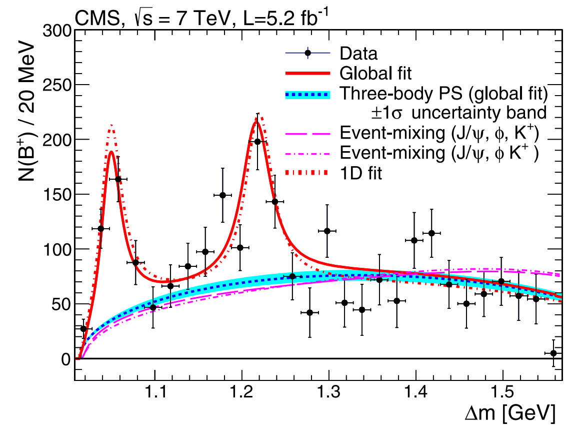

Fig. 3. The number of $B^+ \to J/\psi\phi K^+$ candidates as a function of $\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$. The solid curve is the global unbinned maximum-likelihood fit of the data, and the dotted curve is the background contribution assuming three-body PS. The band is the $\pm 1\sigma$ uncertainty range for the background obtained from the global fit. The dashed and dash-dotted curves are background curves obtained from two different event-mixing procedures, as described in the text, and normalized to the number of three-body PS background events. The short dashed curve is the 1D fit to the data.

$B^+ \to \mu^+\mu^-K^+K^-K^+$ candidates are consistent with being solely $J/\psi\phi K^+$, with negligible contribution from $J/\psi f_0(980)K^+$ or non-resonant $J/\psi K^+K^-K^+$.

As seen in Fig. 1, there are two main components to the $J/\psi\phi K^+$ invariant-mass spectrum: the B^+ signal and a smooth background. Possible contributions from other B-hadron decays are examined using MC simulations of inclusive B^+, B^0, and B^0_s decays. Based on this study, the mass-difference region ($\Delta m > 1.568$ GeV) is excluded from the analysis to avoid potential background from $B^0_s \to \psi(2S)\phi \to J/\psi\pi^+\pi^-\phi$ decays, where one pion is assumed to be a kaon and the other is not reconstructed.

To investigate the $J/\psi\phi$ invariant-mass distribution, rather than fitting the distribution itself with its large combinatorial background, the $J/\psi\phi K^+$ candidates are divided into 20 MeV-wide Δm intervals, and the $J/\psi\phi K^+$ mass distributions for each interval are fit to extract the B^+ signal yield in that interval. We use a second-degree polynomial for the combinatorial background and two Gaussians for the B^+ signal. The fit is performed separately for each data set. The mean values of the two Gaussians are fixed to the B^+ mass [27], and the width values of the Gaussians, as well as their relative ratio, are fixed to the values obtained from MC simulation for each specific Δm interval in each data set. The results of all the fits are good descriptions of the data distributions with an average χ^2 per degree of freedom (dof) close to 1. The resulting Δm distribution for the combined data sets is shown in Fig. 3. Two peaking structures are observed above the simulated phase-space (PS) continuum distribution shown by the dotted line.

Results obtained from both data sets are consistent. We have checked that events with multiple B^+ candidates do not artificially enhance the two structures. The total number of B^+ signal events in the Δm intervals below 1.568 GeV is 2320 ± 110 (stat.), which is consistent with the total number of B^+ candidates estimated from the mass spectrum in Fig. 1.

A full study of the $J/\psi\phi$ resonant pattern in the $B^+ \to \mu^+\mu^-K^+K^-K^+$ decay via an amplitude analysis of the five-body decay would require a data sample at least an order of magnitude larger than is currently available, as well as more precise information on possible ϕK^+ or $J/\psi K^+$ resonances that may contribute to this decay. Instead, the Δm distribution is studied, since it is related to the projection of the two-dimensional (2D) $J/\psi\phi K^+$ Dalitz plot onto the $m^2(J/\psi\phi)$ axis.

Before fitting the Δm distribution, it must be corrected for the relative detection and reconstruction efficiencies of the candidate events. Since no branching fractions are being determined, only the relative efficiency over the Dalitz plot is required. If a possible ϕK^+ or $J/\psi K^+$ resonance did exist, the density of events would depend on the quantum numbers of the resonance and on the interference of the two structures with the possible resonance. Ignoring these possible interference effects, the MC simulation is used to determine the efficiency over the $m^2(\phi K^+)$ vs. $m^2(J/\psi\phi)$ Dalitz plot, assuming a PS distribution for the three-body decay $B^+ \to J/\psi\phi K^+$. The J/ψ and ϕ vector meson decays are simulated using their known angular distributions according to the VLL and VSS model in EVTGEN, while we assume there is no polarization for the two vectors. The PS MC simulation is reweighted assuming either transverse or longitudinal J/ψ and ϕ polarization. The effect of either polarization is found to be negligible. The measured efficiency is fairly uniform, varying by less than 25% over the entire allowed three-body PS. Assuming a uniform PS distribution, the efficiency for each Δm bin is taken to be the average of the efficiencies over the full kinematically allowed $m(\phi K^+)$ range. To estimate the systematic uncertainty in the efficiency caused by its dependence on the unknown quantum numbers of the structures, and hence on their unknown decay angular distributions, the efficiency is evaluated under the assumption of both a $\cos^2\theta$ and $\sin^2\theta$ dependence, where θ is the helicity angle, defined as the angle in the $J/\psi\phi$ rest frame between the direction of the boost from the laboratory frame and the J/ψ direction. Since the efficiency tends to be lower towards the edge of the Dalitz plot, the $\cos^2\theta$ dependence gives a lower average efficiency than the default efficiency, while the $\sin^2\theta$ dependence gives a slightly higher average efficiency. This variation (10%) is taken as the systematic uncertainty in the efficiency from our lack of knowledge of the quantum numbers of the structures and the effects of interference with possible two-body resonances.

