



Observation of the $\Lambda_b^0 \rightarrow J/\psi \Lambda \phi$ decay in proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$

The CMS Collaboration*

CERN, Switzerland

ARTICLE INFO

Article history:

Received 9 November 2019
 Received in revised form 3 January 2020
 Accepted 6 January 2020
 Available online 9 January 2020
 Editor: M. Doser

Keywords:

CMS
 b physics
 Heavy-flavor spectroscopy
 Computing

ABSTRACT

The observation of the $\Lambda_b^0 \rightarrow J/\psi \Lambda \phi$ decay is reported using proton-proton collision data collected at $\sqrt{s} = 13 \text{ TeV}$ by the CMS experiment at the LHC in 2018, corresponding to an integrated luminosity of 60 fb^{-1} . The ratio of the branching fractions $\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi \Lambda \phi) / \mathcal{B}(\Lambda_b^0 \rightarrow \psi(2S) \Lambda)$ is measured to be $(8.26 \pm 0.90(\text{stat}) \pm 0.68(\text{syst}) \pm 0.11(\mathcal{B})) \times 10^{-2}$, where the first uncertainty is statistical, the second is systematic, and the last uncertainty reflects the uncertainties in the world-average branching fractions of ϕ and $\psi(2S)$ decays to the reconstructed final states.

© 2020 The Author. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP³.

1. Introduction

Studies of b baryon decays are of great importance for probing the dynamics of heavy-flavor decay processes. Since the observation of the lightest b baryon Λ_b^0 by the UA1 Collaboration [1] at the CERN Sp $\bar{p}S$, followed by extensive studies at the Fermilab Tevatron by the CDF [2–11] and D0 [12–17] Collaborations, the ATLAS, CMS, and LHCb experiments have accomplished numerous Λ_b^0 baryon studies, made possible by the large production cross section of $b\bar{b}$ pairs at the CERN LHC. Among these studies are precision mass measurements of the ground and excited states [18, 19], as well as lifetime and polarization measurements [20–23]. Most of these studies have been performed in the $\Lambda_b^0 \rightarrow J/\psi \Lambda$ decay channel. Recently, an observation of the Λ_b^0 baryon decay to an excited charmonium state $\Lambda_b^0 \rightarrow \psi(2S) \Lambda$ has been reported by the ATLAS Collaboration [24], while the LHCb Collaboration observed other, higher-multiplicity decays involving charmonium states [25, 26]. Decays of the Λ_b^0 baryon also proved to be a rich source of exotic spectroscopy, as has been demonstrated by the observation by LHCb [27, 28] of new pentaquark states $P_c(4312)^+$, $P_c(4380)^+$, and $P_c(4450)^+$ in the invariant mass distribution of the $J/\psi p$ system produced in the $\Lambda_b^0 \rightarrow J/\psi p K^-$ decay. Further studies of the Λ_b^0 baryon decay modes involving charmonium states may shed

light on the strong interaction processes in hadronic decays of b baryons and on the production of exotic multi-quark states.

This Letter reports the observation of the $\Lambda_b^0 \rightarrow J/\psi \Lambda \phi$ decay mode and the measurement of the branching fraction ratio $\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi \Lambda \phi) / \mathcal{B}(\Lambda_b^0 \rightarrow \psi(2S) \Lambda)$, by the CMS experiment. Here and thereafter, ϕ refers to the $\phi(1020)$ meson. The J/ψ , Λ , ϕ , and $\psi(2S)$ candidates are reconstructed in $\mu^+ \mu^-$, $p \pi^-$, $K^+ K^-$, and $J/\psi \pi^+ \pi^-$ final states, respectively. The $\Lambda_b^0 \rightarrow \psi(2S) \Lambda \rightarrow J/\psi \pi^+ \pi^- p \pi^- \rightarrow \mu^+ \mu^- \pi^+ \pi^- p \pi^-$ decay is used as the normalization channel, owing to its similar decay topology.

The branching fraction ratio $\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi \Lambda \phi) / \mathcal{B}(\Lambda_b^0 \rightarrow \psi(2S) \Lambda)$ is measured as:

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi \Lambda \phi)}{\mathcal{B}(\Lambda_b^0 \rightarrow \psi(2S) \Lambda)} = \frac{N(\Lambda_b^0 \rightarrow J/\psi \Lambda \phi)}{N(\Lambda_b^0 \rightarrow \psi(2S) \Lambda)} \times \frac{\epsilon(\Lambda_b^0 \rightarrow \psi(2S) \Lambda) \mathcal{B}(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)}{\epsilon(\Lambda_b^0 \rightarrow J/\psi \Lambda \phi) \mathcal{B}(\phi \rightarrow K^+ K^-)}, \quad (1)$$

where $N(\Lambda_b^0 \rightarrow J/\psi \Lambda \phi)$ and $N(\Lambda_b^0 \rightarrow \psi(2S) \Lambda)$ are the measured Λ_b^0 yields for the signal and normalization channels, respectively. The terms $\epsilon(\Lambda_b^0 \rightarrow J/\psi \Lambda \phi)$ and $\epsilon(\Lambda_b^0 \rightarrow \psi(2S) \Lambda)$ are the respective overall efficiencies that include the detector acceptance and the reconstruction efficiency. The branching fractions $\mathcal{B}(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)$ and $\mathcal{B}(\phi \rightarrow K^+ K^-)$ are taken from the Particle Data Group (PDG) [29].

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

The $\Lambda_b^0 \rightarrow J/\psi \Lambda \phi$ decay is expected to proceed via the $b \rightarrow c\bar{c}s$ process, similarly to the $\Lambda_b^0 \rightarrow J/\psi \Lambda$ decay, but requires an additional $s\bar{s}$ pair. Consequently, the measurement of its branching fraction could enhance the understanding of the final-state strong interactions in b baryon decays and test heavy-quark effective theory [30]. In addition, the $\Lambda_b^0 \rightarrow J/\psi \Lambda \phi$ decay is a baryonic analog of the $B^+ \rightarrow J/\psi \phi K^+$ decay, where a rich resonant structure in the $J/\psi \phi$ system has been observed by several experiments [31–34]. Therefore, detailed studies of the $J/\psi \phi$ spectrum produced in baryonic decays may provide an important test for the production of these states. Recently, the existence of a hidden-charm pentaquark spectra was predicted for the $J/\psi \Lambda$ final state [35], which can be investigated in the $\Lambda_b^0 \rightarrow J/\psi \Lambda \phi$ decay, once a sufficient number of signal events is accumulated.

2. The CMS detector

The central feature of the CMS apparatus [36] is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are 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. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. The main sub-detectors used for the present analysis are the silicon tracker and the muon system.

The silicon tracker measures charged particles within the range $|\eta| < 2.5$. During the LHC running period when the data used in this Letter were recorded, the silicon tracker consisted of 1856 silicon pixel and 15 148 silicon strip detector modules. For non-isolated particles with transverse momentum $1 < p_T < 10$ GeV and $|\eta| < 1.4$, the track resolution is typically 1.5% in p_T .

Muons are measured within $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. Tracks in the muon system are matched to those measured in the silicon tracker. The relative p_T resolution is measured to be in the range 0.8–3.0% for muons with $p_T < 10$ GeV used in this analysis, depending on the muon $|\eta|$ [37].

Events of interest are selected using a two-tiered trigger system [38]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate up to 100 kHz within a fixed time interval of less than 4 μ s. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [36].

3. Data sample and event selection

The analysis described in this Letter is based on a data sample of proton-proton collisions at a center-of-mass energy of 13 TeV, collected with the CMS detector in 2018 and corresponding to an integrated luminosity of 60 fb⁻¹.

Data were recorded with a dedicated trigger, optimized for the selection of b hadrons decaying to $J/\psi(\mu^+\mu^-)$ and two additional tracks from the charged hadrons emerging from the decay. The L1 trigger requires two oppositely charged muons with p_T of at least 4 GeV, or two muons in the barrel region ($|\eta| < 1.479$) without any p_T threshold. At the HLT, a J/ψ candidate decaying into a $\mu^+\mu^-$

pair displaced from the interaction point is required, along with at least two tracks consistent with the displaced vertex. Each muon p_T is required to be at least 4 GeV, while the dimuon p_T is required to exceed 6.9 GeV. The J/ψ candidates reconstructed from dimuons are required to have an invariant mass between 2.9 and 3.3 GeV. The three-dimensional distance of closest approach of the two muons to each other is required to be less than 0.5 cm. The fitted dimuon vertex is required to have a transverse decay length significance $L_{xy}(J/\psi)/\sigma_{L_{xy}}(J/\psi) > 3$, where $L_{xy}(J/\psi)$ and $\sigma_{L_{xy}}(J/\psi)$ are, respectively, the distance from the common vertex to the beam axis in the transverse plane and its uncertainty. Finally, the dimuon vertex fit probability, calculated using the χ^2 and the number of degrees of freedom of the fit, is required to exceed 10%, while the angle α between the dimuon p_T vector and the direction connecting the beam axis and the dimuon vertex in the transverse plane is required to satisfy $\cos\alpha > 0.9$. Given the lack of a dedicated kaon identification, the two additional tracks are assigned a kaon mass hypothesis and required to have $p_T > 0.8$ GeV, $|\eta| < 2.5$, and an invariant mass in a range of 0.95–1.30 GeV.

