Observation of the $B^0_s \rightarrow X(3872)\phi$ decay

The CMS Collaboration

Abstract

Using a data sample of proton-proton collisions at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of $140 \text{ fb}^{-1}$ collected by the CMS experiment in 2016–2018, the $B^0_s \rightarrow X(3872)\phi$ decay is observed. Decays into $J/\psi \pi^+ \pi^-$ and $K^+K^-$ are used to reconstruct, respectively, the $X(3872)$ and $\phi$. The ratio of the product of branching fractions $B(B^0_s \rightarrow X(3872)\phi) B(X(3872) \rightarrow J/\psi \pi^+ \pi^-)$ to the product $B(B^0 \rightarrow \psi(2S)\phi) B(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)$ is measured to be $(2.21 \pm 0.29 \text{ (stat)} \pm 0.17 \text{ (syst)})\%$. The ratio $B(B^0_s \rightarrow X(3872)\phi)/B(B^0 \rightarrow X(3872)K^0)$ is found to be consistent with one, while the ratio $B(B^0_s \rightarrow X(3872)\phi)/B(B^+ \rightarrow X(3872)K^+)$ is two times smaller. This suggests a difference in the production dynamics of the $X(3872)$ in $B^0$ and $B^0_s$ meson decays compared to $B^+$. The reported observation may shed new light on the nature of the $X(3872)$ particle.

Submitted to Physical Review Letters

*See Appendix A for the list of collaboration members
The observed spectrum of $c\bar{c}$ states below $D\bar{D}$ threshold agrees well with theoretical predictions \cite{1, 2}. Since the advent of the BaBar and Belle experiments at the B factories and their discovery of several charmonium-like states, the conventional charmonium model above $D\bar{D}$ threshold has become the subject of intense discussions. In 2003, the Belle Collaboration observed a new particle in the $B^+ \to J/\psi \pi^+ \pi^- K^+$ decay \cite{3}, named $X(3872)$ and decaying to $J/\psi \pi^+ \pi^-$, with a very small natural width for a state above $D\bar{D}$ threshold. Its world-average mass is $3871.69 \pm 0.17$ MeV, which is extremely close to the $D^0 D^{*0}$ threshold of $3872.68 \pm 0.07$ MeV \cite{4}. With this mass and a total width less than 1.2 MeV \cite{4}, the $X(3872)$ particle did not match any of the theoretically predicted charmonium resonances.

The discovery of the $X(3872)$ opened a new era of exotic, quarkonium-like spectroscopy. Many new states with unusual properties have been observed, including several charged states \cite{4, 6, 10–12}. At hadron colliders, prompt processes were found to be the dominant $X(3872)$ production mechanism \cite{7–9}. The nature of the $X(3872)$, also known as $\chi_{c1}(3872)$, is still unexplained in spite of the determination of its quantum numbers ($J^{PC} = 1^{++}$) \cite{10–12}. The studies of the dipion mass spectrum \cite{5, 8, 13} clearly favor the presence of the intermediate $\rho^0(770)$ state in the isospin violating $X(3872) \to J/\psi \pi^+ \pi^-$ decay. Important information about the $X(3872)$ production in weak decays can be extracted by comparing the branching fractions $B(B \to X(3872) h)$ for different $B$ mesons, where $h$ denotes a light hadron. More measurements of $b$ hadron decays involving $X(3872)$ production would provide important inputs for understanding its internal structure and creation dynamics.

This Letter reports the first observation of the $B_s^0 \to X(3872) \phi$ decay, where $X(3872) \to J/\psi \pi^+ \pi^-$ and $\phi \to K^+ K^-$ decays are used to reconstruct the intermediate resonances, and the measurement of the following ratio of branching fractions:

$$R \equiv \frac{B(B_s^0 \to X(3872) \phi) B(X(3872) \to J/\psi \pi^+ \pi^-)}{B(B_s^0 \to \psi(2S) \phi) B(\psi(2S) \to J/\psi \pi^+ \pi^-)} = \frac{N(B_s^0 \to X(3872) \phi)}{N(B_s^0 \to \psi(2S) \phi)} \frac{\epsilon_{B_s^0 \to X(3872) \phi}}{\epsilon_{B_s^0 \to \psi(2S) \phi}}$$

(1)

In this expression, $N$ stands for the measured number of signal events in data and $\epsilon$ stands for the efficiency. The $J/\psi$ and $\phi(1020)$ (referred to as $\phi$ throughout the Letter) mesons are reconstructed in the $\mu^+ \mu^-$ and $K^+ K^-$ channels, respectively. The normalization is done via the $B_s^0 \to \psi(2S) \phi$ decay, with a subsequent $\psi(2S) \to J/\psi \pi^+ \pi^-$ decay. The similarity of the decay topology of the signal and normalization channels results in nearly identical kinematics, leading to the cancellation of many systematic uncertainties in the ratio.

The central feature of the CMS apparatus \cite{14} 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. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. The analysis uses proton-proton ($pp$) collision data recorded by the CMS detector during the LHC Run 2 in 2016–2018 at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 140 fb$^{-1}$. Events of interest are selected using a two-tiered trigger system \cite{15}. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 $\mu$s. The L1 trigger used in the analysis requires at least two muons. 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. The HLT algorithm used in the analysis requires two opposite-sign (OS) muons compatible with the dimuon decay of a $J/\psi$ meson at a significant distance from the beam axis, and an additional track with transverse momentum $p_T > 1.2$ GeV, compatible with the dimuon vertex.
Simulated event samples for the $B_s^0 \rightarrow X(3872)\phi$ and $B_s^0 \rightarrow \psi(2S)\phi$ decays are generated in the analysis. The 
PYTHIA 8.230 package [16] is used to simulate the production of the $B_s^0$ mesons, which are subsequently decayed with 
\textsc{evtgen} 1.6.0 [17], where the final-state photon radiation is included using 
\textsc{photos} 3.6.1 [18,19]. Generated events are then passed to a detailed \textsc{geant4}-based simulation [20] of the CMS detector, followed by the same trigger and reconstruction algorithms as used for the collision data. The simulation includes effects from multiple pp interactions in the same or nearby bunch crossings (pileup) with the multiplicity distribution tuned to match the data.