We investigate the possibility that the two structures in the Δm distribution are caused by reflections from resonances in the other two-body systems, $J/\psi K^+$ and ϕK^+. Such reflections are well known in the two-body systems from other three-body decays because of kinematic constraints. There are candidate states that decay to ϕK^+ [27], although they are not well established. These could potentially produce reflected structures in the $J/\psi\phi$ spectrum. In particular, a D-wave contribution to K^-p scattering in the mass region around 1.7–1.8 GeV has been reported by several fixed-target experiments [29–31]. This is interpreted as two interfering broad $J^P = 2^-$ resonances, labeled $K_2(1770)$ and

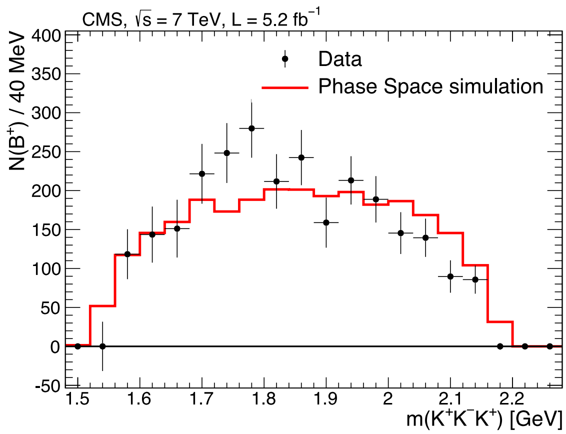

Fig. 4. The yield of $B^+ \to J/\psi K^+K^-K^+$ candidates in the data as a function of the $K^+K^-K^+$ invariant mass. The error bars represent the statistical uncertainties. The solid curve is the prediction from the PS simulation.

$K_2(1820)$, with widths in the range 200–300 MeV. These resonances at relatively low ϕK^+ mass cannot affect the $J/\psi\phi$ structure near threshold, but could contribute to the second $J/\psi\phi$ structure near $\Delta m = 1.2$ GeV. To study possible reflections from the ϕK^+ spectrum, we consider ϕK^+ resonances with various masses, widths, and helicity angle distributions, but are not able to reproduce the pattern of structures seen in the $J/\psi\phi$ spectrum. Moreover, we separately analyze the $J/\psi\phi$ spectrum for values of the ϕK^+ masses larger than 1.9 GeV, a region of the Dalitz plot unaffected by postulated ϕK^+ resonances, and still observe the structure near $\Delta m = 1.2$ GeV.

There are no candidate $J/\psi K^+$ resonances reported in the literature. Still, we have considered such resonances with various masses, widths, and helicity angle distributions. No combination produces a reflected spectrum that matches the observed $J/\psi\phi$ spectrum.

We have also checked the events with Δm larger than 1.568 GeV that had been eliminated from the analysis to ensure that they could not cause similar reflections in the low-Δm region. After subtraction of the B^0_s background the Δm distribution of events with Δm larger than 1.568 GeV is consistent with the prediction based on the three-body phase-space hypothesis for the nonresonant background. (Please see the supplemental material in the online version at http://dx.doi.org/10.1016/j.physletb.2014.05.055 for plots.)

The results of these studies make it improbable that the two structures seen in the $J/\psi\phi$ spectrum are solely caused by reflections from resonances in the other two-body systems. However, we cannot entirely exclude the possibility of such resonances. For instance, the $K^+K^-K^+$ spectrum shown in Fig. 4 displays an excess of events above the predicted PS distribution in the 1.7–1.8 GeV region, an excess that cannot be attributed to the presence of the $J/\psi\phi$ structure near threshold. Fig. 4 is obtained by dividing the $J/\psi\phi K^+$ candidates into 40 MeV-wide $K^+K^-K^+$ mass intervals and fitting the $J/\psi\phi K^+$ invariant-mass distributions for each interval to extract the B^+ signal yield in that interval. The Δm distribution after excluding the region $(1.68 < m(K^+K^-K^+) < 1.88$ GeV) with the excess of events is shown in the left plot of Fig. 5 and the corresponding distribution for the excluded Δm region in the right plot. The presence of the lower-mass structure is still apparent in the left plot, while that of the higher-mass structure is reduced though still visible. Possible interference effects over the Dalitz plot could therefore distort the shape of the observed $J/\psi\phi$ structures and affect the extraction of the resonance parameters. The event sample is not large enough to investigate these effects further. We assume that any interference effects can be neglected. The structures in the $J/\psi\phi$ mass spectrum are described in terms of zero, one, or two noninterfering resonances and a nonresonant continuum component.

We fit the two structures with S-wave relativistic BW functions convolved with a Gaussian mass resolution function whose width varies linearly from 1 MeV at threshold to about 4 MeV at $\Delta m = 1.25$ GeV, as determined from simulation. Each structure is described by a mass, width, and yield, all determined from the fit. The continuum is assumed to follow a three-body PS shape. As an alternative, to check the sensitivity of the result to this assumption, the shape of the continuum is obtained from an event-mixing technique where the J/ψ, ϕ, and K^+ candidates are selected from different events. We use two versions of the event mixing, which differ by the ϕ and K^+ candidates being selected in the same event or not; they lead to almost identical shapes. The differences between the two event-mixing shapes and the three-body PS are used to evaluate the systematic uncertainties in the continuum modeling. To further investigate the effect of a possible ϕK^+ resonance around 1.7 GeV as shown in Fig. 4, we reweight our phase-space MC events with a ϕK^+ mass distribution corresponding to a BW with a mass of 1.773 GeV and a width of 200–300 MeV [27]. The helicity angle in the ϕK^+ system is then weighted to correspond to several different assumptions about the decay of the possible resonance. We estimate the yield of the possible ϕK^+ resonance in Fig. 4 to be 10% of the total number of events. We find that the shape of the PS Δm distribution is always above the various distributions obtained from the above mixing in the range $\Delta m < 1.12$ GeV. Thus, we conclude that using the PS distribution

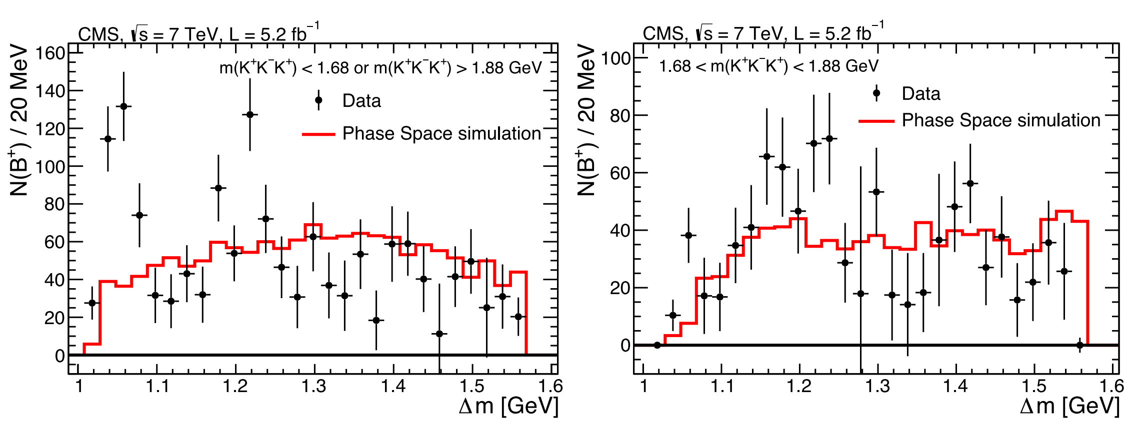

Fig. 5. The number of $B^+ \to J/\psi\phi K^+$ candidates as a function of Δm requiring either $m(\phi K^+) < 1.68$ GeV or $m(\phi K^+) > 1.88$ GeV (left), or $1.68 < m(\phi K^+) < 1.88$ GeV (right). The solid curve is the prediction from the PS simulation.

as the default background curve is more conservative with respect to the significance of the low-mass peak if there is a possible effect from a ϕK^+ resonance.