In the subsequent offline analysis we follow closely the selection of Ref. [39]. The p_T threshold on the two muon candidates of 4 GeV and the requirement of $|\eta| < 2.4$ are kept. Two oppositely charged muon candidates are paired and required to originate from a common vertex. The vertex requirements applied at the HLT are confirmed in the offline selection. Also both muon candidates must match those that triggered the event readout. Dimuon candidates with an invariant mass within 100 MeV, which corresponds to approximately four effective widths, around the J/ψ meson mass $M_{J/\psi}^{\text{PDG}}$ are selected (hereafter, M_X^{PDG} denotes the world-average mass of hadron X [29]), and the p_T of the J/ψ meson is required to exceed 7 GeV.

To reconstruct a Λ_b^0 candidate, the J/ψ candidate is combined with two oppositely charged, high-purity [40] tracks, assumed to be kaon candidates, and a Λ candidate. The p_T of the tracks is required to exceed 0.8 GeV, and their invariant mass must satisfy $0.99 < M(K^+K^-) < 1.05$ GeV. The Λ candidates are formed from displaced two-prong vertices under the assumption of the $\Lambda \rightarrow p\pi^-$ decay, as described in Ref. [41]. Daughter particles of the Λ candidate are refitted to a common vertex with their invariant mass constrained to M_{Λ}^{PDG} , and the vertex fit probability is required to exceed 1%. The proton mass is assigned to the higher-momentum daughter track. To select the candidates in the Λ signal region, the following additional requirement is applied: $|M(p\pi^-) - M_{\Lambda}^{\text{PDG}}| < 7.5$ MeV. The width of this window is chosen to correspond to approximately three times the effective width of the reconstructed Λ candidates. In addition, the Λ candidate is required to have a transverse momentum in excess of 1 GeV.

As the last step of the reconstruction, a fit to the common vertex of the Λ candidate, the two kaon tracks, and the dimuon pair is performed, with the dimuon mass constrained to $M_{J/\psi}^{\text{PDG}}$; this vertex is referred to as the Λ_b^0 vertex. The kinematic vertex fit probability of the Λ_b^0 candidate is required to exceed 1%. The selected candidates are required to have $p_T(\Lambda_b^0) > 10$ GeV.

Multiple proton-proton interactions in the same or nearby beam crossing (pileup) are present in the data, with an average multiplicity of 32, resulting in multiple reconstructed vertices in an event. The vertex with the lowest three-dimensional angle between the line connecting this vertex with the Λ_b^0 vertex and the Λ_b^0 candidate momentum is chosen as the primary vertex (PV). The following requirement is used to select Λ_b^0 candidates consistent with originating from the PV: $\cos\alpha(\Lambda_b^0, \text{PV}) > 0.99$, where $\alpha(\Lambda_b^0, \text{PV})$ is the two-dimensional angle in the transverse plane between the Λ_b^0 candidate momentum and the vector pointing from

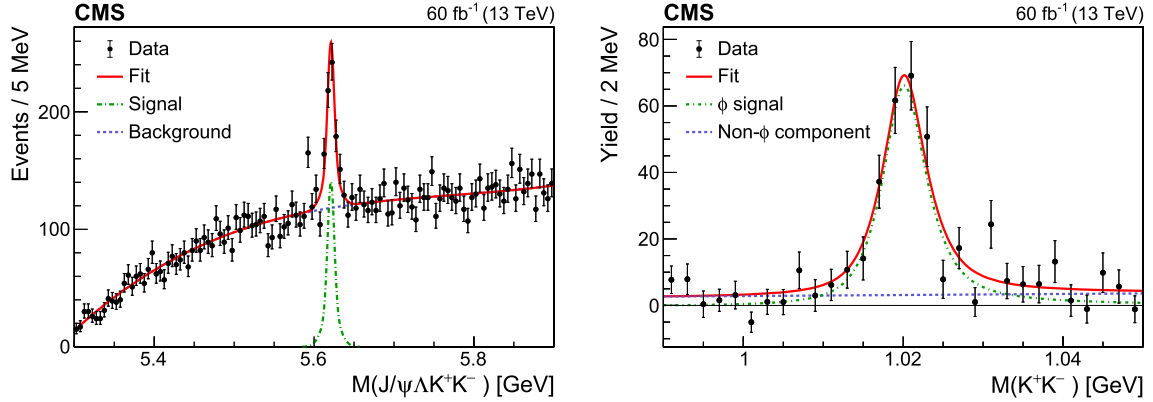


Fig. 1. The invariant mass distributions of (left) $J/\psi\Lambda K^+K^-$ and (right) background-subtracted K^+K^- . The points are the data, with the vertical bars giving the statistical uncertainties, and the lines show the results of the fits described in the text.

the PV to the Λ_b^0 vertex. The following requirement on the Λ_b^0 vertex displacement is also applied: $L_{xy}(\Lambda_b^0)/\sigma_{L_{xy}(\Lambda_b^0)} > 3$, where $L_{xy}(\Lambda_b^0)$ is the distance between the primary and Λ_b^0 vertices in the transverse plane, and $\sigma_{L_{xy}(\Lambda_b^0)}$ is its uncertainty.

Candidate decays for the normalization channel $\Lambda_b^0 \rightarrow \psi(2S)\Lambda$, with $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$, are selected using the same reconstruction chain. Identical requirements are used to select the J/ψ candidate, π^+ and π^- tracks, and Λ candidate. An additional requirement is placed on the $J/\psi\pi^+\pi^-$ invariant mass, $|M(J/\psi\pi^+\pi^-) - M_{\psi(2S)}^{PDG}| < 15$ MeV, to select $\psi(2S)$ candidates, where this window corresponds to approximately three effective widths of a reconstructed $\psi(2S)$ candidate.

In case of multiple Λ_b^0 candidates per event, the one with the highest vertex fit probability is chosen for both the signal and normalization channels. There are 18.9 and 7.4% of events with two or more reconstructed candidates for signal and normalization channels, respectively. When there are two or more candidates in an event, the MC simulation predicts that the correct candidate is chosen 84 ± 5 and $93 \pm 13\%$ of the time for the signal and normalization channels, respectively.

To calculate the reconstruction efficiency, a study based on simulated signal events for both channels is performed. The events are generated with PYTHIA 8.230 [42]. The Λ_b^0 baryon decays are modeled with EVTGEN [43] v1.6.0 for both the $\Lambda_b^0 \rightarrow J/\psi\Lambda\phi$ and $\Lambda_b^0 \rightarrow \psi(2S)\Lambda$ decay channels, following the three-body phase space model. The events are then passed through a detailed CMS detector simulation based on GEANT4 [44].

4. Signal yield extraction

The invariant mass distribution of the $\Lambda_b^0 \rightarrow J/\psi\Lambda K^+K^-$ candidates selected using the strategy described in the previous section is shown in Fig. 1 (left). An unbinned, extended maximum-likelihood fit to a signal plus background hypothesis is performed on this observable and further mass distributions.

The signal is described by a double-Gaussian function with a floating common mean and total normalization, while the two widths and the relative fraction of the two Gaussian functions are fixed to the values obtained from simulation. The double-Gaussian function was chosen as a model that provides the best description of the simulated sample. The background is parameterized by a third-order Bernstein polynomial. The fit results in a signal yield of 380 ± 32 events. The signal significance is calculated to be 9.7 standard deviations in the asymptotic approximation [45], using the profile likelihood ratio of the signal plus background over the

background-only hypothesis as the test statistic. Including modeling uncertainties in the signal and background shapes (described in Section 6) results in a reduction of the significance value to 9.4 standard deviations.

There is a bin with the yield significantly higher than the average background level in the left panel of Fig. 1, just below the signal Λ_b^0 peak. The local significance of the excess is estimated to be less than three standard deviations. Several cross-checks have been performed to investigate this enhancement. The $M(\Lambda_b^0 \rightarrow J/\psi\Lambda K^+K^-)$ distribution with the requirement on the ϕ candidates to have a mass within 10 MeV of the nominal value shows no significant excess in this bin. The statistical significance of the Λ_b^0 signal is 10.3 standard deviations in the asymptotic approximation. A statistically independent data set, collected in 2017, has been examined with the same selection, and no significant excess below the Λ_b^0 peak was observed. As a result of these cross-checks, we attribute the excess to a statistical fluctuation.

An unbinned likelihood fit to the $M(\Lambda_b^0 \rightarrow J/\psi\Lambda K^+K^-)$ observable is employed to separate the signal and background components statistically, which is then used with the *sPlot* technique [46] to obtain the $M(K^+K^-)$ data distribution corresponding to signal $\Lambda_b^0 \rightarrow J/\psi\Lambda K^+K^-$ decays. To extract the $\Lambda_b^0 \rightarrow J/\psi\Lambda\phi$ decay yield, the background-subtracted $M(K^+K^-)$ distribution is fitted with the convolution of a double-Gaussian and relativistic Breit-Wigner functions for the ϕ signal and a first-order Bernstein polynomial for the nonresonant component. The natural width of the ϕ meson is fixed to the world-average value [29]. It was checked that the natural width of the ϕ meson obtained from the fit when it was allowed to float was consistent with the world-average value within the uncertainties. Both widths and the relative fraction of the two Gaussians are fixed to the values obtained from fitting the simulated signal sample. The fit results in a signal yield of 286 ± 29 events. The $M(K^+K^-)$ invariant mass distribution, along with the result of the fit, are shown in Fig. 1 (right).