The event selection begins by requiring two OS muons with $p_T > 4\text{ GeV}$ passing the soft-muon identification criteria [21] and matching those that triggered the event readout. The dimuon mass is required to be compatible with the world-average $J/\psi$ mass [4], $m_{J/\psi}^{\text{PDG}}$. The $B_s^0 \rightarrow J/\psi K^+ K^- \pi^+ \pi^-$ candidates are obtained by combining the selected $J/\psi$ candidate with four high-purity tracks [22] with total charge of zero that are not matched with the selected muons. At least one of the four tracks is required to have $p_T > 1.2\text{ GeV}$ and transverse impact parameter significance greater than 2.0, to match the trigger requirement. A kinematic vertex fit that constrains the dimuon invariant mass to $m_{J/\psi}^{\text{PDG}}$ is performed on the two muons and four tracks. From all reconstructed pp collision vertices, the primary vertex (PV) is chosen as the one with the smallest pointing angle, as done in Refs. [23–28]. The pointing angle is the angle between the $B_s^0$ candidate momentum and the vector joining the PV and the reconstructed $B_s^0$ candidate decay vertex. Signal events are eventually selected based on the corrected invariant mass $m(B_s^0) = m(J/\psi K^+ K^- \pi^+ \pi^-) - m(J/\psi \pi^+ \pi^-) + m_{J/\psi}^{\text{PDG}}$, where $m_{J/\psi}^{\text{PDG}}$ and $m_{X(3872)}^{\text{PDG}}$ are the world-average $\psi(2S)$ and $X(3872)$ masses, respectively. This approach ensures the independence between the reconstructed $B_s^0$ and $J/\psi \pi^+ \pi^-$ masses, and improves the $B_s^0$ mass resolution.

To select the $B_s^0 \rightarrow J/\psi K^+ K^- \pi^+ \pi^-$ candidates, one must choose which two OS tracks are from kaons, with the other two tracks then being associated with pions. Since the decays of interest have narrow intermediate states $\phi \rightarrow K^+ K^-$ and either $\psi(2S)$ or $X(3872) \rightarrow J/\psi \pi^+ \pi^-$, the following criteria are used to assign the tracks for the selected $J/\psi K^+ K^- \pi^+ \pi^-$ candidates:

- $3.60 < m(J/\psi \pi^+ \pi^-) < 3.95\text{ GeV}$,
- $1.00 < m(K^+ K^-) < 1.04\text{ GeV}$,
- $5.32 < m(B_s^0) < 5.42\text{ GeV}$,
- if more than one combination of mass assignments passes the three selections above, the candidate is discarded.

The selected mass windows are wide enough to allow fits to the mass distributions, while maintaining a selection efficiency above 99%.

The selection criteria are optimized using the Punzi figure of merit [29], which does not rely on the signal normalization. Data sidebands are used to estimate the background, and the $B_s^0 \rightarrow X(3872)\phi$ simulated sample is used to measure the signal efficiency. The resulting selection criteria are: $p_T(B_s^0) > 10\text{ GeV}$, vertex $x^2$ fit probability $P_{\text{vtx}}(B_s^0) > 7\%$, $p_T(\pi^\pm) > 0.7\text{ GeV}$, $\min(p_T(K^\pm)) > 1.5\text{ GeV}$, $\max(p_T(K^\pm)) > 2.2\text{ GeV}$, and the decay length of the $B_s^0$ candidate in the transverse plane $L_{xy}(B_s^0) > 15\sigma_{L_{xy}}(B_s^0)$, where $\sigma_{L_{xy}}$ is the uncertainty in $L_{xy}$. Additionally, the cosine of the angle between the transverse momentum of the $B_s^0$ candidate and the displacement vector must satisfy $\cos(p_T, L_{xy}) > 0.999$, and the invariant mass of the two pions is required to be above 0.45 (0.70) GeV in the $\psi(2S)$ ($X(3872)$) channel.

The signal yields of the $B_s^0 \rightarrow X(3872)\phi$ and $B_s^0 \rightarrow \psi(2S)\phi$ decays are extracted using a two-
dimensional (2D) maximum likelihood fit to the $m(J/\psi \pi^+\pi^-)$ and $m(K^+K^-)$ distributions for $B^0_s$ candidates in the range $5.32 < m(B^0_s) < 5.42\text{ GeV}$. The numbers of $X(3872)\phi$ and $\psi(2S)\phi$ signal events from the fit are assumed to come solely from the corresponding $B^0_s$ decays. A systematic uncertainty related to this assumption is evaluated below.

Figure 1 shows the observed $m(J/\psi \pi^+\pi^-)$ (left) and $m(K^+K^-)$ (right) invariant mass distributions for the $\psi(2S)\phi$ candidates with $3.60 < m(J/\psi \pi^+\pi^-) < 3.75\text{ GeV}$. Overlaid are the projections of the 2D fit function, which consists of the following four components:

- $(\psi(2S), \phi)$, for the signal component,
- $(\text{bkg}, \phi)$, for events containing genuine $\phi \rightarrow K^+K^-$ decays and background $J/\psi \pi^+\pi^-$ combinations,
- $(\psi(2S), \text{bkg})$, for events containing genuine $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$ decays and background $K^+K^-$ combinations,
- $(\text{bkg}, \text{bkg})$, for the background in both dimensions.

Each component is a product of two one-dimensional functions. For the $\phi \rightarrow K^+K^-$ signal, a relativistic Breit–Wigner function convolved with the detector mass resolution is used, where the $\phi$ natural width is fixed to its known value [4]. The mass resolution is determined from simulated event samples to be about 1.3 MeV. The background in the $K^+K^-$ mass distribution is modeled with a threshold function multiplied by a first-order polynomial: $(m(K^+K^-) - x_0)^\alpha \cdot \text{Pol}_1(m(K^+K^-))$, where $x_0$ is the threshold value equal to twice the kaon mass and $\alpha$ is a free parameter. The $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$ signal is described with a double-Gaussian (DG) function with all parameters left free. The background in the $m(J/\psi \pi^+\pi^-)$ distribution is modeled with a modified threshold function: $(m(J/\psi \pi^+\pi^-) - y_0)^\beta \cdot \text{Pol}_1(m(J/\psi \pi^+\pi^-))$, where $y_0$ is the threshold value equal to $m_{J/\psi}^{\text{PDG}} + 0.45\text{ GeV}$ (corresponding to the requirement $m(\pi^+\pi^-) > 0.45\text{ GeV}$), and $\beta$ is a free parameter.

The following parameters are free in the fit: numbers of events in the four components, $\phi$ and $\psi(2S)$ meson masses, $\psi(2S)$ resolution parameters, and background parameters of $m(K^+K^-)$ and $m(J/\psi \pi^+\pi^-)$. The fitted yield for the $\psi(2S) + \phi$ component is $N(B^0_s \rightarrow \psi(2S)\phi) = 15359 \pm 171$.

![Figure 1](image_url)

Figure 1: The observed $J/\psi \pi^+\pi^-$ (left) and $K^+K^-$ (right) invariant mass distributions for the $B^0_s \rightarrow \psi(2S)\phi$ candidates are shown by the points, with the vertical bars representing the statistical uncertainties. The projections of the 2D fit and its various components are shown by the lines.

For the $X(3872)$ mass region, defined as $3.80 < m(J/\psi \pi^+\pi^-) < 3.95\text{ GeV}$, the same fit function is used as in the $\psi(2S)$ channel, but additional constraints are made because of the lower number of signal events. The shape of the $X(3872) \rightarrow J/\psi \pi^+\pi^-$ signal is fixed to the one obtained in data for $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$, with one floating parameter responsible for the resolution scal-
ing. The \( X(3872) \) mass is left free in the fit and the returned value is in agreement with the known mass [4]. The threshold value \( y_0 \) is changed to \( m^{PDG}_{J/\psi} + 0.7 \) GeV to account for the different requirement on the dipion invariant mass applied in the \( X(3872) \) channel. The invariant mass distributions and the projections of the 2D fit are shown in Fig. 2. The measured signal yield is \( N(B^0_s \to X(3872)\phi) = 299 \pm 39 \).