The masses and widths of the two structures are extracted by dividing the $J/\psi\phi K^+$ candidates into 20 MeV-wide intervals of Δm from 1.008 to 1.568 GeV and performing a global unbinned maximum-likelihood (UML) fit to the $J/\psi\phi K^+$ invariant-mass distribution in each Δm interval. The two data sets are fitted separately, with a total of 56 mass spectra fitted simultaneously. In each fit, the B^+ mass is fixed to its nominal value and the mass resolution δ is calculated using:

$$\delta = a_0 + a_1\langle\Delta m\rangle + a_2\langle\Delta m\rangle^2,$$

where $\langle\Delta m\rangle$ is the value of Δm at the center of the bin, and a_0, a_1, and a_2 are determined from simulation, separately for the two data sets. The combinatorial background in each bin is modeled as a second-degree polynomial. In the global fit, the B^+ yield is expressed as the product of the relative efficiency times the number of signal events from the two BWs and the nonresonant continuum events. We fit the $J/\psi\phi K^+$ invariant-mass distribution for each Δm bin from the two data sets simultaneously by projecting the above product into each bin. The UML fit returns signal event yields of 310 ± 70 (stat.) and 418 ± 170 (stat.) for the lower- and higher-mass structures, respectively. The corresponding mass difference and width values are: $\Delta m_1 = 1051.3 \pm 2.4$ (stat.) MeV, $\Gamma_1 = 28^{+15}_{-11}$ (stat.) MeV; $\Delta m_2 = 1217.1 \pm 5.3$ (stat.) MeV, $\Gamma_2 = 38^{+30}_{-15}$ (stat.) MeV. The projection of the UML fit assuming two structures onto the $J/\psi\phi$ mass spectrum is represented as the solid line in Fig. 3.

As a check on the fitting procedure, we perform an alternative one-dimensional (1D) binned χ^2 fit to the Δm spectrum shown in Fig. 3. The same signal and background functions are used in the 1D fit as in the global fit. The result of the 1D fit, assuming two structures, is shown as the dashed line in Fig. 3. The measurements of the masses, widths, and yields of the two structures from the global and 1D fits are in good agreement.

To evaluate the significance of each of the two structures, three UML and three 1D (binned χ^2) fits are performed on the data shown in Fig. 3: (1) a background-only fit (null-hypothesis); (2) a background plus a single S-wave relativistic BW signal function convolved with a Gaussian resolution function having a width of 2 MeV for the lower-mass structure; and (3) a background plus two S-wave relativistic BW functions convolved with a Gaussian resolution function to model both structures. The log-likelihood ratio $-2\Delta\ln\mathcal{L}$ in the case of the UML fits or the χ^2 change $\Delta\chi^2$ for the 1D fits between (1) and (2) is then a measure of the statistical significance of the lower-mass structure, while the corresponding values between fits (2) and (3) give a measure of the statistical significance of the higher-mass structure. The resulting values for a decrease in dof of 3 are $-2\Delta\ln\mathcal{L} = 58$ and $\Delta\chi^2 = 53$ for the lower-mass structure, and 36 and 37 for the higher-mass structure.

Simulated samples are used to estimate the probability that background fluctuations alone could give rise to a signal as significant as that seen in the data for the lower-mass structure. Over 50 million Δm spectra were generated between 1.008 and 1.568 GeV with 2300 events for each spectrum based on a three-body PS shape. The most significant fluctuation in each spectrum is found whose $J/\psi\phi$ invariant mass is within ± 3 times the uncertainty in the CDF mass value of 4.140 GeV and having a width between 10 MeV (half the Δm bin width) to 80 MeV (half the separation between the two structures). We then obtain the $\Delta\chi^2$ distributions in the simulated pure background samples and compare them with the corresponding value of the signal in the data.

Table 1
Systematic uncertainties in the measured masses and widths of the two peaking structures from the sources listed and the total uncertainties.

	m_1 (MeV)	Γ_1 (MeV)	m_2 (MeV)	Γ_2 (MeV)
B^+ background PDF	0.8	7.4	2.6	9.9
B^+ signal PDF	0.2	3.6	2.7	0.2
Relative efficiency	4.8	6.0	0.9	10.0
Δm binning	3.7	1.5	2.7	0.2
Δm structure PDF	0.8	9.3	0.6	4.9
Δm mass resolution	0.8	6.4	0.6	4.6
Δm background shape	0.2	7.0	0.3	0.2
Selection requirements	0.8	7.8	5.5	1.8
Total	6.3	19	7.3	16

No generated spectrum is found with a fluctuation having a $\Delta\chi^2$ greater than or equal to the value obtained in the data (53). The resulting p-value, taken as the fraction of the simulated samples with a $\Delta\chi^2$ value greater than or equal to the value obtained in the data, is less than 2×10^{-8}, which corresponds to a significance of more than 5 standard deviations. Because the second structure could be affected by possible ϕK^+ resonances, it is difficult to model the background shape in that mass range, and we do not quote a numeric significance for the higher-mass structure. However, there is clear evidence for a second structure around $\Delta m = 1.2$ GeV even after excluding the region with possible K_2 resonances. There is also a small excess of events around $\Delta m = 1.4$ GeV, but with a local significance of less than 3 standard deviations.