Fig. 2 displays the invariant mass distribution of $\Lambda_b^0 \rightarrow \psi(2S)\Lambda$ candidates. The points represent the data and the curve is the result of the fit. The signal is described by a double-Gaussian function with floating common mean and total normalization, while the individual widths and the relative fraction of the two Gaussians are fixed from the fit to a simulated signal sample. The background is described by a third-order Bernstein polynomial function. The fit results in a signal yield of 884 ± 37 events. The non- $\psi(2S)$ contribution in the $\Lambda_b^0 \rightarrow J/\psi\pi^+\pi^-\Lambda$ signal was estimated to be negligible in the selected mass window $|M(J/\psi\pi^+\pi^-) - M_{\psi(2S)}^{PDG}| < 15$ MeV.

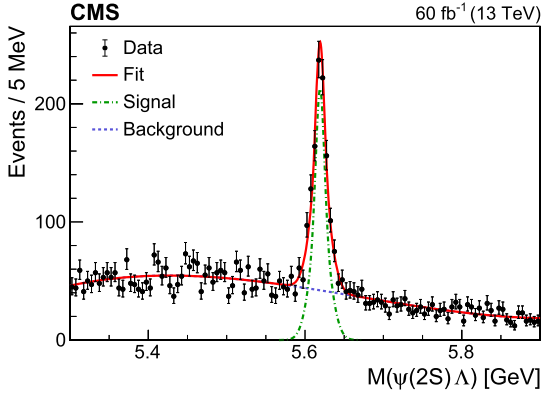


Fig. 2. The invariant mass distribution of $\Lambda_b^0 \rightarrow \psi(2S)\Lambda$ candidates. The points are the data and the lines give the result of the fit described in the text.

5. Efficiency calculation

The Λ_b^0 selection efficiencies in the signal and normalization channels are calculated as the ratio of the numbers of selected to generated events in simulated signal samples. The overall efficiency includes the trigger and reconstruction efficiencies and the detector acceptance. The efficiency in each channel is obtained using the simulated samples described in Section 3. The efficiency ratio, which is used in the branching fraction ratio measurement, is found to be $\epsilon(\Lambda_b^0 \rightarrow \psi(2S)\Lambda)/\epsilon(\Lambda_b^0 \rightarrow J/\psi\Lambda\phi) = 0.363 \pm 0.011$, where the uncertainty is statistical only and accounts for the limited event counts in the corresponding simulated samples. The p_T spectrum of pions from the $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ decay in the normalization channel is softer than the p_T spectrum of kaons from the $\phi \rightarrow K^+K^-$ decay in the signal channel, resulting in an efficiency ratio significantly below unity.

6. Systematic uncertainties

In this section we discuss various sources of systematic uncertainty contributing to the measurement of the ratio $\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi\Lambda\phi)/\mathcal{B}(\Lambda_b^0 \rightarrow \psi(2S)\Lambda)$, as defined in Eq. (1).

Since both the $\Lambda_b^0 \rightarrow J/\psi\Lambda\phi \rightarrow \mu^+\mu^-\rho\pi^-K^+K^-$ and $\Lambda_b^0 \rightarrow \psi(2S)\Lambda \rightarrow \mu^+\mu^-\rho\pi^-\pi^+\pi^-$ decay modes have the same topology, the systematic uncertainties related to the muon and track reconstruction, as well as the trigger efficiency, mostly cancel in the ratio. To test this assumption, simulated samples were compared with background-subtracted data in a number of kinematic distributions. As a result of these studies, an additional systematic uncertainty is assigned to account for the observed difference between data and simulation in the Λ_b^0 rapidity distribution for the normalization channel, as well as for the difference in the two-body invariant mass distributions $M(J/\psi\Lambda)$, $M(J/\psi\phi)$, and $M(\Lambda\phi)$ in data and simulation for the signal channel. The latter discrepancy could be caused by a deviation from the pure phase space decay model used in the simulation due to contributions from intermediate resonant states; however, the statistical power of the present data set is insufficient to perform a more detailed investigation. To estimate this systematic uncertainty, the simulated samples were reweighted to match the distributions observed in data. The difference in the efficiency ratio before and after the reweighting is taken as the corresponding systematic uncertainty.

The systematic uncertainty related to the choice of the background model is estimated separately for the signal channel, normalization channel, and $\phi \rightarrow K^+K^-$ decays. The variation of the background model includes Bernstein polynomials of second and fourth orders, independently for the signal and normalization

channels, and an exponential function for the background in the $\phi \rightarrow K^+K^-$ invariant mass distribution. For the signal channel, an additional background function with a threshold behavior is also tested: $(x - x_0)^\beta$ multiplied by the Bernstein polynomials of first and second orders, where $x_0 = M_{J/\psi}^{\text{PDG}} + M_{\Lambda}^{\text{PDG}} + M_{\phi}^{\text{PDG}}$ and the exponent β is allowed to vary freely in the fit. In each case, the maximum deviation in the measured signal yield within the variations of the background model is used as the systematic uncertainty.

Another source of systematic uncertainty is the signal shape modeling in the $M(J/\psi\Lambda K^+K^-)$, $M(\psi(2S)\Lambda)$, and $M(K^+K^-)$ distributions. This uncertainty is estimated by using alternative signal models whose parameters were obtained by fitting the simulated invariant mass distributions. The variation of signal models includes a triple-Gaussian function and a sum of two Crystal Ball [47] functions for the $\Lambda_b^0 \rightarrow J/\psi\Lambda K^+K^-$ invariant mass distribution; a sum of two Crystal Ball functions for the $\Lambda_b^0 \rightarrow \psi(2S)\Lambda$ channel; and a convolution of a double Crystal Ball [48] and relativistic Breit–Wigner functions for the $M(K^+K^-)$ distribution. For each of the variations, the largest deviation in the measured signal yield is taken as the systematic uncertainty.

The next source of systematic uncertainty is the difference in the mass resolution of the Λ_b^0 and ϕ peaks between data and simulation. To estimate this uncertainty, several variations were applied to the resolution functions in the $M(J/\psi\Lambda K^+K^-)$ and $M(\psi(2S)\Lambda)$ distributions: only the ratio of the two Gaussian widths was fixed to the one measured in simulation instead of fixing both widths, as in the nominal fit. For the $M(K^+K^-)$ distribution, a fit with the fixed ratios of the two Gaussian widths and yields, as measured in simulation, is performed. In each case, the maximum variation in the measured Λ_b^0 yield is used as the systematic uncertainty. The difference between data and simulation in the measured Λ_b^0 mass resolution for the $\Lambda_b^0 \rightarrow J/\psi\Lambda K^+K^-$ channel results in the largest systematic uncertainty.

The statistical uncertainty in the efficiency ratio obtained from simulation is also considered as a source of systematic uncertainty. Table 1 summarizes the individual sources of the systematic uncertainty, as well as the overall uncertainty obtained as a quadratic sum of the individual components.

7. Measurement of the branching fraction ratio

Using Eq. (1), the signal and normalization channel yields $N(\Lambda_b^0 \rightarrow J/\psi\Lambda\phi) = 286 \pm 29$ and $N(\Lambda_b^0 \rightarrow \psi(2S)\Lambda) = 884 \pm 37$, the efficiency ratio described in Section 5, and the PDG values of $\mathcal{B}(\psi(2S) \rightarrow J/\psi\pi^+\pi^-) = 0.347 \pm 0.003$ and $\mathcal{B}(\phi \rightarrow K^+K^-) = 0.492 \pm 0.005$, we measure the ratio $\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi\Lambda\phi)/\mathcal{B}(\Lambda_b^0 \rightarrow \psi(2S)\Lambda)$ to be $(8.26 \pm 0.90(\text{stat}) \pm 0.68(\text{syst}) \pm 0.11(\mathcal{B})) \times 10^{-2}$. The first uncertainty is statistical, while the second is systematic (as described in Section 6), and the third is due to the uncertainties in the branching fractions of the decays involved.

8. Summary

The observation of the $\Lambda_b^0 \rightarrow J/\psi\Lambda\phi$ decay and the measurement of the branching fraction ratio $\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi\Lambda\phi)/\mathcal{B}(\Lambda_b^0 \rightarrow \psi(2S)\Lambda)$ is presented using a data sample of proton-proton collisions at $\sqrt{s} = 13\text{ TeV}$ collected in 2018 by the CMS experiment and corresponding to an integrated luminosity of 60 fb^{-1} . The ratio $\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi\Lambda\phi)/\mathcal{B}(\Lambda_b^0 \rightarrow \psi(2S)\Lambda)$ is measured to be $(8.26 \pm 0.90(\text{stat}) \pm 0.68(\text{syst}) \pm 0.11(\mathcal{B})) \times 10^{-2}$, where the first uncertainty is statistical, the second is systematic, and the last uncertainty reflects the uncertainties in the world-average branching fractions of ϕ and $\psi(2S)$ decays to the reconstructed final states. The observation of the $\Lambda_b^0 \rightarrow J/\psi\Lambda\phi$ decay opens a window on

Table 1
Summary of the relative systematic uncertainties in $\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi \Lambda \phi) / \mathcal{B}(\Lambda_b^0 \rightarrow \psi(2S) \Lambda)$.