The statistical significance of the \( B^0_s \to X(3872)\phi \) signal has been evaluated with the likelihood-ratio technique by applying the background-only and signal-plus-background hypotheses. Using the standard asymptotic approximation [30] for the likelihood, since the conditions of the Wilks’ theorem [31] are satisfied, the statistical significance of the \( B^0_s \to X(3872)\phi \) signal is over 6 standard deviations (\( \sigma \)), after accounting for the systematic uncertainties discussed later.

Figure 2: The observed \( J/\psi \pi^+\pi^- \) (left) and \( K^+K^- \) (right) invariant mass distributions for the \( B^0_s \to X(3872)\phi \) candidates are shown by the points, with the vertical bars representing the statistical uncertainties. The projections of the 2D fit and its various components are shown by the lines.

To evaluate the background contribution related to the non-\( B^0_s \) production of \( \psi(2S)\phi \) in the mass range \( 5.32 < m(\psi(2S)\phi) < 5.42 \) GeV, the mass distribution of \( \psi(2S)\phi \) is studied, as shown in Fig. 3 (left). The background-subtraction technique [32] is used, together with the 2D fit described above, to subtract backgrounds from nonresonant \( K^+K^- \) and \( J/\psi \pi^+\pi^- \) combinations. The observed \( m(\psi(2S)\phi) \) distribution is fitted with a DG function for the signal and an exponential for the background, as shown in Fig. 3 (left). The fit returns a non-\( B^0_s \) background contribution of 0.5%. The same procedure is repeated in the \( X(3872)\phi \) channel, shown in Fig. 3 (right), and the measured contribution of the non-\( B^0_s \) background is 1.7%. Thus the ratio of the event yields \( X(3872)/\psi(2S) \) changes by 1.2% after accounting for this background from non-\( B^0_s \) production of \( \psi(2S)\phi \) and \( X(3872)\phi \) combinations. The significance of the \( B^0_s \to X(3872)\phi \) signal extracted from the binned fit to the background-subtracted \( m(X(3872)\phi) \) distribution exceeds \( 10\sigma \).

The efficiencies for the signal and normalization channels are calculated using the simulated event samples. The total efficiency includes the detector acceptance, trigger, and candidate reconstruction efficiencies. Only the ratio of the efficiencies for the \( \psi(2S) \) and \( X(3872) \) decay modes is needed to calculate the ratio \( R \), which eliminates the systematic uncertainties related to the track and muon reconstruction. The obtained efficiency ratio is

\[
e_{B^0_s \to \psi(2S)\phi} / e_{B^0_s \to X(3872)\phi} = 1.136 \pm 0.026,
\]

where the uncertainty is related to the size of the simulated samples. The simulated event samples are validated by comparing distributions of variables used in the candidate selection between the background-subtracted data and simulation. As no significant deviation is found, no additional systematic uncertainty in the efficiency ratio is assigned.

Several sources of systematic uncertainty in the measured ratio \( R \) are considered. To evaluate the systematic uncertainties related to the choice of the fit model, several alternative functions

\[
\sigma = 1.01, 1.02, 1.03, 1.04 \text{ GeV}
\]

\[
\sigma = 1.00, 1.01, 1.02, 1.03, 1.04 \text{ GeV}
\]
are tested. Uncertainties related to the choice of the signal and background models are calculated separately.

The systematic uncertainty in the modeling of the $\phi \rightarrow K^+K^-$ signal is estimated by varying the $\phi$ natural width and the $m(K^+K^-)$ resolution within their uncertainties. The corresponding changes in the ratio $R$ are negligible. The systematic uncertainty in the $m(K^+K^-)$ and $m(J/\psi \pi^+\pi^-)$ background model is estimated by testing alternative models. Instead of the baseline model, either a second-order polynomial or a threshold function multiplied by this polynomial is used. The systematic uncertainty in the $J/\psi \pi^+\pi^-$ signal model is estimated by replacing the DG function with a Student’s t-distribution [33] or, for the $X(3872)$ channel, by conservatively scaling the resolution obtained in the $\psi(2S)$ channel by the ratio of the resolutions of the two channels observed in the simulation.

The systematic uncertainty related to the non-$B^0_s$ background is estimated using the $\mathcal{P}$lot technique to subtract the contributions from nonresonant $K^+K^-$ and $J/\psi \pi^+\pi^-$ combinations from the $m(B^0_s)$ distribution, as described above and shown in Fig. 3. A systematic uncertainty of 1.2% is assigned, based on the fit results to the background-subtracted $m(\psi(2S)\phi)$ and $m(X(3872)\phi)$ distributions.

The uncertainty related to the simulation sample size is 2.2%, as evaluated above. Changes in the detector and trigger conditions in the course of the 2016–2018 data taking are shown to have a negligible effect on the measured ratio, as the signal and normalization processes are very similar. The ratio $R$ is found to be stable across different years of data taking, therefore no related systematic uncertainty is assigned.

Table 1 summarizes the systematic uncertainties described above, together with the total systematic uncertainty, obtained by adding the effects from the different sources in quadrature.

| Source                                      | Uncertainty (%) |
|---------------------------------------------|-----------------|
| $m(K^+K^-)$ signal model                    | < 0.1           |
| $m(K^+K^-)$ background model                | 2.5             |
| $m(J/\psi \pi^+\pi^-)$ signal model        | 5.3             |
| $m(J/\psi \pi^+\pi^-)$ background model    | 4.3             |
| Non-$B^0_s$ background                      | 1.2             |
| Simulated sample size                       | 2.2             |
| Total                                       | 7.7             |
Using Eq. [1], together with the measured signal yields of the $B^0_s \rightarrow X(3872)\phi$ and $B^0_s \rightarrow \psi(2S)\phi$ decays and the corresponding efficiency ratio, the product of the branching fractions, with respect to that of the $B^0_s \rightarrow \psi(2S)\phi$ decay, is measured to be

$$R = (2.21 \pm 0.29 \text{(stat)} \pm 0.17 \text{(syst)})\%.$$  

Multiplying the measured ratio $R$ by the known branching fractions $B(B^0_s \rightarrow \psi(2S)\phi)$ and $B(\psi(2S) \rightarrow J/\psi \pi^+\pi^-)$ [1], we obtain

$$B(B^0_s \rightarrow X(3872)\phi) B(X(3872) \rightarrow J/\psi \pi^+\pi^-) = (4.14 \pm 0.54 \text{(stat)} \pm 0.32 \text{(syst)} \pm 0.46 \text{(B)}) \times 10^{-6},$$

where the last uncertainty is related to the uncertainties in the aforementioned world-average branching fractions.