Various checks are made to examine the robustness of the two structures. Each selection criterion is individually varied, and in no case is there an indication of a bias in the selection procedure. The relative efficiencies for the first five Δm bins are varied by $\pm 20\%$ and the fit repeated, confirming the robustness of the significance of the first structure. The Δm distribution from an sPlot [32] projection is compared to the Δm distribution shown in Fig. 3. No indication of bias is found. The sPlot algorithm is a background-subtraction technique that weights each event based on the observed signal-to-background ratio, in this case from the fit to the $J/\psi\phi K^+$ mass distribution shown in Fig. 1. We repeat the analysis with the tighter requirements discussed earlier that lower the combinatorial background level by a factor of ten and retain 40% of the B^+ events, as shown in the right plot in Fig. 1. The Δm plot for these events looks similar to Fig. 3, showing two peaking structures whose fitted mass and width values are consistent with the results from the nominal data sample. No indication of a possible bias is found.

The estimations of the contributions to the systematic uncertainties in the mass and width measurements of the two structures shown in Table 1, are determined from several studies. The uncertainties owing to the probability density functions (PDFs) for the combinatorial background shape in the $m(J/\psi\phi K^+)$ spectrum and the B^+ signal are studied by using different PDFs such as first- and third-degree polynomials, exponential functions, and a number of Gaussian functions. The uncertainties in the shape of the relative efficiency vs. Δm are evaluated by varying the relative efficiency in various bins and comparing with the 2D efficiencies for correction of $m(J/\psi\phi)$ vs. $m(\phi K^+)$. The uncertainties caused by the binning of the Δm spectrum are studied by using 10 MeV bins instead of 20 MeV bins. To estimate the uncertainty from the signal fitting function, we repeat the fit to the Δm distribution using either a nonrelativistic BW or a P-wave relativistic BW function for each structure. The uncertainties from the Δm mass resolution are studied by varying the mass resolution values obtained from simulation within their statistical uncertainties. To evaluate potential distortions in the Δm background shape caused by possible ϕK^+

resonances, we obtain the Δm background shape from data using an event-mixing technique by applying the same kinematic constraints and taking the ϕ and K^+ candidates from the same event, but the J/ψ candidate from a different event. The uncertainties due to selection requirements are studied in the MC sample. The overall systematic uncertainties in the measurement of the masses and widths of the two structures are found by adding in quadrature the individual combinations summarized in Table 1.

4. Summary

In summary, a peaking structure in the $J/\psi\phi$ mass spectrum from $B^+ \to J/\psi\phi K^+$ decays has been observed in pp collisions at $\sqrt{s} = 7$ TeV by the CMS Collaboration at the LHC. Assuming an S-wave relativistic BW lineshape for this structure above a three-body PS shape for the nonresonant background, a statistical significance of greater than 5 standard deviations is found. Adding the J/ψ mass [27] to the extracted Δm values, the mass and width are measured to be $m_1 = 4148.0 \pm 2.4$ (stat.) ± 6.3 (syst.) MeV and $\Gamma_1 = 28^{+15}_{-11}$ (stat.) ± 19 (syst.) MeV. The measured mass and width are consistent with the Y(4140) values reported by CDF experiment. The relative branching fraction of this peaking structure with respect to the total number of $B^+ \to J/\psi\phi K^+$ events is estimated to be about 0.10, with a statistical uncertainty of about 30%. This is consistent with both the value measured by CDF of $15\% \pm 5\%$ and the upper limit reported by LHCb (0.07). In addition, evidence for a second peaking structure is found in the same mass spectrum, with measured mass and width values of $m_2 = 4313.8 \pm 5.3$ (stat.) ± 7.3 (syst.) MeV and $\Gamma_2 = 38^{+30}_{-15}$ (stat.) ± 16 (syst.) MeV. Because of possible reflections from two-body decays, the statistical significance of the second structure cannot be reliably determined. The two structures are well above the threshold of open charm ($D\bar{D}$) decays and have relatively narrow widths. Conventional charmonium mesons with these masses would be expected to have larger widths and to decay predominantly into open charm pairs with small branching fractions into $J/\psi\phi$. Angular analyses of the $B^+ \to J/\psi\phi K^+$ decays would help elucidate the nature of these structures.

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CMS Collaboration

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

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan [1], M. Friedl, R. Frühwirth [1], V.M. Ghete, N. Hörmann, J. Hrubec, M. Jeitler [1], W. Kiesenhofer, V. Knünz, M. Krammer [1], I. Krätschmer, D. Liko, I. Mikulec, D. Rabady [2], B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, 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, M. Bansal, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, S. Luyckx, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, Z. Staykova, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Universiteit Antwerpen, Antwerpen, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, A. Kalogeropoulos, J. Keaveney, M. Maes, A. Olbrechts, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Vrije Universiteit Brussel, Brussel, Belgium

B. Clerbaux, G. De Lentdecker, L. Favart, A.P.R. Gay, T. Hreus, A. Léonard, P.E. Marage, A. Mohammadi, L. Perniè, T. Reis, T. Seva, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang

Université Libre de Bruxelles, Bruxelles, Belgium

V. Adler, K. Beernaert, L. Benucci, A. Cimmino, S. Costantini, S. Dildick, G. Garcia, B. Klein, J. Lellouch, A. Marinov, J. Mccartin, A.A. Ocampo Rios, D. Ryckbosch, M. Sigamani, N. Strobbe, F. Thyssen, M. Tytgat, S. Walsh, E. Yazgan, N. Zaganidis

Ghent University, Ghent, Belgium

S. Basegmez, C. Beluffi [3], G. Bruno, R. Castello, A. Caudron, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco [4], J. Hollar, P. Jez, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrzkowski, A. Popov [5], M. Selvaggi, J.M. Vizan Garcia

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

N. Beliy, T. Caebergs, E. Daubie, G.H. Hammad

Université de Mons, Mons, Belgium

G.A. Alves, M. Correa Martins Junior, T. Martins, M.E. Pol, M.H.G. Souza

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, W. Carvalho, J. Chinellato [6], A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, M. Malek, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote [6], A. Vilela Pereira

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

C.A. Bernardes [b], F.A. Dias [a,7], T.R. Fernandez Perez Tomei [a], E.M. Gregores [b], C. Lagana [a], F. Marinho [a], P.G. Mercadante [b], S.F. Novaes [a], Sandra S. Padula [a]

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

V. Genchev [2], P. Iaydjiev [2], S. Piperov, M. Rodozov, G. Sultanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Dimitrov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu

Institute of High Energy Physics, Beijing, China

C. Asawatangtrakuldee, Y. Ban, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, D. Wang, L. Zhang, W. Zou

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

C. Avila, C.A. Carrillo Montoya, L.F. Chaparro Sierra, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, R. Plestina [8], D. Polic, I. Puljak

Technical University of Split, Split, Croatia

Z. Antunovic, M. Kovac

University of Split, Split, Croatia

V. Brigljevic, S. Duric, K. Kadija, J. Luetic, D. Mekterovic, S. Morovic, L. Tikvica

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M. Finger, M. Finger Jr.