Source	Relative uncertainty (%)
Data/simulation difference in the Λ_b^0 rapidity and two-body mass distributions	0.1
Background model in the $M(J/\psi \Lambda K^+ K^-)$ distribution	0.6
Background model in the $M(\psi(2S) \Lambda)$ distribution	0.8
Background model in the $M(K^+ K^-)$ distribution	0.8
Signal model in the $M(J/\psi \Lambda K^+ K^-)$ distribution	0.8
Signal model in the $M(\psi(2S) \Lambda)$ distribution	1.1
Signal model in the $M(K^+ K^-)$ distribution	0.5
Data/simulation difference in the Λ_b^0 resolution for the $\Lambda_b^0 \rightarrow J/\psi \Lambda \phi$ decay	6.6
Data/simulation difference in the Λ_b^0 resolution for the $\Lambda_b^0 \rightarrow \psi(2S) \Lambda$ decay	3.1
Data/simulation difference in the ϕ resolution	1.4
Finite size of simulated samples	2.9
Total systematic uncertainty	8.2

future searches for new resonances in the $J/\psi \Lambda$ and $J/\psi \phi$ mass spectra, once a sufficient number of signal events is observed.

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MOST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFI (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MoSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 752730, and 765710 (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science - EOS" - be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z181100004218003; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Lendület ("Momentum") Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFI research grants 123842, 123959, 124845, 124850, 125105, 128713,

128786, and 129058 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Education, grant no. 3.2989.2017 (Russia); the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalís and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Nvidia Corporation; The Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

- [1] C. Albajar, et al., UA1, First observation of the beauty baryon Λ_b^0 in the decay channel $\Lambda_b^0 \rightarrow J/\psi \Lambda$ at the CERN proton-antiproton collider, Phys. Lett. B 273 (1991) 540, [https://doi.org/10.1016/0370-2693\(91\)90311-D](https://doi.org/10.1016/0370-2693(91)90311-D).
- [2] F. Abe, et al., CDF, Search for $\Lambda_b^0 \rightarrow J/\psi \Lambda$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, Phys. Rev. D 47 (1993) R2639, <https://doi.org/10.1103/PhysRevD.47.R2639>.
- [3] F. Abe, et al., CDF, Measurement of Λ_b^0 lifetime using $\Lambda_b^0 \rightarrow \Lambda_c^+ \ell^- \bar{\nu}$, Phys. Rev. Lett. 77 (1996) 1439, <https://doi.org/10.1103/PhysRevLett.77.1439>.
- [4] F. Abe, et al., CDF, Observation of $\Lambda_b^0 \rightarrow J/\psi \Lambda$ at the Fermilab proton-antiproton collider, Phys. Rev. D 55 (1997) 1142, <https://doi.org/10.1103/PhysRevD.55.1142>.
- [5] D. Acosta, et al., CDF, Search for $\Lambda_b^0 \rightarrow p\pi$ and $\Lambda_b^0 \rightarrow pK$ decays in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, Phys. Rev. D 72 (2005) 051104, <https://doi.org/10.1103/PhysRevD.72.051104>, arXiv:hep-ex/0507067.
- [6] A. Abulencia, et al., CDF, Measurement of $\sigma(\Lambda_b^0)/\sigma(\bar{B}^0) \times \text{BR}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-) / \text{BR}(\bar{B}^0 \rightarrow D^+ \pi^-)$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, Phys. Rev. Lett. 98 (2007) 122002, <https://doi.org/10.1103/PhysRevLett.98.122002>, arXiv:hep-ex/0601003.
- [7] A. Abulencia, et al., CDF, Measurement of the Λ_b^0 lifetime in $\Lambda_b^0 \rightarrow J/\psi \Lambda$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, Phys. Rev. Lett. 98 (2007) 122001, <https://doi.org/10.1103/PhysRevLett.98.122001>, arXiv:hep-ex/0609021.
- [8] T. Aaltonen, et al., CDF, First measurement of the ratio of branching fractions $B(\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \bar{\nu}_\mu) / B(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)$, Phys. Rev. D 79 (2009) 032001, <https://doi.org/10.1103/PhysRevD.79.032001>, arXiv:0810.3213.
- [9] T. Aaltonen, et al., CDF, Measurement of the Λ_b^0 lifetime in $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ decays in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, Phys. Rev. Lett. 104 (2010) 102002, <https://doi.org/10.1103/PhysRevLett.104.102002>, arXiv:0912.3566.
- [10] T. Aaltonen, et al., CDF, Observation of the baryonic flavor-changing neutral current decay $\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-$, Phys. Rev. Lett. 107 (2011) 201802, <https://doi.org/10.1103/PhysRevLett.107.201802>, arXiv:1107.3753.
- [11] T. Aaltonen, et al., CDF, Measurement of the branching fraction $\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-)$ at CDF, Phys. Rev. D 85 (2012) 032003, <https://doi.org/10.1103/PhysRevD.85.032003>, arXiv:1112.3334.