This branching fraction product can be compared to similar ones in $B^0$ and $B^+$ decays [4]:

$$B(B^0 \rightarrow X(3872)K^0) B(X(3872) \rightarrow J/\psi \pi^+\pi^-) = (4.3 \pm 1.3) \times 10^{-6} \text{ and } B(B^+ \rightarrow X(3872)K^+) B(X(3872) \rightarrow J/\psi \pi^+\pi^-) = (8.6 \pm 0.8) \times 10^{-6}.$$  

The measured value for $B^0_s$ is consistent with that for $B^0$, but about two times smaller than the one for $B^+$:

$$\frac{B(B^0_s \rightarrow X(3872)\phi)}{B(B^+ \rightarrow X(3872)K^+)} = 0.482 \pm 0.063 \text{(stat)} \pm 0.037 \text{(syst)} \pm 0.070 \text{(B)}.$$  

This ratio is significantly lower than the corresponding one for decays to the charmonium state $\psi(2S)$ of $B(B^0_s \rightarrow \psi(2S)\phi)/B(B^+ \rightarrow \psi(2S)K^+) = 0.87 \pm 0.10$ [4].

In summary, using a data sample corresponding to an integrated luminosity of 140 fb$^{-1}$ of proton-proton collisions collected by the CMS experiment at $\sqrt{s} = 13$ TeV in 2016–2018, the $B^0_s \rightarrow X(3872)\phi$ decay is observed for the first time. The comparison with similar decays of $B^0$ and $B^+$ mesons indicates that the $X(3872)$ formation in $B$ meson decays is different from $\psi(2S)$ formation, suggesting that $X(3872)$ is not a pure charmonium state and supporting similar conclusions derived from other experimental measurements [2, 5, 8–12]. This observation may shed new light on the nature of the $X(3872)$ particle.

Acknowledgments

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); CNRS and IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFIA (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); MIE (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. 3082017; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Deutsche Forschungsgemeinschaft (DFG) under Germany’s Excellence Strategy – EXC 2121 “Quantum Universe” – 390833306; the Lendület (“Momentum”) Programme 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. 14.W03.31.0026 (Russia); the Tomsk Polytechnic University Competitiveness Enhancement Program and “Nauka” Project FSWW-2020-0008 (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 Thalis and Aristeia program 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 Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

[1] M. B. Voloshin, “Charmonium”, *Prog. Part. Nucl. Phys.* **61** (2008) 455, [doi:10.1016/j.ppnp.2008.02.001] [arXiv:0711.4556](https://arxiv.org/abs/0711.4556).

[2] N. Brambilla et al., “Heavy quarkonium: Progress, puzzles, and opportunities”, *Eur. Phys. J. C* **71** (2011) 1534, [doi:10.1140/epjc/s10052-010-1534-9](https://doi.org/10.1140/epjc/s10052-010-1534-9) [arXiv:1010.5827](https://arxiv.org/abs/1010.5827).

[3] Belle Collaboration, “Observation of a narrow charmoniumlike state in exclusive $B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}J/\psi$ decays”, *Phys. Rev. Lett.* **91** (2003) 262001, [doi:10.1103/PhysRevLett.91.262001](https://doi.org/10.1103/PhysRevLett.91.262001) [arXiv:hep-ex/0309032](https://arxiv.org/abs/hep-ex/0309032).

[4] Particle Data Group, M. Tanabashi et al., “Review of particle physics”, *Phys. Rev. D* **98** (2018) 030001, [doi:10.1103/PhysRevD.98.030001](https://doi.org/10.1103/PhysRevD.98.030001).
[5] Belle Collaboration, “Bounds on the width, mass difference and other properties of $X(3872) \to \pi^+\pi^-J/\psi$ decays”, *Phys. Rev. D* **84** (2011) 052004, doi:10.1103/PhysRevD.84.052004, arXiv:1107.0163

[6] N. Brambilla et al., “The XYZ states: experimental and theoretical status and perspectives”, (2019). arXiv:1907.07583

[7] CDF Collaboration, “The X(3872) at CDF II”, *Int. J. Mod. Phys. A* **20** (2005) 3765, doi:10.1142/S0217751X05027552, arXiv:hep-ex/0409052

[8] CMS Collaboration, “Measurement of the $X(3872)$ production cross section via decays to $J/\psi\pi^+\pi^-$ in pp collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **04** (2013) 154, doi:10.1007/JHEP04(2013)154, arXiv:1302.3968

[9] ATLAS Collaboration, “Measurements of $\psi(2S)$ and $X(3872) \to J/\psi\pi^+\pi^-$ production in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector”, *JHEP* **01** (2017) 117, doi:10.1007/JHEP01(2017)117, arXiv:1610.09303

[10] CDF Collaboration, “Analysis of the quantum numbers $J^{PC}$ of the $X(3872)$”, *Phys. Rev. Lett.* **98** (2007) 132002, doi:10.1103/PhysRevLett.98.132002, arXiv:hep-ex/0612053

[11] LHCb Collaboration, “Determination of the $X(3872)$ meson quantum numbers”, *Phys. Rev. Lett.* **110** (2013) 222001, doi:10.1103/PhysRevLett.110.222001, arXiv:1302.6269

[12] LHCb Collaboration, “Quantum numbers of the $X(3872)$ state and orbital angular momentum in its $\rho^0J/\psi$ decay”, *Phys. Rev. D* **92** (2015) 011102, doi:10.1103/PhysRevD.92.011102, arXiv:1504.06339

[13] CDF Collaboration, “Measurement of the dipion mass spectrum in $X(3872) \to J/\psi\pi^+\pi^-$ decays”, *Phys. Rev. Lett.* **96** (2006) 102002, doi:10.1103/PhysRevLett.96.102002, arXiv:hep-ex/0512074

[14] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004

[15] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366

[16] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012

[17] D. J. Lange, “The EvtGen particle decay simulation package”, *Nucl. Instrum. Meth. A* **462** (2001) 152, doi:10.1016/S0168-9002(01)00089-4

[18] E. Barberio, B. van Eijk, and Z. Waś, “PHOTOS — a universal Monte Carlo for QED radiative corrections in decays”, *Comput. Phys. Commun.* **66** (1991) 115, doi:10.1016/0010-4655(91)90012-A

[19] E. Barberio and Z. Waś, “PHOTOS – a universal Monte Carlo for QED radiative corrections: version 2.0”, *Comput. Phys. Commun.* **79** (1994) 291, doi:10.1016/0010-4655(94)90074-4
[20] GEANT4 Collaboration, “GEANT4—A simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, [doi:10.1016/S0168-9002(03)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8)

[21] CMS Collaboration, “Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV”, *JINST* **7** (2012) P10002, [doi:10.1088/1748-0221/7/10/P10002](https://doi.org/10.1088/1748-0221/7/10/P10002), arXiv:1206.4071

[22] CMS Collaboration, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, *JINST* **9** (2014) P10009, [doi:10.1088/1748-0221/9/10/P10009](https://doi.org/10.1088/1748-0221/9/10/P10009), arXiv:1405.6569