Charles University, Prague, Czech Republic

A.A. Abdelalim [9], Y. Assran [10], S. Elgammal [9], A. Ellithi Kamel [11], M.A. Mahmoud [12], A. Radi [13,14]

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

M. Kadastik, M. Müntel, M. Murumaa, M. Raidal, L. Rebane, A. Tiko

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, G. Fedi, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

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

Helsinki Institute of Physics, Helsinki, Finland

A. Korpela, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, S. Choudhury, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault [*], P. Jarry, E. Locci, J. Malcles, L. Millischer, A. Nayak, J. Rander, A. Rosowsky, M. Titov

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj [15], P. Busson, C. Charlot, N. Daci, T. Dahms, M. Dalchenko, L. Dobrzynski, A. Florent, R. Granier de Cassagnac, M. Haguenauer, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

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

J.-L. Agram [16], J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte [16], F. Drouhin [16], J.-C. Fontaine [16], D. Gelé, U. Goerlach, C. Goetzmann, P. Juillot, A.-C. Le Bihan, 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, N. Beaupere, G. Boudoul, S. Brochet, J. Chasserat, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, L. Sgandurra, V. Sordini, Y. Tschudi, 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

Z. Tsamalaidze [17]

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia

C. Autermann, S. Beranek, B. Calpas, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, K. Klein, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov [5]

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

M. Ata, J. Caudron, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, P. Kreuzer, M. Merschmeyer, A. Meyer, M. Olschewski, K. Padeken, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, S. Thüer, M. Weber

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

V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, J. Lingemann [2], A. Nowack, I.M. Nugent, L. Perchalla, O. Pooth, A. Stahl

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

M. Aldaya Martin, I. Asin, N. Bartosik, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz [18], A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, F. Costanza, C. Diez Pardos, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, J. Leonard, K. Lipka, W. Lohmann [18], B. Lutz, R. Mankel, I. Marfin, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, O. Novgorodova, F. Nowak, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, R. Placakyte, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, M.Ö. Sahin, J. Salfeld-Nebgen, R. Schmidt [18], T. Schoerner-Sadenius, N. Sen, M. Stein, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

V. Blobel, H. Enderle, J. Erfle, U. Gebbert, M. Görner, M. Gosselink, J. Haller, K. Heine, R.S. Höing, G. Kaussen, H. Kirschenmann, R. Klanner, R. Kogler, J. Lange, I. Marchesini, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, J. Sibille [19], V. Sola, H. Stadie, G. Steinbrück, J. Thomsen, D. Troendle, L. Vanelderen

University of Hamburg, Hamburg, Germany

C. Barth, C. Baus, J. Berger, C. Böser, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff [2], F. Hartmann [2], T. Hauth [2], H. Held, K.H. Hoffmann, U. Husemann, I. Katkov [5], J.R. Komaragiri, A. Kornmayer [2], P. Lobelle Pardo, D. Martschei, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, J. Ott, G. Quast, K. Rabbertz, F. Ratnikov, S. Röcker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

G. Anagnostou, G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, A. Markou, C. Markou, E. Ntomari

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

L. Gouskos, T.J. Mertzimekis, A. Panagiotou, N. Saoulidou, E. Stiliaris

University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

G. Bencze, C. Hajdu, P. Hidas, D. Horvath [20], B. Radics, F. Sikler, V. Veszpremi, G. Vesztergombi [21], A.J. Zsigmond

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Molnar, J. Palinkas, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

J. Karancsi, P. Raics, Z.L. Trocsanyi, B. Ujvari

University of Debrecen, Debrecen, Hungary

S.K. Swain [22]

National Institute of Science Education and Research, Bhubaneswar, India

S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Kaur, M.Z. Mehta, M. Mittal, N. Nishu, L.K. Saini, A. Sharma, J.B. Singh

Panjab University, Chandigarh, India

Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, S. Malhotra, M. Naimuddin, K. Ranjan, P. Saxena, V. Sharma, R.K. Shivpuri

University of Delhi, Delhi, India

S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, A. Modak, S. Mukherjee, D. Roy, S. Sarkar, M. Sharan, A.P. Singh

Saha Institute of Nuclear Physics, Kolkata, India

A. Abdulsalam, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty [2], L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, R.M. Chatterjee, S. Ganguly, S. Ghosh, M. Guchait [23], A. Gurtu [24], G. Kole, S. Kumar, M. Maity [25], G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage [26]

Tata Institute of Fundamental Research – EHEP, Mumbai, India

S. Banerjee, S. Dugad

Tata Institute of Fundamental Research – HECR, Mumbai, India

H. Arfaei [27], H. Bakhshiansohi, S.M. Etesami [28], A. Fahim [27], H. Hesari, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh [29], M. Zeinali

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

M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia [a,b], L. Barbone [a,b], C. Calabria [a,b], S.S. Chhibra [a,b], A. Colaleo [a], D. Creanza [a,c], N. De Filippis [a,c], M. De Palma [a,b], L. Fiore [a], G. Iaselli [a,c], G. Maggi [a,c], M. Maggi [a], B. Marangelli [a,b], S. My [a,c], S. Nuzzo [a,b], N. Pacifico [a], A. Pompili [a,b], G. Pugliese [a,c], G. Selvaggi [a,b], L. Silvestris [a], G. Singh [a,b], R. Venditti [a,b], P. Verwilligen [a], G. Zito [a]

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

G. Abbiendi [a], A.C. Benvenuti [a], 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], 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,2], M. Meneghelli [a,b], A. Montanari [a], F.L. Navarria [a,b], F. Odorici [a], A. Perrotta [a], F. Primavera [a,b], A.M. Rossi [a,b], T. Rovelli [a,b], G.P. Siroli [a,b], N. Tosi [a,b], R. Travaglini [a,b]

[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], F. Giordano [a,2], 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], S. Frosali [a,b], E. Gallo [a], S. Gonzi [a,b], V. Gori [a,b], P. Lenzi [a,b], M. Meschini [a], S. Paoletti [a], G. Sguazzoni [a], A. Tropiano [a,b]