- [12] V.M. Abazov, et al., D0, Measurement of the Λ_b^0 lifetime in the decay $\Lambda_b^0 \rightarrow J/\psi\Lambda$ with the D0 detector, Phys. Rev. Lett. 94 (2005) 102001, <https://doi.org/10.1103/PhysRevLett.94.102001>, arXiv:hep-ex/0410054.
- [13] V.M. Abazov, et al., D0, Measurement of the Λ_b^0 lifetime in the exclusive decay $\Lambda_b^0 \rightarrow J/\psi\Lambda$, Phys. Rev. Lett. 99 (2007) 142001, <https://doi.org/10.1103/PhysRevLett.99.142001>, arXiv:0704.3909.
- [14] V.M. Abazov, et al., D0, Measurement of the Λ_b^0 lifetime using semileptonic decays, Phys. Rev. Lett. 99 (2007) 182001, <https://doi.org/10.1103/PhysRevLett.99.182001>, arXiv:0706.2358.
- [15] V.M. Abazov, et al., D0, Measurement of the production fraction times branching fraction $f(b \rightarrow \Lambda_b^0) \cdot \mathcal{B}(\Lambda_b^0 \rightarrow J/\psi\Lambda)$, Phys. Rev. D 84 (2011) 031102(R), <https://doi.org/10.1103/PhysRevD.84.031102>, arXiv:1105.0690.
- [16] V.M. Abazov, et al., D0, Measurement of the Λ_b^0 lifetime in the exclusive decay $\Lambda_b^0 \rightarrow J/\psi\Lambda$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, Phys. Rev. D 85 (2012) 112003, <https://doi.org/10.1103/PhysRevD.85.112003>, arXiv:1204.2340.
- [17] V.M. Abazov, et al., D0, Measurement of the forward-backward asymmetry in Λ_b^0 and $\bar{\Lambda}_b^0$ baryon production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, Phys. Rev. D 91 (2015) 072008, <https://doi.org/10.1103/PhysRevD.91.072008>, arXiv:1503.03917.
- [18] LHCb Collaboration, Observation of the decays $\Lambda_b^0 \rightarrow \chi_{c1}pK^-$ and $\Lambda_b^0 \rightarrow \chi_{c2}pK^-$, Phys. Rev. Lett. 119 (2017) 062001, <https://doi.org/10.1103/PhysRevLett.119.062001>, arXiv:1704.07900.
- [19] LHCb Collaboration, Observation of excited Λ_b^0 baryons, Phys. Rev. Lett. 109 (2012) 172003, <https://doi.org/10.1103/PhysRevLett.109.172003>, arXiv:1205.3452.
- [20] ATLAS Collaboration, Measurement of the Λ_b^0 lifetime and mass in the ATLAS experiment, Phys. Rev. D 87 (2013) 032002, <https://doi.org/10.1103/PhysRevD.87.032002>, arXiv:1207.2284.
- [21] LHCb Collaboration, Precision measurement of the ratio of the Λ_b^0 to \bar{B}^0 lifetimes, Phys. Lett. B 734 (2014) 122, <https://doi.org/10.1016/j.physletb.2014.05.021>, arXiv:1402.6242.
- [22] CMS Collaboration, Measurement of the Λ_b^0 polarization and angular parameters in $\Lambda_b^0 \rightarrow J/\psi\Lambda$ decays from pp collisions at $\sqrt{s} = 7$ and 8 TeV, Phys. Rev. D 97 (2018) 072010, <https://doi.org/10.1103/PhysRevD.97.072010>, arXiv:1802.04867.
- [23] CMS Collaboration, Measurement of b hadron lifetimes in pp collisions at $\sqrt{s} = 8$ TeV, Eur. Phys. J. C 78 (2018) 457, <https://doi.org/10.1140/epjc/s10052-018-5929-3>, arXiv:1710.08949, Erratum: <https://doi.org/10.1140/epjc/s10052-018-6014-7>.
- [24] ATLAS Collaboration, Measurement of the branching ratio $\Gamma(\Lambda_b^0 \rightarrow \psi(2S)\Lambda)/\Gamma(\Lambda_b^0 \rightarrow J/\psi\Lambda)$ with the ATLAS detector, Phys. Lett. B 751 (2015) 63, <https://doi.org/10.1016/j.physletb.2015.10.009>, arXiv:1507.08202.
- [25] LHCb Collaboration, Observation of $\Lambda_b^0 \rightarrow \psi(2S)pK^-$ and $\Lambda_b^0 \rightarrow J/\psi\pi^+\pi^-pK^-$ decays and a measurement of the Λ_b^0 baryon mass, J. High Energy Phys. 05 (2016) 132, [https://doi.org/10.1007/JHEP05\(2016\)132](https://doi.org/10.1007/JHEP05(2016)132), arXiv:1603.06961.
- [26] LHCb Collaboration, Observation of the $\Lambda_b^0 \rightarrow \chi_{c1}(3872)pK^-$ decay, J. High Energy Phys. 09 (2019) 028, [https://doi.org/10.1007/JHEP09\(2019\)028](https://doi.org/10.1007/JHEP09(2019)028), arXiv:1907.00954.
- [27] LHCb Collaboration, Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_b^0 \rightarrow J/\psi K^- p$ decays, Phys. Rev. Lett. 115 (2015) 072001, <https://doi.org/10.1103/PhysRevLett.115.072001>, arXiv:1507.03414.
- [28] LHCb Collaboration, Observation of a narrow pentaquark state, $P_c(4312)^+$, and of the two-peak structure of the $P_c(4450)^+$, Phys. Rev. Lett. 122 (2019) 222001, <https://doi.org/10.1103/PhysRevLett.122.222001>, arXiv:1904.03947.
- [29] Particle Data Group, M. Tanabashi, et al., Review of particle physics, Phys. Rev. D 98 (2018) 030001, <https://doi.org/10.1103/PhysRevD.98.030001>.
- [30] Y. Chen, A. Fujimori, T. Müller, W. Stwalley, J. Yang (Eds.), Heavy Quark Effective Theory, Springer, Berlin, Heidelberg, 2004.
- [31] T. Aaltonen, et al., CDF, Observation of the Y(4140) structure in the $J/\psi\phi$ mass spectrum in $B^\pm \rightarrow J/\psi\phi K^\pm$ decays, Mod. Phys. Lett. A 32 (2017) 1750139, <https://doi.org/10.1142/S0217732317501395>, arXiv:1101.6058.
- [32] CMS Collaboration, Observation of a peaking structure in the $J/\psi\phi$ mass spectrum from $B^\pm \rightarrow J/\psi\phi K^\pm$ decays, Phys. Lett. B 734 (2014) 261, <https://doi.org/10.1016/j.physletb.2014.05.055>, arXiv:1309.6920.
- [33] V.M. Abazov, et al., D0, Inclusive production of the X(4140) state in $p\bar{p}$ collisions at D0, Phys. Rev. Lett. 115 (2015) 232001, <https://doi.org/10.1103/PhysRevLett.115.232001>, arXiv:1508.07846.
- [34] LHCb Collaboration, Observation of $J/\psi\phi$ structures consistent with exotic states from amplitude analysis of $B^+ \rightarrow J/\psi\phi K^+$ decays, Phys. Rev. Lett. 118 (2017) 022003, <https://doi.org/10.1103/PhysRevLett.118.022003>, arXiv:1606.07895.
- [35] X.-Z. Weng, X.-L. Chen, W.-Z. Deng, S.-L. Zhu, Hidden-charm pentaquarks and P_c states, Phys. Rev. D 100 (2019) 016014, <https://doi.org/10.1103/PhysRevD.100.016014>, arXiv:1904.09891.
- [36] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, <https://doi.org/10.1088/1748-0221/3/08/S08004>.
- [37] CMS Collaboration, Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV, J. Instrum. 13 (2018) P06015, <https://doi.org/10.1088/1748-0221/13/06/P06015>, arXiv:1804.04528.
- [38] CMS Collaboration, The CMS trigger system, J. Instrum. 12 (2017) P01020, <https://doi.org/10.1088/1748-0221/12/01/P01020>, arXiv:1609.02366.
- [39] CMS Collaboration, Study of the $B^+ \rightarrow J/\psi\Lambda p$ decay in proton-proton collisions at $\sqrt{s} = 8$ TeV, J. High Energy Phys. 12 (2019) 100, [https://doi.org/10.1007/JHEP12\(2019\)100](https://doi.org/10.1007/JHEP12(2019)100), arXiv:1907.05461, submitted for publication.
- [40] CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, J. Instrum. 9 (2014) P10009, <https://doi.org/10.1088/1748-0221/9/10/P10009>, arXiv:1405.6569.
- [41] CMS Collaboration, CMS tracking performance results from early LHC operation, Eur. Phys. J. C 70 (2010) 1165, <https://doi.org/10.1140/epjc/s10052-010-1491-3>, arXiv:1007.1988.
- [42] T. Sjöstrand, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C.O. Rasmussen, P.Z. Skands, An introduction to PYTHIA 8.2, Comput. Phys. Commun. 191 (2015) 159, <https://doi.org/10.1016/j.cpc.2015.01.024>, arXiv:1410.3012.
- [43] D.J. Lange, The EVTGEN particle decay simulation package, Nucl. Instrum. Methods A 462 (2001) 152, [https://doi.org/10.1016/S0168-9002\(01\)00089-4](https://doi.org/10.1016/S0168-9002(01)00089-4).
- [44] S. Agostinelli, et al., GEANT4, GEANT4—a simulation toolkit, Nucl. Instrum. Methods A 506 (2003) 250, [https://doi.org/10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8).
- [45] G. Cowan, K. Cranmer, E. Gross, O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, Eur. Phys. J. C 71 (2011) 1554, <https://doi.org/10.1140/epjc/s10052-011-1554-0>, arXiv:1007.1727, Erratum: <https://doi.org/10.1140/epjc/s10052-013-2501-z>.
- [46] M. Pivk, F.R. Le Diberder, SPlot: a statistical tool to unfold data distributions, Nucl. Instrum. Methods A 555 (2005) 356, <https://doi.org/10.1016/j.nima.2005.08.106>, arXiv:physics/0402083.
- [47] M.J. Oreglia, A study of the reactions $\psi' \rightarrow \gamma\gamma\psi$, Ph.D. thesis, SLAC Report SLAC-R-236, Stanford University, 1980, <http://www.slac.stanford.edu/pubs/slacreports/slac-r-236.html>.
- [48] J.E. Gaiser, Charmonium spectroscopy from radiative decays of the J/ψ and ψ' , Ph.D. thesis, SLAC Report SLAC-R-255, Stanford University, 1982, <https://www-public.slac.stanford.edu/sciDoc/docMeta.aspx?slacPubNumber=slac-R-255>.

The CMS Collaboration

A.M. Sirunyan[†], A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, F. Ambrogi, T. Bergauer, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth¹, M. Jeitler¹, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, J. Schieck¹, R. Schöfbeck, M. Spanring, W. Waltenberger, C.-E. Wulz¹, M. Zarucki

Institut für Hochenergiephysik, Wien, Austria

V. Drugakov, V. Mossolov, J. Suarez Gonzalez

Institute for Nuclear Problems, Minsk, Belarus

M.R. Darwish, E.A. De Wolf, D. Di Croce, X. Janssen, A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haevermaet, P. Van Mechelen, S. Van Putte, N. Van Remortel

Universiteit Antwerpen, Antwerpen, Belgium

F. Blekman, E.S. Bols, S.S. Chhibra, J. D'Hondt, J. De Clercq, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders

Vrije Universiteit Brussel, Brussel, Belgium

D. Beghin, B. Bilin, B. Clerboux, G. De Lentdecker, H. Delannoy, B. Dorney, L. Favart, A. Grebenyuk, A.K. Kalsi, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium

T. Cornelis, D. Dobur, I. Khvastunov², M. Niedziela, C. Roskas, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

Ghent University, Ghent, Belgium

O. Bondu, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, V. Lemaitre, J. Prisciandaro, A. Saggio, M. Vidal Marono, P. Vischia, J. Zobec

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

F.L. Alves, G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes, P. Rebello Teles

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato³, E. Coelho, E.M. Da Costa, G.G. Da Silveira⁴, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, J. Martins⁵, D. Matos Figueiredo, M. Medina Jaime⁶, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote³, F. Torres Da Silva De Araujo, A. Vilela Pereira

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

C.A. Bernardes^a, L. Calligaris^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, D.S. Lemos, 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*

A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

W. Fang⁷, X. Gao⁷, L. Yuan

Beihang University, Beijing, China

G.M. Chen, H.S. Chen, M. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang⁸, J. Zhao

Institute of High Energy Physics, Beijing, China

A. Agapitos, Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Q. Wang

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

M. Ahmad, Z. Hu, Y. Wang

Tsinghua University, Beijing, China

M. Xiao

Zhejiang University, Hangzhou, China

C. Avila, A. Cabrera, C. Florez, C.F. González Hernández, M.A. Segura Delgado

Universidad de Los Andes, Bogota, Colombia

J. Mejia Guisao, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

Universidad de Antioquia, Medellin, Colombia

D. Giljanović, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

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, B. Mesic, M. Roguljic, A. Starodumov⁹, T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

M.W. Ather, A. Attikis, E. Erodotou, A. Ioannou, M. Kolosova, S. Konstantinou, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, D. Tsiakkouri

University of Cyprus, Nicosia, Cyprus

M. Finger¹⁰, M. Finger Jr.¹⁰, A. Kveton, J. Tomsa

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

Y. Assran^{11,12}, S. Elgammal¹²

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

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

F. Garcia, J. Havukainen, J.K. Heikkilä, V. Karimäki, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

Helsinki Institute of Physics, Helsinki, Finland

T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, 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, C. Leloup, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro¹³, M. Titov, G.B. Yu

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

S. Ahuja, C. Amendola, F. Beaudette, P. Busson, C. Charlot, B. Diab, G. Falmagne, R. Granier de Cassagnac, I. Kucher, A. Lobanov, C. Martin Perez, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, France

J.-L. Agram¹⁴, J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte¹⁴, J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, F. Lagarde, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

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

T. Toriashvili¹⁵

Georgian Technical University, Tbilisi, Georgia

Z. Tsamalaidze¹⁰

Tbilisi State University, Tbilisi, Georgia

C. Autermann, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M.P. Rauch, J. Schulz, M. Teroerde, B. Wittmer

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

M. Erdmann, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, T. Quast, M. Radziej, Y. Rath, H. Reithler, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, S. Wiedenbeck, S. Zaleski