[23] CMS Collaboration, “Search for the X(5568) state decaying into $B_0^s \pi^\pm$ in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *Phys. Rev. Lett.* **120** (2018) 202005, [doi:10.1103/PhysRevLett.120.202005](https://doi.org/10.1103/PhysRevLett.120.202005), arXiv:1712.06144

[24] CMS Collaboration, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, *JINST* **9** (2014) P10009, [doi:10.1088/1748-0221/9/10/P10009](https://doi.org/10.1088/1748-0221/9/10/P10009), arXiv:1405.6569

[25] CMS Collaboration, “Study of excited $\Lambda^0_b$ states decaying to $\Lambda^0_b \pi^+ \pi^-$ in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **803** (2020) 135345, [doi:10.1016/j.physletb.2020.135345](https://doi.org/10.1016/j.physletb.2020.135345), arXiv:2001.06533

[26] CMS Collaboration, “Observation of two excited $B^+_c$ states and measurement of the $B^+_c(2S)$ mass in pp collisions at $\sqrt{s} = 13$ TeV”, *Phys. Rev. Lett.* **122** (2019) 132001, [doi:10.1103/PhysRevLett.122.132001](https://doi.org/10.1103/PhysRevLett.122.132001), arXiv:1902.00571

[27] CMS Collaboration, “Observation of two excited $B^+_c$ states and measurement of the $B^+_c(2S)$ mass in pp collisions at $\sqrt{s} = 13$ TeV”, *Phys. Rev. Lett.* **122** (2019) 132001, [doi:10.1103/PhysRevLett.122.132001](https://doi.org/10.1103/PhysRevLett.122.132001), arXiv:1902.00571

[28] CMS Collaboration, “Study of excited $\Lambda^0_b$ states decaying to $\Lambda^0_b \pi^+ \pi^-$ in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **803** (2020) 135345, [doi:10.1016/j.physletb.2020.135345](https://doi.org/10.1016/j.physletb.2020.135345), arXiv:2001.06533

[29] G. Punzi, “Sensitivity of searches for new signals and its optimization”, in *Statistical problems in particle physics, astrophysics and cosmology. Proceedings, Conference, PHYSTAT 2003*, p. MODT002. Stanford, USA, September, 2003, [arXiv:physics/0308063](https://arxiv.org/abs/physics/0308063).

[30] S. S. Wilks, “The large-sample distribution of the likelihood ratio for testing composite hypotheses”, *Annals Math. Statist.* **9** (1938) 60, [doi:10.1214/aoms/1177732360](https://doi.org/10.1214/aoms/1177732360).

[31] M. Pivk and F. R. Le Diberder, “sPlot: a statistical tool to unfold data distributions”, *Nucl. Instrum. Meth. A* **555** (2005) 356, [doi:10.1016/j.nima.2005.08.106](https://doi.org/10.1016/j.nima.2005.08.106), arXiv:physics/0402083.

[32] S. Jackman, “Bayesian analysis for the social sciences”. John Wiley & Sons, New Jersey, USA, 2009. [doi:10.1002/9780470686621](https://doi.org/10.1002/9780470686621).
A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria
W. Adam, F. Ambrogi, T. Bergauer, M. Dragicevic, J. Erö, A. Escalante Del Valle, R. Frühwirth, M. Jeitler, N. Krammer, L. Lechner, D. Liko, T. Madlener, I. Mikulec, F.M. Pitters, N. Rad, J. Schieck, R. Schöfbeck, M. Spanring, S. Templ, W. Waltenberger, C.-E. Wulz, M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus
V. Chekhrkovsky, A. Litomin, V. Makarenko, J. Suarez Gonzalez

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

Vrije Universiteit Brussel, Brussel, Belgium
F. Blekman, E.S. Bols, S.S. Chhibra, J. D’Hondt, J. De Clercq, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, A. Morton, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders

Université Libre de Bruxelles, Bruxelles, Belgium
D. Beighin, B. Bilin, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, L. Favart, A. Grebenyuk, A.K. Kalsi, I. Makarenko, L. Moureaux, L. Petrè, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, L. Wezenbeek

Ghent University, Ghent, Belgium
T. Cornelis, D. Dobur, M. Gruchala, I. Khvastunov, M. Niedziela, C. Roskas, M. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, M. Delcourt, I.S. Donertas, A. Giammanco, V. Lemaitre, K. Mondal, J. Prisciandaro, A. Taliercio, M. Teklishyn, P. Vischia, S. Wuyckens, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, E. Belchior Batista Das Chagas, H. BRANDAO MALBOUISSON, W. Carvalho, J. Chinellato, E. Coelho, E.M. Da Costa, G.G. Da Silveira, D. De Jesus Damiao, S. Fonseca De Souza, J. Martins, D. Matos Figueiredo, M. Medina Jaime, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, P. Rebello Teles, L.J. Sanchez Rosas, A. Santoro, S.M. Silva Do Amaral, A. Szajder, M. Thiel, E.J. Tonelli Manganote, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista a, Universidade Federal do ABC b, São Paulo, Brazil
C.A. Bernardes, L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, D.S. Lemos, P.G. Mercadante, S.F. Novaes, SandraS. Padula

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, I. Atanasov, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov
University of Sofia, Sofia, Bulgaria
M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

Beihang University, Beijing, China
W. Fang, Q. Guo, H. Wang, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
M. Ahmad, Z. Hu, Y. Wang

Institute of High Energy Physics, Beijing, China
E. Chapon, G.M. Chen, H.S. Chen, M. Chen, D. Leggat, H. Liao, Z. Liu, R. Sharma, A. Spiezia, J. Tao, J. Thomas-wilsker, J. Wang, H. Zhang, S. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ban, C. Chen, A. Levin, J. Li, Q. Li, M. Lu, X. Lyu, Y. Mao, S.J. Qian, D. Wang, Q. Wang, J. Xiao

Sun Yat-Sen University, Guangzhou, China
Z. You

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
X. Gao

Zhejiang University, Hangzhou, China
M. Xiao

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C. Florez, J. Fraga, A. Sarkar, M.A. Segura Delgado

Universidad de Antioquia, Medellin, Colombia
J. Jaramillo, J. Mejia Guisao, F. Ramirez, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
D. Giljanovic, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, D. Majumder, B. Mesic, M. Roguljic, A. Starodumov, T. Susa

University of Cyprus, Nicosia, Cyprus
M.W. Ather, A. Attikis, E. Erodontou, A. Ioannou, G. Kole, M. Kolosova, S. Konstantinou, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, D. Tsiakkouri

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr., A. Kveton, J. Tomsa

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin
Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
E. Salama

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
A. Lotfy, M.A. Mahmoud

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
E. Brücken, F. Garcia, J. Havukainen, V. Karimäki, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, H. Siikonen, E. Tuominen, J. Tuominen

Lappeenranta University of Technology, Lappeenranta, Finland
P. Luukka, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.O. Sahin, A. Savoy-Navarro, M. Titov, G.B. Yu