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

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

P. Fabbricatore [a], R. Musenich [a], S. Tosi [a,b]

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

A. Benaglia [a], F. De Guio [a,b], L. Di Matteo [a,b], S. Fiorendi [a,b], S. Gennai [a], A. Ghezzi [a,b], P. Govoni [a,b], M.T. Lucchini [a,b,2], S. Malvezzi [a], R.A. Manzoni [a,b,2], A. Martelli [a,b,2], D. Menasce [a], L. Moroni [a], M. Paganoni [a,b], D. Pedrini [a], S. Ragazzi [a,b], N. Redaelli [a], 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], A. De Cosa [a,b], F. Fabozzi [a,c], A.O.M. Iorio [a,b], L. Lista [a], S. Meola [a,d,2], M. Merola [a], P. Paolucci [a,2]

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

P. Azzi [a], N. Bacchetta [a], M. Bellato [a], D. Bisello [a,b], A. Branca [a,b], R. Carlin [a,b], P. Checchia [a], T. Dorigo [a], M. Galanti [a,b,2], F. Gasparini [a,b], U. Gasparini [a,b], P. Giubilato [a,b], F. Gonella [a], A. Gozzelino [a], K. Kanishchev [a,c], S. Lacaprara [a], I. Lazzizzera [a,c], M. Margoni [a,b], A.T. Meneguzzo [a,b], F. Montecassiano [a], J. Pazzini [a,b], N. Pozzobon [a,b], P. Ronchese [a,b], F. Simonetto [a,b], E. Torassa [a], M. Tosi [a,b], S. Vanini [a,b], 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), Padova, Italy

M. Gabusi [a,b], S.P. Ratti [a,b], C. Riccardi [a,b], P. Vitulo [a,b]

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

M. Biasini [a,b], G.M. Bilei [a], L. Fanò [a,b], P. Lariccia [a,b], G. Mantovani [a,b], M. Menichelli [a], A. Nappi [a,b,†], F. Romeo [a,b], A. Saha [a], A. Santocchia [a,b], A. Spiezia [a,b]

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

K. Androsov [a,30], P. Azzurri [a], G. Bagliesi [a], J. Bernardini [a], T. Boccali [a], G. Broccolo [a,c], R. Castaldi [a], R.T. D'Agnolo [a,c,2], R. Dell'Orso [a], F. Fiori [a,c], L. Foà [a,c], A. Giassi [a], M.T. Grippo [a,30], A. Kraan [a], F. Ligabue [a,c], T. Lomtadze [a], L. Martini [a,30], A. Messineo [a,b], F. Palla [a], A. Rizzi [a,b], A.T. Serban [a], P. Spagnolo [a], P. Squillacioti [a], R. Tenchini [a], G. Tonelli [a,b], A. Venturi [a], P.G. Verdini [a], C. Vernieri [a,c]

[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], D. Del Re [a,b], M. Diemoz [a], M. Grassi [a,b,2], E. Longo [a,b], F. Margaroli [a,b], P. Meridiani [a], F. Micheli [a,b], S. Nourbakhsh [a,b], G. Organtini [a,b], R. Paramatti [a], S. Rahatlou [a,b], L. Soffi [a,b]

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

N. Amapane [a,b], R. Arcidiacono [a,c], S. Argiro [a,b], M. Arneodo [a,c], C. Biino [a], N. Cartiglia [a], S. Casasso [a,b], M. Costa [a,b], N. Demaria [a], C. Mariotti [a], S. Maselli [a], E. Migliore [a,b], V. Monaco [a,b], M. Musich [a], M.M. Obertino [a,c], G. Ortona [a,b], N. Pastrone [a], M. Pelliccioni [a,2], A. Potenza [a,b], A. Romero [a,b], M. Ruspa [a,c], R. Sacchi [a,b], A. Solano [a,b], A. Staiano [a], U. Tamponi [a]

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

S. Belforte [a], V. Candelise [a,b], M. Casarsa [a], F. Cossutti [a,2], G. Della Ricca [a,b], B. Gobbo [a], C. La Licata [a,b], M. Marone [a,b], D. Montanino [a,b], A. Penzo [a], A. Schizzi [a,b], A. Zanetti [a]

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

S. Chang, T.Y. Kim, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, Y.D. Oh, H. Park, D.C. Son

Kyungpook National University, Daegu, Republic of Korea

J.Y. Kim, Zero J. Kim, S. Song

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

S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, T.J. Kim, K.S. Lee, S.K. Park, Y. Roh

Korea University, Seoul, Republic of Korea

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

University of Seoul, Seoul, Republic of Korea

Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, E. Kwon, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

I. Grigelionis, A. Juodagalvis

Vilnius University, Vilnius, Lithuania

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz [31], R. Lopez-Fernandez, J. Martínez-Ortega, A. Sanchez-Hernandez, L.M. Villasenor-Cendejas

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

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

H.A. Salazar Ibarguen

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

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

D. Krofcheck

University of Auckland, Auckland, New Zealand

A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

University of Canterbury, Christchurch, New Zealand

M. Ahmad, M.I. Asghar, J. Butt, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

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

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

National Centre for Nuclear Research, Swierk, Poland

G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, W. Wolszczak

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

N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Rodrigues Antunes, J. Seixas [2], J. Varela, P. Vischia

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

S. Afanasiev, P. Bunin, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, G. Kozlov, A. Lanev, A. Malakhov, V. Matveev, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, N. Skatchkov, V. Smirnov, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

S. Evstyukhin, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

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

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

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, M. Erofeeva, V. Gavrilov, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, A. Spiridonov, V. Stolin, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Belyaev, E. Boos, M. Dubinin [7], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

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

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

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

P. Adzic [32], M. Djordjevic, M. Ekmedzic, D. Krpic [32], J. Milosevic

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

M. Aguilar-Benitez, J. Alcaraz Maestre, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas [2], N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, E. Navarro De Martino, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

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

C. Albajar, J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J. Piedra Gomez

Universidad de Oviedo, Oviedo, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, A. Graziano, C. Jorda, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, 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, J. Bendavid, J.F. Benitez, C. Bernet [8], G. Bianchi, P. Bloch, A. Bocci, A. Bonato, O. Bondu, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, S. Colafranceschi [33], D. d'Enterria, A. Dabrowski, A. De Roeck, S. De Visscher, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, J. Eugster, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Girone, M. Giunta, F. Glege, R. Gomez-Reino Garrido, S. Gowdy, R. Guida, J. Hammer, M. Hansen, P. Harris, C. Hartl, A. Hinzmann, V. Innocente, P. Janot, E. Karavakis, K. Kousouris, K. Krajczar, P. Lecoq, Y.-J. Lee, C. Lourenço, N. Magini, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, L. Moneta, R. Moser, M. Mulders, P. Musella, E. Nesvold, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzi, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, M. Plagge, G. Polese, L. Quertenmont, A. Racz, W. Reece, G. Rolandi [34], C. Rovelli [35], M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas [36], D. Spiga, M. Stoye, A. Tsirou, G.I. Veres [21], J.R. Vlimant, H.K. Wöhri, S.D. Worm [37], W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