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

G. Flügge, W. Haj Ahmad¹⁶, O. Hlushchenko, T. Kress, T. Müller, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl¹⁷

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

M. Aldaya Martin, P. Asmuss, I. Babounikau, H. Bakhshiansohi, K. Beernaert, O. Behnke, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borrás¹⁸, V. Botta, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, A. Elwood, E. Eren, E. Gallo¹⁹, A. Geiser, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, A. Jafari, N.Z. Jomhari, H. Jung, A. Kasem¹⁸, M. Kasemann, H. Kaveh, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann²⁰, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, J. Mnich, A. Mussgiller, V. Myronenko, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saibel,

M. Savitskyi, V. Scheurer, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, M. Van De Klundert, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev, R. Zlebcik

Deutsches Elektronen-Synchrotron, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, V. Blobel, T. Dreyer, A. Ebrahimi, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, T. Lange, A. Malara, J. Multhaup, C.E.N. Niemeyer, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, B. Vormwald, I. Zoi

University of Hamburg, Hamburg, Germany

M. Akbiyik, C. Barth, M. Baselga, S. Baur, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, M. Giffels, P. Goldenzweig, A. Gottmann, M.A. Harrendorf, F. Hartmann¹⁷, U. Husemann, S. Kudella, S. Mitra, M.U. Mozer, D. Müller, Th. Müller, M. Musich, A. Nürnberg, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Wassmer, M. Weber, C. Wöhrmann, R. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G. Anagnostou, P. Asenov, G. Daskalakis, T. Gerasis, A. Kyriakis, D. Loukas, G. Paspalaki

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

M. Diamantopoulou, G. Karathanasis, P. Kontaxakis, A. Manousakis-katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, A. Stakia, K. Theofilatos, K. Vellidis, E. Vourliotis

National and Kapodistrian University of Athens, Athens, Greece

G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

National Technical University of Athens, Athens, Greece

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitaras, N. Manthos, I. Papadopoulos, J. Strologas, F.A. Triantis, D. Tsitsonis

University of Ioánnina, Ioánnina, Greece

M. Bartók²¹, R. Chudasama, M. Csanad, P. Major, K. Mandal, A. Mehta, M.I. Nagy, G. Pasztor, O. Surányi, G.I. Veres

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

G. Bencze, C. Hajdu, D. Horvath²², F. Sikler, T.A. Vámi, V. Veszpremi, G. Vesztergombi[†]

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi²¹, J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

P. Raics, D. Teyssier, Z.L. Trocsanyi, B. Ujvari

Institute of Physics, University of Debrecen, Debrecen, Hungary

T. Csorgo, W.J. Metzger, F. Nemes, T. Novak

Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary

S. Choudhury, J.R. Komaragiri, P.C. Tiwari

Indian Institute of Science (IISc), Bangalore, India

S. Bahinipati²³, C. Kar, G. Kole, P. Mal, V.K. Muraleedharan Nair Bindhu, A. Nayak²⁴, D.K. Sahoo²³, S.K. Swain

National Institute of Science Education and Research, HBNI, Bhubaneswar, India

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Viridi, G. Walia

Panjab University, Chandigarh, India

A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, Ashok Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

University of Delhi, Delhi, India

R. Bhardwaj²⁵, M. Bharti²⁵, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep²⁵, D. Bhowmik, S. Dutta, S. Ghosh, B. Gomber²⁶, M. Maity²⁷, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, G. Saha, S. Sarkar, T. Sarkar²⁷, M. Sharan, B. Singh²⁵, S. Thakur²⁵

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera, P. Kalbhor, A. Muhammad, P.R. Pujahari, A. Sharma, A.K. Sikdar

Indian Institute of Technology Madras, Madras, India

D. Dutta, V. Jha, V. Kumar, D.K. Mishra, P.K. Netrakanti, L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, Ravindra Kumar Verma

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo, S. Sawant

Tata Institute of Fundamental Research-B, Mumbai, India

S. Dube, B. Kansal, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

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

S. Chenarani²⁸, E. Eskandari Tadavani, S.M. Etesami²⁸, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia^{a,b}, R. Aly^{a,b,29}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, A. Di Florio^{a,b}, W. Elmetenawee^{a,b}, L. Fiore^a, A. Gelmi^{a,b}, G. Iaselli^{a,c}, M. Ince^{a,b}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, J.A. Merlin, G. Miniello^{a,b}, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^a, A. Ranieri^a, G. Selvaggi^{a,b}, L. Silvestris^a, F.M. Simone^{a,b}, R. Venditti^a, 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^{a,b}, D. Bonacorsi^{a,b}, L. Borgonovi^{a,b}, S. Braibant-Giacomelli^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, C. Ciocca^a, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, E. Fontanesi^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b},

F. Iemmi ^{a,b}, S. Lo Meo ^{a,30}, S. Marcellini ^a, G. Masetti ^a, F.L. Navarria ^{a,b}, A. Perrotta ^a, F. Primavera ^{a,b}, A.M. Rossi ^{a,b}, T. Rovelli ^{a,b}, G.P. Siroli ^{a,b}, N. Tosi ^a

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, Italy

S. Albergo ^{a,b,31}, S. Costa ^{a,b}, A. Di Mattia ^a, R. Potenza ^{a,b}, A. Tricomi ^{a,b,31}, C. Tuve ^{a,b}

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, Italy

G. Barbagli ^a, A. Cassese, R. Ceccarelli, V. Ciulli ^{a,b}, C. Civinini ^a, R. D'Alessandro ^{a,b}, F. Fiori ^a, E. Focardi ^{a,b}, G. Latino ^{a,b}, P. Lenzi ^{a,b}, M. Meschini ^a, S. Paoletti ^a, G. Sguazzoni ^a, L. Viliani ^a

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

M. Bozzo ^{a,b}, F. Ferro ^a, R. Mulargia ^{a,b}, E. Robutti ^a, S. Tosi ^{a,b}

^a INFN Sezione di Genova, Genova, Italy

^b Università di Genova, Genova, Italy

A. Benaglia ^a, A. Beschi ^{a,b}, F. Brivio ^{a,b}, V. Ciriolo ^{a,b,17}, M.E. Dinardo ^{a,b}, P. Dini ^a, S. Gennai ^a, A. Ghezzi ^{a,b}, P. Govoni ^{a,b}, L. Guzzi ^{a,b}, M. Malberti ^a, S. Malvezzi ^a, D. Menasce ^a, F. Monti ^{a,b}, L. Moroni ^a, M. Paganoni ^{a,b}, D. Pedrini ^a, S. Ragazzi ^{a,b}, T. Tabarelli de Fatis ^{a,b}, D. Valsecchi ^{a,b}, D. Zuolo ^{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 Iorio ^{a,b}, A. Di Crescenzo ^{a,b}, F. Fabozzi ^{a,c}, F. Fienga ^a, G. Galati ^a, A.O.M. Iorio ^{a,b}, L. Lista ^{a,b}, S. Meola ^{a,d,17}, P. Paolucci ^{a,17}, B. Rossi ^a, C. Sciacca ^{a,b}, E. Voevodina ^{a,b}

^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, N. Bacchetta ^a, D. Bisello ^{a,b}, A. Boletti ^{a,b}, A. Bragagnolo ^{a,b}, R. Carlin ^{a,b}, P. Checchia ^a, P. De Castro Manzano ^a, T. Dorigo ^a, U. Dosselli ^a, F. Gasparini ^{a,b}, U. Gasparini ^{a,b}, A. Gozzelino ^a, S.Y. Hoh ^{a,b}, S. Lacaprara ^a, M. Margoni ^{a,b}, A.T. Meneguzzo ^{a,b}, J. Pazzini ^{a,b}, M. Presilla ^b, P. Ronchese ^{a,b}, R. Rossin ^{a,b}, F. Simonetto ^{a,b}, A. Tiko ^a, M. Tosi ^{a,b}, M. Zanetti ^{a,b}, P. Zotto ^{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, D. Fiorina ^{a,b}, P. Montagna ^{a,b}, S.P. Ratti ^{a,b}, V. Re ^a, M. Ressegotti ^{a,b}, C. Riccardi ^{a,b}, P. Salvini ^a, I. Vai ^a, 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, D. Ciangottini ^{a,b}, L. Fanò ^{a,b}, P. Lariccia ^{a,b}, R. Leonardi ^{a,b}, E. Manoni ^a, G. Mantovani ^{a,b}, V. Mariani ^{a,b}, M. Menichelli ^a, A. Rossi ^{a,b}, A. Santocchia ^{a,b}, D. Spiga ^a

^a INFN Sezione di Perugia, Perugia, Italy

^b Università di Perugia, Perugia, Italy

K. Androsov ^a, P. Azzurri ^a, G. Bagliesi ^a, V. Bertacchi ^{a,c}, L. Bianchini ^a, T. Boccali ^a, R. Castaldi ^a, M.A. Ciocci ^{a,b}, R. Dell'Orso ^a, S. Donato ^a, G. Fedi ^a, L. Giannini ^{a,c}, A. Giassi ^a, M.T. Grippo ^a, F. Ligabue ^{a,c}

E. Manca ^{a,c}, G. Mandorli ^{a,c}, A. Messineo ^{a,b}, F. Palla ^a, A. Rizzi ^{a,b}, G. Rolandi ³², S. Roy Chowdhury, A. Scribano ^a, P. Spagnolo ^a, R. Tenchini ^a, G. Tonelli ^{a,b}, N. Turini, 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