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, France
S. Ahuja, F. Beaudette, M. Bonanomi, A. Buchot Perraguin, P. Busson, C. Charlot, O. Davignon, B. Diab, G. Falmagne, R. Granier de Cassagnac, A. Hakimi, I. Kucher, A. Lobanov, C. Martin Perez, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Siros, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram, J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, J.-C. Fontaine, D. Gelé, U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
E. Asilar, S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, S. Jain, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, L. Trerotot, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia
I. Bagaturia, Z. Tsamalaidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M.P. Rauch, J. Schulz, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
D. Eliseev, M. Erdmann, P. Fackeldey, 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 B, Aachen, Germany

C. Dziwok, G. Flügge, W. Haj Ahmad17, O. Hlushchenko, T. Kress, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl18, T. Ziemons

Deutsches Elektronen-Synchrotron, Hamburg, Germany

H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, I. Babounikau, S. Baxter, O. Behnke, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras19, V. Botta, D. Brunner, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, V. Danilov, A. De Wit, M.M. Defranchis, L. Didukh, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, A. Elwood, L.I. Estevez Banos, E. Gallo20, A. Geiser, A. Giraldi, A. Grohsjean, M. Guthoff, A. Harb, A. Jafari21, N.Z. Jomhari, H. Jung, A. Kasem19, M. Kasemann, H. Kaveh, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann22, R. Mankel, I.-A. Melzer-Pellmann, J. Metwally, A.B. Meyer, M. Meyer, M. Missiroli, J. Mnich, A. Mussgiller, V. Myronenko, Y. Otarid, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saggio, A. Saibél, M. Savitskyi, V. Scheurer, P. Schütze, C. Schwanenberg, R. Shevchenko, A. Singh, R.E. Sosa Ricardo, H. Tholen, N. Tonon, O. Turkot, A. Vagnerini, M. Van De Klundert, R. Walsh, D. Walter, Y. Wen, K. Wichmann, C. Wissing, S. Wucherl, O. Zenaiev, R. Zlebcik

University of Hamburg, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, K. De Leo, T. Dreyer, A. Ebrahimi, M. Eich, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, V. Kutzner, J. Lange, T. Lange, A. Malara, J. Multhaup, C.E.N. Niemeyer, A. Nigamova, K.J. Pena Rodriguez, O. Rieger, P. Schleper, S. Schumann, J. Schwandt, D. Schwarz, J. Sonneveld, H. Stadie, G. Steinbrück, B. Vormwald, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

M. Baselga, S. Baur, J. Bechtel, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, A. Droll, K. El Morabit, N. Faltermann, K. Flöh, M. Giffels, A. Gottmann, F. Hartmann19, C. Heidecker, U. Husemann, M.A. Iqbal, I. Katkov23, P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra, M.U. Mozer, D. Müller, Th. Müller, M. Musich, G. Quast, K. Rabbertz, J. Raiser, S. Savoiu, D. Schäfer, M. Schnepf, M. Schröder, D. Seith, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Wassmer, M. Weber, C. Wöhrmann, R. Wolf, S. Wozniowski

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

G. Anagnostou, P. Asenov, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Pasralaki, A. Stakia

National and Kapodistrian University of Athens, Athens, Greece

M. Diamantopoulos, D. Karasavvas, G. Karathanasis, P. Kontaxakis, C.K. Koraka, A. Manousakis-katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, K. Vellidis, E. Vourliotis

National Technical University of Athens, Athens, Greece

G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsiotis, A. Zacharopoulos

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitara, N. Manthos, I. Papadopoulos, J. Strologas
MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Bartók, R. Chudasama, M. Csanad, M.M.A. Gadallah, S. Lőkös, P. Major, K. Mandal, A. Mehta, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath, S. Sikler, V. Veszpremi, G. Vesztergombi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
S. Czellar, J. Karancsi, J. Molnar, Z. Szillasi, D. Teyssier

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, Z.L. Trocsanyi, B. Ujvari

Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary
T. Csorgo, F. Nemes, T. Novak

Indian Institute of Science (IISc), Bangalore, India
S. Choudhury, J.R. Komaragiri, D. Kumar, L. Panwar, P.C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India
S. Bahinipati, D. Dash, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu, A. Nayak, D.K. Sahoo, N. Sur, S.K. Swain

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, N. Dholga, R. Gupta, A. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Virdi

University of Delhi, Delhi, India
A. Ahmed, A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, A. Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, A. Shah

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
M. Bharti, R. Bhattacharya, S. Bhattacharya, D. Bhower, S. Dutta, S. Ghosh, B. Gomber, M. Maiti, S. Nandan, P. Palit, A. Purohit, P.K. Rout, G. Saha, S. Sarkar, M. Sharan, B. Singh, S. Thakur

Indian Institute of Technology Madras, Madras, India
P.K. Behera, S.C. Behera, P. Kalbhor, A. Muhammad, R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar

Bhabha Atomic Research Centre, Mumbai, India
D. Dutta, V. Jha, V. Kumar, D.K. Mishra, K. Naskar, P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, M.A. Bhat, S. Dugad, R. Kumar Verma, U. Sarkar

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, D. Roy, N. Sahoo

Indian Institute of Science Education and Research (IISER), Pune, India
S. Dube, B. Kansal, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi
INFIN Sezione di Perugia $^a$, Università di Perugia $^b$, Perugia, Italy
M. Biasini$^{a,b}$, G.M. Bilei$^a$, D. Ciangottini$^{a,b}$, L. Fanò$^{a,b}$, P. Lariccia$^{a,b}$, G. Mantovani$^{a,b}$, V. Mariani$^{a,b}$, M. Menichelli$^a$, F. Moscatelli$^a$, A. Rossi$^{a,b}$, A. Santocchia$^{a,b}$, D. Spiga$^a$, T. Tedeschi$^{a,b}$

INFIN Sezione di Pisa $^a$, Università di Pisa $^b$, Scuola Normale Superiore di Pisa $^c$, Pisa, 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$^a$, M.R. Di Domenico$^{a,b}$, S. Donato$^a$, 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$^a$, G. Ramirez-Sanchez$^{a,c}$, A. Rizzi$^{a,b}$, G. Rolandi$^{a,c}$, S. Roy Chowdhury$^{a,c}$, A. Scribano$^a$, N. Shafiei$^{a,b}$, P. Spagnolo$^a$, R. Tenchini$^a$, G. Tonelli$^a$, F. Vazzoler$^a$

INFIN Sezione di Roma $^a$, Sapienza Università di Roma $^b$, Rome, 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$^{a,b}$, R. Tramontano$^{a,b}$

INFIN Sezione di Torino $^a$, Università di Torino $^b$, Torino, Italy, Università del Piemonte Orientale $^c$, Novara, 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$^{a,b}$, 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$^a$, C. Mariotti$^a$, S. Maselli$^a$, E. Migliore$^{a,b}$, V. Monaco$^{a,b}$, E. Montell$^{a,b}$, M. Monteno$^a$, M.M. Obertino$^{a,b}$, G. Ortona$^a$, L. Pacher$^{a,b}$, N. Pastrone$^a$, M. Pelliccioni$^a$, G.L. Pinna Angioni$^a$, M. Ruspa$^{a,c}$, R. Salvatico$^{a,b}$, F. Siviero$^{a,b}$, V. Sola$^a$, A. Solano$^{a,b}$, D. Soldi$^{a,b}$, A. Staiano$^a$, D. Trocino$^{a,b}$