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

Paul Scherrer Institut, Villigen, Switzerland

F. Bachmair, L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Lustermann, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli [38], P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov [39], B. Stieger, M. Takahashi, L. Tauscher [†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

C. Amsler [40], V. Chiochia, C. Favaro, M. Ivova Rikova, B. Kilminster, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Taroni, S. Tupputi, M. Verzetti

Universität Zürich, Zurich, Switzerland

M. Cardaci, K.H. Chen, C. Ferro, C.M. Kuo, S.W. Li, W. Lin, Y.J. Lu, R. Volpe, S.S. Yu

National Central University, Chung-Li, Taiwan

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J.G. Shiu, Y.M. Tzeng, M. Wang

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, N. Suwonjandee

Chulalongkorn University, Bangkok, Thailand

A. Adiguzel, M.N. Bakirci [41], S. Cerci [42], C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, A. Kayis Topaksu, G. Onengut [43], K. Ozdemir, S. Ozturk [41], A. Polatoz, K. Sogut [44], D. Sunar Cerci [42], B. Tali [42], H. Topakli [41], M. Vergili

Cukurova University, Adana, Turkey

I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, G. Karapinar [45], K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, B. Isildak [46], M. Kaya [47], O. Kaya [47], S. Ozkorucuklu [48], N. Sonmez [49]

Bogazici University, Istanbul, Turkey

H. Bahtiyar [50], E. Barlas, K. Cankocak, Y.O. Günaydin [51], F.I. Vardarlı, M. Yücel

Istanbul Technical University, Istanbul, Turkey

L. Levchuk, P. Sorokin

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

J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold [37], K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

University of Bristol, Bristol, United Kingdom

L. Basso [52], K.W. Bell, A. Belyaev [52], C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, O. Buchmuller, D. Burton, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas [37], L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko [39], J. Pela, M. Pesaresi, K. Petridis, M. Pioppi [53], D.M. Raymond, S. Rogerson, A. Rose, C. Seez, P. Sharp [†], A. Sparrow, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie

Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, T. Scarborough

Baylor University, Waco, USA

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

The University of Alabama, Tuscaloosa, USA

A. Avetisyan, T. Bose, C. Fantasia, A. Heister, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, J. St. John, L. Sulak

Boston University, Boston, USA

J. Alimena, S. Bhattacharya, G. Christopher, D. Cutts, Z. Demiragli, A. Ferapontov, A. Garabedian, U. Heintz, S. Jabeen, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, M. Segala, T. Sinthuprasith, T. Speer

Brown University, Providence, USA

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, M. Gardner, R. Houtz, W. Ko, A. Kopecky, R. Lander, O. Mall, T. Miceli, R. Nelson, D. Pellett, F. Ricci-Tam, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, S. Wilbur, R. Yohay

University of California, Davis, Davis, USA

V. Andreev, D. Cline, R. Cousins, S. Erhan, P. Everaerts, C. Farrell, M. Felcini, J. Hauser, M. Ignatenko, C. Jarvis, G. Rakness, P. Schlein[†], E. Takasugi, P. Traczyk, V. Valuev, M. Weber

University of California, Los Angeles, USA

J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, G. Hanson, H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, Riverside, Riverside, USA

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech[54], F. Würthwein, A. Yagil, J. Yoo

University of California, San Diego, La Jolla, USA

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, C. George, F. Golf, J. Incandela, C. Justus, P. Kalavase, D. Kovalskyi, V. Krutelyov, S. Lowette, R. Magaña Villalba, N. Mccoll, V. Pavlunin, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, C. West

University of California, Santa Barbara, Santa Barbara, USA

A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, E. Di Marco, J. Duarte, D. Kcira, Y. Ma, A. Mott, H.B. Newman, C. Rogan, M. Spiropulu, V. Timciuc, J. Veverka, R. Wilkinson, S. Xie, Y. Yang, R.Y. Zhu

California Institute of Technology, Pasadena, USA

V. Azzolini, A. Calamba, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, Y.F. Liu, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, B.R. Drell, W.T. Ford, A. Gaz, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner

University of Colorado at Boulder, Boulder, USA

J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, W. Hopkins, A. Khukhunaishvili, B. Kreis, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, L. Winstrom, P. Wittich

Cornell University, Ithaca, USA

D. Winn

Fairfield University, Fairfield, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, L. Gray, D. Green, O. Gutsche, D. Hare, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Klima, S. Kunori, S. Kwan, J. Linacre, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko[55], C. Newman-Holmes, V. O'Dell, O. Prokofyev, N. Ratnikova, E. Sexton-Kennedy,

S. Sharma, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, J.C. Yun

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, D. Bourilkov, M. Chen, T. Cheng, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic [56], G. Mitselmakher, L. Muniz, R. Remington, A. Rinkevicius, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

University of Florida, Gainesville, USA

V. Gaultney, S. Hewamanage, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida International University, Miami, USA

T. Adams, A. Askew, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida State University, Tallahassee, USA

M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, V.E. Bazterra, R.R. Betts, I. Bucinskaite, J. Callner, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, P. Kurt, F. Lacroix, D.H. Moon, C. O'Brien, C. Silkworth, D. Strom, P. Turner, N. Varelas

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

U. Akgun, E.A. Albayrak [50], B. Bilki [57], W. Clarida, K. Dilsiz, F. Duru, S. Griffiths, M. Haytmyradov, J.-P. Merlo, H. Mermerkaya [58], A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, H. Ogul, Y. Onel, F. Ozok [50], S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin [59], K. Yi

The University of Iowa, Iowa City, USA

B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, G. Giurgiu, A.V. Gritsan, G. Hu, P. Maksimovic, M. Swartz, A. Whitbeck

Johns Hopkins University, Baltimore, USA

P. Baringer, A. Bean, G. Benelli, R.P. Kenny III, M. Murray, D. Noonan, S. Sanders, R. Stringer, J.S. Wood

The University of Kansas, Lawrence, USA

A.F. Barfuss, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze

Kansas State University, Manhattan, USA

J. Gronberg, D. Lange, F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, K. Pedro, A. Peterman, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar

University of Maryland, College Park, USA

A. Apyan, G. Bauer, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, Y. Kim, M. Klute, Y.S. Lai, A. Levin, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, R. Wolf, B. Wyslouch, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti, V. Zhukova

Massachusetts Institute of Technology, Cambridge, USA

B. Dahmes, A. De Benedetti, G. Franzoni, A. Gude, J. Haupt, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, R. Rusack, M. Sasseville, A. Singovsky, N. Tambe, J. Turkewitz

University of Minnesota, Minneapolis, USA

L.M. Cremaldi, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders, D. Summers

University of Mississippi, Oxford, USA

E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, M. Eads, R. Gonzalez Suarez, J. Keller, I. Kravchenko, J. Lazo-Flores, S. Malik, F. Meier, G.R. Snow

University of Nebraska–Lincoln, Lincoln, USA

J. Dolen, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S. Rappoccio, Z. Wan

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, A. Massironi, D. Nash, T. Orimoto, D. Trocino, D. Wood, J. Zhang

Northeastern University, Boston, USA

A. Anastassov, K.A. Hahn, A. Kubik, L. Lusito, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

Northwestern University, Evanston, USA

D. Berry, A. Brinkerhoff, K.M. Chan, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, M. Planer, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, M. Wolf

University of Notre Dame, Notre Dame, USA

L. Antonelli, B. Bylsma, L.S. Durkin, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, G. Smith, C. Vuosalo, G. Williams, B.L. Winer, H. Wolfe

The Ohio State University, Columbus, USA

E. Berry, P. Elmer, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, S.A. Koay, D. Lopes Pegna, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, H. Saka, D. Stickland, C. Tully, J.S. Werner, S.C. Zenz, A. Zuranski

Princeton University, Princeton, USA

E. Brownson, A. Lopez, H. Mendez, J.E. Ramirez Vargas

University of Puerto Rico, Mayaguez, USA

E. Alagoz, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu, M. Jones, K. Jung, O. Koybasi, M. Kress, N. Leonardo, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, M. Vidal Marono, F. Wang, L. Xu, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University, West Lafayette, USA

S. Guragain, N. Parashar

Purdue University Calumet, Hammond, USA

A. Adair, B. Akgun, K.M. Ecklund, F.J.M. Geurts, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

Rice University, Houston, USA

B. Betchart, A. Bodek, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, D.C. Miner, G. Petrillo, D. Vishnevskiy, M. Zielinski

University of Rochester, Rochester, USA

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, S. Malik, C. Mesropian

The Rockefeller University, New York, USA

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, A. Lath, S. Panwalkar, M. Park, R. Patel, V. Rekovic, J. Robles, K. Rose, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas, M. Walker

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

G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

University of Tennessee, Knoxville, USA

O. Bouhali [60], R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon [61], V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, I. Suarez, A. Tatarinov, D. Toback

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, C. Dragoiu, P.R. Dudero, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, I. Volobouev

Texas Tech University, Lubbock, USA

E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, W. Johns, C. Maguire, Y. Mao, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

Vanderbilt University, Nashville, USA

M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, J. Wood

University of Virginia, Charlottesville, USA

S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

Wayne State University, Detroit, USA

M. Anderson, D.A. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, E. Friis, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, K. Kaadze, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, R. Loveless, A. Mohapatra, M.U. Mozer, I. Ojalvo, G.A. Pierro, I. Ross, A. Savin, W.H. Smith, J. Swanson

University of Wisconsin, Madison, USA

* Corresponding author.
† Deceased.
1 Also at Vienna University of Technology, Vienna, Austria.
2 Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
3 Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.
4 Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.
5 Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
6 Also at Universidade Estadual de Campinas, Campinas, Brazil.
7 Also at California Institute of Technology, Pasadena, USA.
8 Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
9 Also at Zewail City of Science and Technology, Zewail, Egypt.
10 Also at Suez Canal University, Suez, Egypt.
11 Also at Cairo University, Cairo, Egypt.
12 Also at Fayoum University, El-Fayoum, Egypt.
13 Also at British University in Egypt, Cairo, Egypt.
14 Now at Ain Shams University, Cairo, Egypt.
15 Also at National Centre for Nuclear Research, Swierk, Poland.
16 Also at Université de Haute Alsace, Mulhouse, France.

[17] Also at Joint Institute for Nuclear Research, Dubna, Russia.
[18] Also at Brandenburg University of Technology, Cottbus, Germany.
[19] Also at The University of Kansas, Lawrence, USA.
[20] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[21] Also at Eötvös Loránd University, Budapest, Hungary.
[22] Also at Tata Institute of Fundamental Research – EHEP, Mumbai, India.
[23] Also at Tata Institute of Fundamental Research – HECR, Mumbai, India.
[24] Now at King Abdulaziz University, Jeddah, Saudi Arabia.
[25] Also at University of Visva-Bharati, Santiniketan, India.
[26] Also at University of Ruhuna, Matara, Sri Lanka.
[27] Also at Sharif University of Technology, Tehran, Iran.
[28] Also at Isfahan University of Technology, Isfahan, Iran.
[29] Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[30] Also at Università degli Studi di Siena, Siena, Italy.
[31] Also at Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico.
[32] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[33] Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
[34] Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[35] Also at INFN Sezione di Roma, Roma, Italy.
[36] Also at University of Athens, Athens, Greece.
[37] Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[38] Also at Paul Scherrer Institut, Villigen, Switzerland.
[39] Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[40] Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
[41] Also at Gaziosmanpasa University, Tokat, Turkey.
[42] Also at Adiyaman University, Adiyaman, Turkey.
[43] Also at Cag University, Mersin, Turkey.
[44] Also at Mersin University, Mersin, Turkey.
[45] Also at Izmir Institute of Technology, Izmir, Turkey.
[46] Also at Ozyegin University, Istanbul, Turkey.
[47] Also at Kafkas University, Kars, Turkey.
[48] Also at Suleyman Demirel University, Isparta, Turkey.
[49] Also at Ege University, Izmir, Turkey.
[50] Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[51] Also at Kahramanmaras Sütcü Imam University, Kahramanmaras, Turkey.
[52] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[53] Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy.
[54] Also at Utah Valley University, Orem, USA.
[55] Also at Institute for Nuclear Research, Moscow, Russia.
[56] Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[57] Also at Argonne National Laboratory, Argonne, USA.
[58] Also at Erzincan University, Erzincan, Turkey.
[59] Also at Yildiz Technical University, Istanbul, Turkey.
[60] Also at Texas A&M University at Qatar, Doha, Qatar.
[61] Also at Kyungpook National University, Daegu, Republic of Korea.