F. Cavallari ^a, M. Cipriani ^{a,b}, D. Del Re ^{a,b}, E. Di Marco ^a, M. Diemoz ^a, E. Longo ^{a,b}, P. Meridiani ^a, G. Organtini ^{a,b}, F. Pandolfi ^a, R. Paramatti ^{a,b}, C. Quaranta ^{a,b}, S. Rahatlou ^{a,b}, C. Rovelli ^a, F. Santanastasio ^{a,b}, L. Soffi ^{a,b}

^a INFN Sezione di Roma, Rome, Italy

^b Sapienza Università di Roma, Rome, Italy

N. Amapane ^{a,b}, R. Arcidiacono ^{a,c}, S. Argiro ^{a,b}, M. Arneodo ^{a,c}, N. Bartosik ^a, R. Bellan ^{a,b}, A. Bellora, C. Biino ^a, A. Cappati ^{a,b}, N. Cartiglia ^a, S. Cometti ^a, M. Costa ^{a,b}, R. Covarelli ^{a,b}, N. Demaria ^a, B. Kiani ^{a,b}, F. Legger, C. Mariotti ^a, S. Maselli ^a, E. Migliore ^{a,b}, V. Monaco ^{a,b}, E. Monteil ^{a,b}, M. Monteno ^a, M.M. Obertino ^{a,b}, G. Ortona ^{a,b}, L. Pacher ^{a,b}, N. Pastrone ^a, M. Pelliccioni ^a, G.L. Pinna Angioni ^{a,b}, A. Romero ^{a,b}, M. Ruspa ^{a,c}, R. Salvatico ^{a,b}, V. Sola ^a, A. Solano ^{a,b}, D. Soldi ^{a,b}, A. Staiano ^a, D. Trocino ^{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, V. Candelise ^{a,b}, M. Casarsa ^a, F. Cossutti ^a, A. Da Rold ^{a,b}, G. Della Ricca ^{a,b}, F. Vazzoler ^{a,b}, A. Zanetti ^a

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

B. Kim, D.H. Kim, G.N. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, S. Sekmen, D.C. Son, Y.C. Yang

Kyungpook National University, Daegu, Republic of Korea

H. Kim, D.H. Moon, G. Oh

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

B. Francois, T.J. Kim, J. Park

Hanyang University, Seoul, Republic of Korea

S. Cho, S. Choi, Y. Go, S. Ha, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, Y. Roh, J. Yoo

Korea University, Seoul, Republic of Korea

J. Goh

Kyung Hee University, Department of Physics, Seoul, Republic of Korea

H.S. Kim

Sejong University, Seoul, Republic of Korea

J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, H. Lee, K. Lee, S. Lee, K. Nam, M. Oh, S.B. Oh, B.C. Radburn-Smith, U.K. Yang, H.D. Yoo, I. Yoon

Seoul National University, Seoul, Republic of Korea

D. Jeon, J.H. Kim, J.S.H. Lee, I.C. Park, I.J. Watson

University of Seoul, Seoul, Republic of Korea

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

Sungkyunkwan University, Suwon, Republic of Korea

V. Veckalns³³

Riga Technical University, Riga, Latvia

V. Dudenas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

Z.A. Ibrahim, F. Mohamad Idris³⁴, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

Universidad de Sonora (UNISON), Hermosillo, Mexico

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz³⁵, R. Lopez-Fernandez, A. Sanchez-Hernandez

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

S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

J. Eysermans, I. Pedraza, H.A. Salazar Ibarquen, C. Uribe Estrada

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

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

J. Mijuskovic², N. Raicevic

University of Montenegro, Podgorica, Montenegro

D. Krofcheck

University of Auckland, Auckland, New Zealand

S. Bheesette, 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

V. Avati, L. Grzanka, M. Malawski

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland

H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, A. Byszuk³⁶, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Olszewski, M. Walczak

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

M. Araujo, P. Bargassa, D. Bastos, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, J. Seixas, K. Shchelina, G. Strong, O. Toldaiev, J. Varela

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

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev^{37,38}, P. Moisenz, V. Palichik, V. Perelygin, M. Savina, 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. Kim³⁹, E. Kuznetsova⁴⁰, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, 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. Gavrillov, N. Lychkovskaya, A. Nikitenko⁴¹, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepanov, M. Toms, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia

T. Aushev, N. Petrov

Moscow Institute of Physics and Technology, Moscow, Russia

O. Bychkova, R. Chistov⁴², M. Danilov⁴², A. Nigamova, S. Polikarpov⁴², E. Tarkovskii

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

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Belyaev, E. Boos, M. Dubinin⁴³, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

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

A. Barnyakov⁴⁴, V. Blinov⁴⁴, T. Dimova⁴⁴, L. Kardapoltsev⁴⁴, Y. Skovpen⁴⁴

Novosibirsk State University (NSU), Novosibirsk, Russia

I. Azhgirey, I. Bayshev, S. Bitiukov, V. Kachanov, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia

A. Babaev, A. Iuzhakov, V. Okhotnikov

National Research Tomsk Polytechnic University, Tomsk, Russia

V. Borchsh, V. Ivanchenko, E. Tcherniaev

Tomsk State University, Tomsk, Russia

P. Adzic⁴⁵, P. Cirkovic, M. Dordevic, P. Milenovic, J. Milosevic, M. Stojanovic

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

M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, Cristina F. Bedoya, J.A. Brochero Cifuentes, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi, C. Willmott

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

C. Albajar, J.F. de Trocóniz, R. Reyes-Almanza

Universidad Autónoma de Madrid, Madrid, Spain

B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain

I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Russo⁴⁶, L. Scodellaro, I. Vila, J.M. Vizan Garcia

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

K. Malagalage

University of Colombo, Colombo, Sri Lanka

W.G.D. Dharmaratna, N. Wickramage

University of Ruhuna, Department of Physics, Matara, Sri Lanka

D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, P. Bortignon, E. Bossini, E. Brondolin, T. Camporesi, A. Caratelli, G. Cerminara, E. Chapon, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, O. Davignon, A. De Roeck, M. Deile, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita⁴⁷, D. Fasanella, S. Fiorendi, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, Y. Iiyama, V. Innocente, T. James, P. Janot, O. Karacheban²⁰, J. Kaspar, J. Kieseler, M. Krammer¹, N. Kratochwil, C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, J. Niedziela, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo¹⁷, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, M. Rieger, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas⁴⁸, J. Steggemann, S. Summers, V.R. Tavolaro, D. Treille, A. Tsiros, G.P. Van Onsem, A. Vartak, M. Verzetti, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

L. Caminada⁴⁹, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

Paul Scherrer Institut, Villigen, Switzerland

M. Backhaus, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, R.A. Manzoni, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

ETH Zurich – Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

T.K. Aarrestad, C. AMSler⁵⁰, C. Botta, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, B. Kilminster, S. Leontsinis, V.M. Mikuni, I. Neutelings, G. Rauco, P. Robmann, K. Schweiger, C. Seitz, Y. Takahashi, S. Wertz, A. Zucchetta

Universität Zürich, Zurich, Switzerland

T.H. Doan, C.M. Kuo, W. Lin, A. Roy, S.S. Yu

National Central University, Chung-Li, Taiwan

P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas, N. Suwonjandee

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

A. Bat, F. Boran, A. Celik⁵¹, S. Damarseckin⁵², Z.S. Demiroglu, F. Dolek, C. Dozen⁵³, I. Dumanoglu, G. Gokbulut, Emine Gurpinar Guler⁵⁴, Y. Guler, I. Hos⁵⁵, C. Isik, E.E. Kangal⁵⁶, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir⁵⁷, S. Ozturk⁵⁸, A.E. Simsek, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

B. Isildak⁵⁹, G. Karapinar⁶⁰, M. Yalvac

Middle East Technical University, Physics Department, Ankara, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya⁶¹, O. Kaya⁶², Ö. Özçelik, S. Tekten, E.A. Yetkin⁶³

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak, Y. Komurcu, S. Sen⁶⁴

Istanbul Technical University, Istanbul, Turkey

S. Cerci⁶⁵, B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci⁶⁵

Istanbul University, Istanbul, Turkey

B. Grynyov

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

L. Levchuk

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

E. Bhal, S. Bologna, J.J. Brooke, D. Burns⁶⁶, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, B. Penning, T. Sakuma, S. Seif El Nasr-Storey, V.J. Smith, J. Taylor, A. Titterton

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev⁶⁷, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, Gurpreet Singh Chahal⁶⁸, D. Colling, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, P. Everaerts, G. Hall, G. Iles, M. Komm, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, A. Morton, J. Nash⁶⁹, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, T. Strebler, A. Tapper, K. Uchida, T. Virdee¹⁷, N. Wardle, D. Winterbottom, A.G. Zecchinelli, S.C. Zenz

Imperial College, London, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, I.D. Reid, L. Teodorescu, S. Zahid

Brunel University, Uxbridge, United Kingdom

K. Call, B. Caraway, J. Dittmann, K. Hatakeyama, C. Madrid, B. McMaster, N. Pastika, C. Smith

Baylor University, Waco, USA

R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

Catholic University of America, Washington, DC, USA

A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

The University of Alabama, Tuscaloosa, USA

A. Albert, D. Arcaro, Z. Demiragli, D. Gastler, C. Richardson, J. Rohlf, D. Sperka, D. Spitzbart, I. Suarez, L. Sulak, D. Zou

Boston University, Boston, USA

G. Benelli, B. Burkley, X. Coubez¹⁸, D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan⁷⁰, K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, M. Narain, S. Sagir⁷¹, R. Syarif, E. Usai, W.Y. Wong, D. Yu, W. Zhang

Brown University, Providence, USA

R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko[†], O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

University of California, Davis, Davis, USA

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, W.A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

University of California, Los Angeles, USA

K. Burt, Y. Chen, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, S. Wimpenny, B.R. Yates, Y. Zhang

University of California, Riverside, Riverside, USA

J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, D. Klein, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

N. Amin, R. Bhandari, C. Campagnari, M. Citron, V. Dutta, M. Franco Sevilla, J. Incandela, B. Marsh, H. Mei, A. Ovcharova, H. Qu, J. Richman, U. Sarica, D. Stuart, S. Wang

University of California, Santa Barbara – Department of Physics, Santa Barbara, USA

D. Anderson, A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, T.Q. Nguyen, J. Pata, M. Spiropulu, J.R. Vlimant, S. Xie, Z. Zhang, R.Y. Zhu

California Institute of Technology, Pasadena, USA

M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, W.T. Ford, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

University of Colorado Boulder, Boulder, USA

J. Alexander, Y. Cheng, J. Chu, A. Datta, A. Frankenthal, K. Mcdermott, J.R. Patterson, D. Quach, A. Ryd, S.M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

Cornell University, Ithaca, USA

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, R. Heller, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijsma, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, J. Lewis, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena, G. Rakness, F. Ravera, A. Reinsvold Hall, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, R. Vidal, M. Wang, H.A. Weber

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, V. Cherepanov, F. Errico, R.D. Field, S.V. Gleyzer, D. Guerrero, B.M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Wang, S. Wang, X. Zuo

University of Florida, Gainesville, USA

Y.R. Joshi

Florida International University, Miami, USA

T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, T. Perry, H. Prosper, C. Schiber, R. Yohay, J. Zhang

Florida State University, Tallahassee, USA

M.M. Baarmand, M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, C. Mills, T. Roy, M.B. Tonjes, N. Varelas, J. Viinikainen, H. Wang, X. Wang, Z. Wu

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

M. Alhousseini, B. Bilki⁵⁴, K. Dilsiz⁷², S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili⁷³, A. Moeller, J. Nachtman, H. Ogul⁷⁴, Y. Onel, F. Ozok⁷⁵, A. Penzo, C. Snyder, E. Tiras, J. Wetzel

The University of Iowa, Iowa City, USA

B. Blumenfeld, A. Cocoros, N. Eminizer, A.V. Gritsan, W.T. Hung, S. Kyriacou, P. Maksimovic, J. Roskes, M. Swartz

Johns Hopkins University, Baltimore, USA

C. Baldenegro Barrera, P. Baringer, A. Bean, S. Boren, J. Bowen, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, D. Majumder, W. Mcbrayer, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

The University of Kansas, Lawrence, USA

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

Kansas State University, Manhattan, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, A.C. Mignerey, S. Nabili, F. Ricci-Tam, M. Seidel, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

University of Maryland, College Park, USA

D. Abercrombie, B. Allen, A. Baty, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

Massachusetts Institute of Technology, Cambridge, USA

R.M. Chatterjee, A. Evans, S. Guts[†], P. Hansen, J. Hiltbrand, Sh. Jain, Y. Kubota, Z. Lesko, J. Mans, M. Reverting, R. Rusack, R. Saradhy, N. Schroeder, M.A. Wadud

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

K. Bloom, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, R. Kamalieddin, I. Kravchenko, J.E. Siado, G.R. Snow[†], B. Stieger, W. Tabb

University of Nebraska-Lincoln, Lincoln, USA

G. Agarwal, C. Harrington, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, A. Parker, J. Pekkanen, S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, B. Marzocchi, D.M. Morse, T. Orimoto, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northeastern University, Boston, USA

S. Bhattacharya, J. Bueghly, A. Gilbert, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

Northwestern University, Evanston, USA

R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, Y. Musienko³⁷, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

J. Alimena, B. Bylsma, L.S. Durkin, B. Francis, C. Hill, W. Ji, A. Lefeld, T.Y. Ling, B.L. Winer

The Ohio State University, Columbus, USA

G. Dezoort, P. Elmer, J. Hardenbrook, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

Princeton University, Princeton, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, USA

A. Barker, V.E. Barnes, S. Das, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, B. Mahakud, D.H. Miller, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, H. Qiu, J.F. Schulte, N. Trevisani, F. Wang, R. Xiao, W. Xie

Purdue University, West Lafayette, USA

T. Cheng, J. Dolen, N. Parashar

Purdue University Northwest, Hammond, USA

U. Behrens, S. Dildick, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, Arun Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, W. Shi, A.G. Stahl Leiton, Z. Tu, A. Zhang

Rice University, Houston, USA

A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus

University of Rochester, Rochester, USA

B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas

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

H. Acharya, A.G. Delannoy, S. Spanier

University of Tennessee, Knoxville, USA

O. Bouhali⁷⁶, M. Dalchenko, M. De Mattia, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁷⁷, H. Kim, S. Luo, S. Malhotra, D. Marley, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, F. De Guio, V. Hegde, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

Texas Tech University, Lubbock, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij

Vanderbilt University, Nashville, USA

M.W. Arenton, P. Barria, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA

R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa

Wayne State University, Detroit, USA

T. Bose, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, C. Galloni, H. He, M. Herndon, A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, K. Long, R. Loveless, J. Madhusudanan Sreekala, D. Pinna, T. Ruggles, A. Savin, V. Sharma, W.H. Smith, D. Teague, S. Trembath-reichert

University of Wisconsin – Madison, Madison, WI, USA

† Deceased.

¹ Also at Vienna University of Technology, Vienna, Austria.

² Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.

³ Also at Universidade Estadual de Campinas, Campinas, Brazil.

⁴ Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.

⁵ Also at UFMS, Nova Andradina, Brazil.

- 6 Also at Universidade Federal de Pelotas, Pelotas, Brazil.
- 7 Also at Université Libre de Bruxelles, Bruxelles, Belgium.
- 8 Also at University of Chinese Academy of Sciences, Beijing, China.
- 9 Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia.
- 10 Also at Joint Institute for Nuclear Research, Dubna, Russia.
- 11 Also at Suez University, Suez, Egypt.
- 12 Now at British University in Egypt, Cairo, Egypt.
- 13 Also at Purdue University, West Lafayette, USA.
- 14 Also at Université de Haute Alsace, Mulhouse, France.
- 15 Also at Tbilisi State University, Tbilisi, Georgia.
- 16 Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
- 17 Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
- 18 Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
- 19 Also at University of Hamburg, Hamburg, Germany.
- 20 Also at Brandenburg University of Technology, Cottbus, Germany.
- 21 Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary.
- 22 Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
- 23 Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India.
- 24 Also at Institute of Physics, Bhubaneswar, India.
- 25 Also at Shoolini University, Solan, India.
- 26 Also at University of Hyderabad, Hyderabad, India.
- 27 Also at University of Visva-Bharati, Santiniketan, India.
- 28 Also at Isfahan University of Technology, Isfahan, Iran.
- 29 Now at INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy.
- 30 Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
- 31 Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
- 32 Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- 33 Also at Riga Technical University, Riga, Latvia, Riga, Latvia.
- 34 Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
- 35 Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
- 36 Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
- 37 Also at Institute for Nuclear Research, Moscow, Russia.
- 38 Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
- 39 Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- 40 Also at University of Florida, Gainesville, USA.
- 41 Also at Imperial College, London, United Kingdom.
- 42 Also at P.N. Lebedev Physical Institute, Moscow, Russia.
- 43 Also at California Institute of Technology, Pasadena, USA.
- 44 Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
- 45 Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- 46 Also at Università degli Studi di Siena, Siena, Italy.
- 47 Also at INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy, Pavia, Italy.
- 48 Also at National and Kapodistrian University of Athens, Athens, Greece.
- 49 Also at Universität Zürich, Zurich, Switzerland.
- 50 Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria.
- 51 Also at Burdur Mehmet Akif Ersoy University, BURDUR, Turkey.
- 52 Also at Şırnak University, Şırnak, Turkey.
- 53 Also at Tsinghua University, Beijing, China.
- 54 Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey.
- 55 Also at Istanbul Aydin University, Istanbul, Turkey.
- 56 Also at Mersin University, Mersin, Turkey.
- 57 Also at Piri Reis University, Istanbul, Turkey.
- 58 Also at Gaziosmanpasa University, Tokat, Turkey.
- 59 Also at Ozyegin University, Istanbul, Turkey.
- 60 Also at Izmir Institute of Technology, Izmir, Turkey.
- 61 Also at Marmara University, Istanbul, Turkey.
- 62 Also at Kafkas University, Kars, Turkey.
- 63 Also at Istanbul Bilgi University, Istanbul, Turkey.
- 64 Also at Hacettepe University, Ankara, Turkey.
- 65 Also at Adiyaman University, Adiyaman, Turkey.
- 66 Also at Vrije Universiteit Brussel, Brussel, Belgium.
- 67 Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- 68 Also at IPPP Durham University, Durham, United Kingdom.
- 69 Also at Monash University, Faculty of Science, Clayton, Australia.
- 70 Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA.
- 71 Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
- 72 Also at Bingol University, Bingol, Turkey.
- 73 Also at Georgian Technical University, Tbilisi, Georgia.
- 74 Also at Sinop University, Sinop, Turkey.

⁷⁵ Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.

⁷⁶ Also at Texas A&M University at Qatar, Doha, Qatar.

⁷⁷ Also at Kyungpook National University, Daegu, Korea, Daegu, Republic of Korea.