INFIN Sezione di Trieste $^a$, Università di Trieste $^b$, Trieste, 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$^{a,b}$

Kyungpook National University, Daegu, Korea
S. Dogra, C. Huh, B. Kim, D.H. Kim, G.N. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, S. Sekmen, Y.C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D.H. Moon

Hanyang University, Seoul, Korea
B. Francois, T.J. Kim, J. Park

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

Kyung Hee University, Department of Physics, Seoul, Republic of Korea
J. Goh, A. Gurtu

Sejong University, Seoul, Korea
H.S. Kim, Y. Kim

Seoul National University, Seoul, Korea
J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, S. Ko, H. Kwon, H. Lee, K. Lee, S. Lee, K. Nam, B.H. Oh, M. Oh, S.B. Oh, B.C. Radburn-Smith, H. Seo, U.K. Yang, I. Yoon
University of Seoul, Seoul, Korea
D. Jeon, J.H. Kim, B. Ko, J.S.H. Lee, I.C. Park, Y. Roh, D. Song, I.J. Watson

Yonsei University, Department of Physics, Seoul, Korea
H.D. Yoo

Sungkyunkwan University, Suwon, Korea
Y. Choi, C. Hwang, Y. Jeong, H. Lee, Y. Lee, I. Yu

Riga Technical University, Riga, Latvia
V. Veckalns

Vilnius University, Vilnius, Lithuania
A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz, R. Lopez-Fernandez, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

University of Montenegro, Podgorica, Montenegro
J. Mijuskovic, N. Raicevic

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
S. Bheesette, P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M.I. Asghar, M.I.M. Awan, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoail, M. Waqas

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górska, M. Kazana, M. Szleper, P. Traczyk, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Olszewski, M. Walczak
Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araújo, P. Bargassa, D. Bastos, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, J. Seixas, K. Shchelina, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev\textsuperscript{43,44}, P. Moisenz, V. Palichik, V. Perelygin, M. Savina, D. Seitova, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, A. Zarubin, I. Zhizhin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
G. Gavrilov, V. Golovtsov, Y. Ivanov, V. Kim\textsuperscript{45}, E. Kuznetsova\textsuperscript{46}, V. Murzin, V. Oreshkin, I. Smirnov, D. Sokolov, V. Sushin, S. Volkov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenen, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, G. Pivovarov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko\textsuperscript{47}, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepenov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev

National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
R. Chistov\textsuperscript{48}, M. Danilov\textsuperscript{49}, A. Oskin, P. Parygin, S. Polikarpov\textsuperscript{48}

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, M. Dubinin\textsuperscript{50}, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov\textsuperscript{51}, T. Dimova\textsuperscript{51}, L. Kardapoltsev\textsuperscript{51}, I. Ovtin\textsuperscript{51}, Y. Skovpen\textsuperscript{51}

Institute for High Energy Physics of National Research Centre ‘Kurchatov Institute’, Protvino, Russia
I. Azhgirey, I. Bayshev, V. Kachanov, A. Kalinin, D. Konstantinov, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, A. Iuzhakov, V. Okhotnikov, L. Sukhikh

Tomsk State University, Tomsk, Russia
V. Borchsh, V. Ivanchenko, E. Tcherniaev

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Serbia
P. Adzic\textsuperscript{52}, P. Cirkovic, M. Dordevic, P. Milenovic, J. Milosevic
C. Dorfer, T. Gadek, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Listermann, A.-M. Lyon, R.A. Manzoni, M.T. Meinhard, F. Micheli, F. Nessi-Tedaldi, F. Pauss, V. Perovic, G. Perrin, L. Perrozzi, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönberger, L. Shchutska, V. Stampf, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland
C. Amsler

National Central University, Chung-Li, Taiwan
C. Adloff

National Taiwan University (NTU), Taipei, Taiwan
L. Ceard, 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, E. Yazgan

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
F. Boran, S. Damarseckin60, Z.S. Demiroglu, F. Dolek, C. Dozen61, I. Dumanoglu62, E. Esik, G. Gokbulut, Y. Guler, E. Gürpinar Guler63, I. Hos64, C. Isik, E.E. Kangal65, O. Kara, A. Kayis Topaksu, U. Kimsu, G. Onengut, K. Ozturk, A. Polatoz, A.E. Simsek, B. Tali67, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
B. Isildak68, G. Karapinar69, K. Ocalan70, M. Yalvac71

Bogazici University, Istanbul, Turkey
I.O. Atakisi, E. Gülmez, M. Kaya72, O. Kaya73, Ö. Özçelik, S. Tekten74, E.A. Yetkin75

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak62, Y. Komurcu, S. Sen76

Istanbul University, Istanbul, Turkey
F. Aydogmus Sen, S. Cerci67, B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci67

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

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

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev77, C. Brew, R.M. Brown, D.J.A. Cockerill, K.V. Ellis, 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
Imperial College, London, United Kingdom
R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, V. Cepaitis, G.S. Chahal, D. Colling, P. Dauncey, G. Davies, M. Della Negra, P. Everaerts, G. Fedi, G. Hall, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, J. Nash, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, A. Tapper, K. Uchida, T. Virdee, N. Wardle, S.N. Webb, D. Winterbottom, A.G. Zecchinelli, S.C. Zenz

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

Baylor University, Waco, USA
A. Brinkerhoff, K. Call, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, C. Madrid, B. McMaster, N. Pastika, S. Sawant, C. Smith

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, USA
A. Buccilli, O. Charaf, S.I. Cooper, S.V. Gleyzer, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA
A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiraghi, D. Gastler, C. Richardson, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, S. Yuan, D. Zou

Brown University, Providence, USA
G. Benelli, B. Burkle, X. Coubez, D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan, K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, M. Narain, S. Sagir, R. Syarif, E. Usai, W.Y. Wong, D. Yu, W. Zhang

University of California, Davis, Davis, 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, Y. Yao, F. Zhang

University of California, Los Angeles, USA
M. Bachtis, R. Cousins, A. Dasgupta, A. Florent, D. Hamilton, J. Hauser, M. Ignatenko, T. Lam, N. Mccoll, W.A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

University of California, Riverside, Riverside, USA
K. Burt, Y. Chen, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, M. Olmedo Negrete, M.I. Paneva, W. Si, S. Wimpenny, Y. Zhang

University of California, San Diego, La Jolla, USA
J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, M. Derdzinski, J. Duarte, 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

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA
N. Amin, C. Campagnari, M. Citron, A. Dorsett, V. Dutta, J. Incandela, B. Marsh, H. Mei, A. Ovcharova, H. Qu, M. Quinnan, J. Richman, U. Sarica, D. Stuart, S. Wang

California Institute of Technology, Pasadena, 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
The University of Kansas, Lawrence, USA
C. Baldenegro Barrera, P. Baringer, A. Bean, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

Kansas State University, Manhattan, USA
S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

Lawrence Livermore National Laboratory, Livermore, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, USA
E. Adams, A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, T. Koeth, A.C. Mignerey, S. Nabi, M. Seidel, A. Skuja, S.C. Tonwar, L. Wang, K. Wong

Massachusetts Institute of Technology, Cambridge, USA
D. Abercrombie, B. Allen, R. Bi, S. Brandt, W. Busza, I.A. Cali, Y. Chen, M. D’Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, J. Krupa, Y-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Ni, 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, Z. Wang, B. Wyslouch

University of Minnesota, Minneapolis, USA
R.M. Chatterjee, A. Evans, S. Guts†, P. Hansen, J. Hiltbrand, Sh. Jain, M. Krohn, Y. Kubota, Z. Lesko, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA
K. Bloom, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, J.R. González Fernández, I. Kravchenko, J.E. Siado, G.R. Snow†, B. Stieger, W. Tabb

State University of New York at Buffalo, Buffalo, USA
G. Agarwal, C. Harrington, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, A. Parker, J. Pekkanen, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA
G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, B. Marzocchi, D.M. Morse, V. Nguyen, T. Orimoto, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. WiseCarver, D. Wood

Northwestern University, Evanston, USA
S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Velasco

University of Notre Dame, Notre Dame, 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, K. Mohrman, Y. Musienko, R. Ruchti, P. Siddireddy, S. Taroni, M. Wayne, A. Wightman, M. Wolf, L. Zygala
The Ohio State University, Columbus, USA
J. Alimena, B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, A. Lefeld, B.L. Winer, B.R. Yates

Princeton University, Princeton, USA
G. Dezoort, P. Elmer, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, 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

University of Puerto Rico, Mayaguez, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, USA
V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, B. Mahakud, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, H. Qiu, J.F. Schulte, N. Trevisani, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, USA
T. Cheng, J. Dolen, N. Parashar, M. Stojanovic

Rice University, Houston, USA
A. Baty, S. Dildick, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, W. Shi, A.G. Stahl Leiton, A. Zhang

University of Rochester, Rochester, 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

Rutgers, The State University of New Jersey, Piscataway, USA
B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, O. Karacheban, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

University of Tennessee, Knoxville, USA
H. Acharya, A.G. Delannoy, S. Spanier

Texas A&M University, College Station, USA
O. Bouhali, M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon, H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Saforon, J. Sturdy

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, V. Hegde, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

Vanderbilt University, Nashville, USA
E. Appelt, 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

University of Virginia, Charlottesville, USA
L. Ang, M.W. Arenton, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA
P.E. Karchin, N. Poudyal, P. Thapa

University of Wisconsin - Madison, Madison, WI, USA
K. Black, T. Bose, J. Buchanan, C. Caillol, S. Dasu, I. De Bruyn, C. Galloni, H. He, M. Herndon,
A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, D. Pinna, T. Ruggles, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, S. Trembath-reichert, W. Vetens

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at Department of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt
3: Also at Université Libre de Bruxelles, Bruxelles, Belgium
4: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
5: Also at Universidade Estadual de Campinas, Campinas, Brazil
6: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
7: Also at UFMS, Nova Andradina, Brazil
8: Also at Universidade Federal de Pelotas, Pelotas, Brazil
9: Also at University of Chinese Academy of Sciences, Beijing, China
10: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia
11: Also at Joint Institute for Nuclear Research, Dubna, Russia
12: Also at British University in Egypt, Cairo, Egypt
13: Now at Ain Shams University, Cairo, Egypt
14: Also at Purdue University, West Lafayette, USA
15: Also at Université de Haute Alsace, Mulhouse, France
16: Also at Ilia State University, Tbilisi, Georgia
17: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
18: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
19: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
20: Also at University of Hamburg, Hamburg, Germany
21: Also at Isfahan University of Technology, Isfahan, Iran, Isfahan, Iran
22: Also at Brandenburg University of Technology, Cottbus, Germany
23: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
24: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary
25: Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
26: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary, Budapest, Hungary
27: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
28: Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India
29: Also at Institute of Physics, Bhubaneswar, India
30: Also at G.H.G. Khalsa College, Punjab, India
31: Also at Shoolini University, Solan, India
32: Also at University of Hyderabad, Hyderabad, India
33: Also at University of Visva-Bharati, Santiniketan, India
34: Also at Indian Institute of Technology (IIT), Mumbai, India
35: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
36: Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
37: Now at INFN Sezione di Bari a, Università di Bari b, Politecnico di Bari c, Bari, Italy
38: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
39: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
40: Also at Riga Technical University, Riga, Latvia, Riga, Latvia
41: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
42: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
43: Also at Institute for Nuclear Research, Moscow, Russia
44: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
45: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
46: Also at University of Florida, Gainesville, USA
47: Also at Imperial College, London, United Kingdom
48: Also at P.N. Lebedev Physical Institute, Moscow, Russia
49: Also at Moscow Institute of Physics and Technology, Moscow, Russia, Moscow, Russia
50: Also at California Institute of Technology, Pasadena, USA
51: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
52: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
53: Also at Università degli Studi di Siena, Siena, Italy
54: Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
55: Also at INFN Sezione di Pavia a, Università di Pavia b, Pavia, Italy, Pavia, Italy
56: Also at National and Kapodistrian University of Athens, Athens, Greece
57: Also at Universitàt Zürich, Zurich, Switzerland
58: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria
59: Also at Laboratoire d’Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
60: Also at Şırnak University, Sirnak, Turkey
61: Also at Department of Physics, Tsinghua University, Beijing, China, Beijing, China
62: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey
63: Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey
64: Also at Istanbul Aydin University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey
65: Also at Mersin University, Mersin, Turkey
66: Also at Piri Reis University, Istanbul, Turkey
67: Also at Adiyaman University, Adiyaman, Turkey
68: Also at Ozyegin University, Istanbul, Turkey
69: Also at Izmir Institute of Technology, Izmir, Turkey
70: Also at Necmettin Erbakan University, Konya, Turkey
71: Also at Bozok Universitetesı Rektörlüğü, Yozgat, Turkey
72: Also at Marmara University, Istanbul, Turkey
73: Also at Milli Savunma University, Istanbul, Turkey
74: Also at Kafkas University, Kars, Turkey
75: Also at Istanbul Bilgi University, Istanbul, Turkey
76: Also at Hacettepe University, Ankara, Turkey
77: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
78: Also at IPPP Durham University, Durham, United Kingdom
79: Also at Monash University, Faculty of Science, Clayton, Australia
80: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA
81: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
82: Also at Bingol University, Bingol, Turkey
83: Also at Georgian Technical University, Tbilisi, Georgia
84: Also at Sinop University, Sinop, Turkey
85: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
86: Also at Nanjing Normal University Department of Physics, Nanjing, China
87: Also at Texas A&M University at Qatar, Doha, Qatar
88: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea