Observation of the $B_s^0 \to X(3872)\phi$ Decay

A. M. Sirunyan *et al.*[*]
(CMS Collaboration)

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

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The observed spectrum of $c\bar{c}$ states below the $D\bar{D}$ threshold agrees well with theoretical predictions [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 the $D\bar{D}$ 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 [3] named $X(3872)$ and decaying to $J/\psi\pi^+\pi^-$, with a very small natural width for a state above the $D\bar{D}$ threshold. Its world-average mass is 3871.69 ± 0.17 MeV, which is extremely close to the $\bar{D}^0D^{*0}$ threshold of 3872.68 ± 0.07 MeV [4]. With this mass and a total width less than 2 MeV [5,6], the $X(3872)$ particle did not match any of the theoretically predicted charmonium resonances.

The discovery of $X(3872)$ opened a new era of exotic, quarkonium-like spectroscopy. Many new states with unusual properties have been observed, including several charged states [4,7]. At hadron colliders, prompt processes were found to be the dominant $X(3872)$ production mechanism [8–10]. The nature of $X(3872)$, also known as $\chi_{c1}(3872)$, is still unexplained in spite of the determination of its quantum numbers ($J^{PC} = 1^{++}$) [11–13]. The studies of the dipion mass spectrum [5,9–14] 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 $\mathcal{B}[B \to X(3872)h]$ 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:

$$R \equiv \frac{\mathcal{B}[B_s^0 \to X(3872)\phi]\mathcal{B}[X(3872) \to J/\psi\pi^+\pi^-]}{\mathcal{B}[B_s^0 \to \psi(2S)\phi]\mathcal{B}[\psi(2S) \to J/\psi\pi^+\pi^-]} = \frac{N[B_s^0 \to X(3872)\phi]}{N[B_s^0 \to \psi(2S)\phi]}\frac{\epsilon_{B_s^0\to\psi(2S)\phi}}{\epsilon_{B_s^0\to X(3872)\phi}}. \quad (1)$$

In this expression, N stands for the measured number of signal events in data, and ϵ stands for the efficiency. The J/ψ and $\phi(1020)$ (referred to as ϕ 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 [15] 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)

[*]Full author list given at the end of the article.

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 [16]. 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 μs. The L1 trigger used in the analysis requires at least two muons. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing that reduces the event rate to around 1 kHz before data storage. The high-level trigger algorithm used in the analysis requires two opposite-sign (OS) muons compatible with the dimuon decay of a J/ψ meson at a significant distance from the beam axis, as well as an additional track with transverse momentum $p_T > 1.2$ GeV, compatible with being produced in the dimuon vertex.

Simulated event samples for the $B_s^0 \to X(3872)\phi$ and $B_s^0 \to \psi(2S)\phi$ decays are generated in the analysis. The PYTHIA 8.230 package [17] is used to simulate the production of the B_s^0 mesons, which are subsequently decayed with EVTGEN 1.6.0 [18], where the final-state photon radiation is included using PHOTOS 3.61 [19,20]. Generated events are then passed to a detailed GEANT4-based simulation [21] 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 $p_T > 4$ GeV passing the soft-muon identification criteria [22] and matching those that triggered the event readout. The dimuon mass is required to be compatible with the world-average J/ψ mass [4], $m_{J/\psi}^{\mathrm{PDG}}$. The $B_s^0 \to J/\psi K^+K^-\pi^+\pi^-$ candidates are obtained by combining the selected J/ψ candidate with four high-purity tracks [23] with a total charge of zero that are not matched with the selected muons. At least one of the four tracks is required to have $p_T > 1.2$ GeV and a transverse impact parameter significance greater than 2 to match the trigger requirement. A kinematic vertex fit that constrains the dimuon invariant mass to $m_{J/\psi}^{\mathrm{PDG}}$ is performed on the two muons and four tracks. From all reconstructed pp collision vertices, the primary vertex is chosen as the one with the smallest pointing angle, as done in Refs. [24–29]. The pointing angle is the angle between the B_s^0 candidate momentum and the vector joining the primary vertex and the reconstructed B_s^0 candidate decay vertex. Signal events are eventually selected based on the corrected invariant mass $m(B_s^0) = m(J/\psi K^+K^-\pi^+\pi^-) - m(J/\psi\pi^+\pi^-) + m_{\psi(2S)/X(3872)}^{\mathrm{PDG}}$, where $m_{\psi(2S)}^{\mathrm{PDG}}$ and $m_{X(3872)}^{\mathrm{PDG}}$ 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 $B_s^0 \to J/\psi K^+K^-\pi^+\pi^-$ 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 $\phi \to K^+K^-$ and either $\psi(2S)$ or $X(3872) \to J/\psi\pi^+\pi^-$, the following criteria are used to assign the tracks for the selected $J/\psi K^+K^-\pi^+\pi^-$ candidates: (i) $3.60 < m(J/\psi\pi^+\pi^-) < 3.95$ GeV (ii) $1.00 < m(K^+K^-) < 1.04$ GeV (iii) $5.32 < m(B_s^0) < 5.42$ GeV (iv) if more than one of the 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 [30], which does not rely on the signal normalization. Data sidebands are used to estimate the background, and the $B_s^0 \to X(3872)\phi$ simulated sample is used to measure the signal efficiency. The resulting selection criteria are as follows: $p_T(B_s^0) > 10$ GeV, vertex χ^2 fit probability $P_{\mathrm{vtx}}(B_s^0) > 7\%$, $p_T(\pi^\pm) > 0.7$ GeV, $\min[p_T(K^\pm)] > 1.5$ GeV, $\max[p_T(K^\pm)] > 2.2$ 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 $\cos(\vec{p}_T, \vec{L}_{xy}) > 0.999$, 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 $B_s^0 \to X(3872)\phi$ and $B_s^0 \to \psi(2S)\phi$ 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_s^0 candidates in the range $5.32 < m(B_s^0) < 5.42$ 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_s^0 decays. A systematic uncertainty related to this assumption is evaluated below.

Figure 1 shows the observed $m(J/\psi\pi^+\pi^-)$ (upper) and $m(K^+K^-)$ (lower) invariant mass distributions for the $\psi(2S)\phi$ candidates with $3.60 < m(J/\psi\pi^+\pi^-) < 3.75$ GeV. Overlaid are the projections of the 2D fit function, which consists of the following four components: (i) $(\psi(2S), \phi)$, for the signal component (ii) (bkg, ϕ), for events containing genuine $\phi \to K^+K^-$ decays and background $J/\psi\pi^+\pi^-$ combinations (iii) $(\psi(2S), \mathrm{bkg})$, for events containing genuine $\psi(2S) \to J/\psi\pi^+\pi^-$ decays and background K^+K^- combinations (iv) (bkg, bkg), for the background in both dimensions. Each component is a product of two one-dimensional functions. For the $\phi \to K^+K^-$ signal, a relativistic Breit-Wigner function

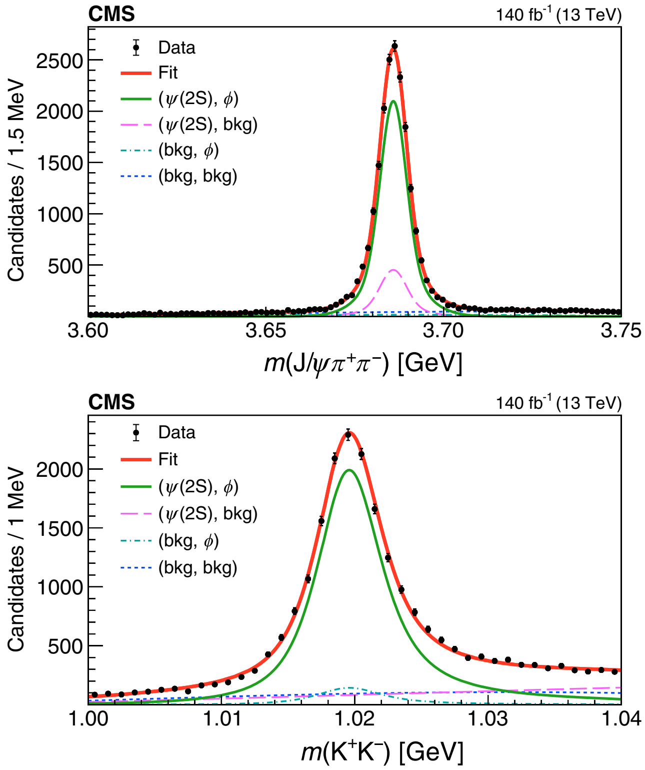

FIG. 1. The observed $J/\psi\pi^+\pi^-$ (upper) and K^+K^- (lower) invariant mass distributions for the $B_s^0 \to \psi(2S)\phi$ candidates are shown by the points, with the vertical bars representing the statistical uncertainties. The projections of the 2D fit and its various components are shown by the lines.

convolved with the detector mass resolution is used, where the ϕ 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: $[m(K^+K^-) - x_0]^\alpha Pol_1[m(K^+K^-)]$, where x_0 is the threshold value equal to twice the kaon mass and α is a free parameter. The $\psi(2S) \to J/\psi\pi^+\pi^-$ 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: $[m(J/\psi\pi^+\pi^-) - y_0]^\beta Pol_1[m(J/\psi\pi^+\pi^-)]$, where y_0 is the threshold value equal to $m_{J/\psi}^{\mathrm{PDG}} + 0.45$ GeV [corresponding to the requirement $m(\pi^+\pi^-) > 0.45$ GeV], and β is a free parameter.

The following parameters are free in the fit: numbers of events in the four components, ϕ 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 $N[B_s^0 \to \psi(2S)\phi] = 15\,359 \pm 171$.

For the $X(3872)$ mass region, defined as $3.80 < m(J/\psi\pi^+\pi^-) < 3.95$ 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 $X(3872) \to J/\psi\pi^+\pi^-$ signal is fixed to the one obtained in data for $\psi(2S) \to J/\psi\pi^+\pi^-$, with one floating parameter responsible for the resolution scaling. 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 $m_{J/\psi}^{\mathrm{PDG}} + 0.7$ 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. Additional projections of the 2D fit in different ranges of $m(J/\psi\pi^+\pi^-)$ and $m(K^+K^-)$ are presented in the Supplemental Material [31]. The measured signal yield is $N[B_s^0 \to X(3872)\phi] = 299 \pm 39$.

The statistical significance of the $B_s^0 \to X(3872)\phi$ signal has been evaluated with the likelihood ratio technique by applying the background-only and signal-plus-background hypotheses. Using the standard asymptotic approximation [32] for the likelihood, since the conditions of the Wilks' theorem [33] are satisfied, the statistical significance of the $B_s^0 \to X(3872)\phi$ signal is over 6 standard deviations (σ) after accounting for the systematic uncertainties discussed later.

To evaluate the background contribution related to the non-B_s^0 production of $\psi(2S)\phi$ in the mass range

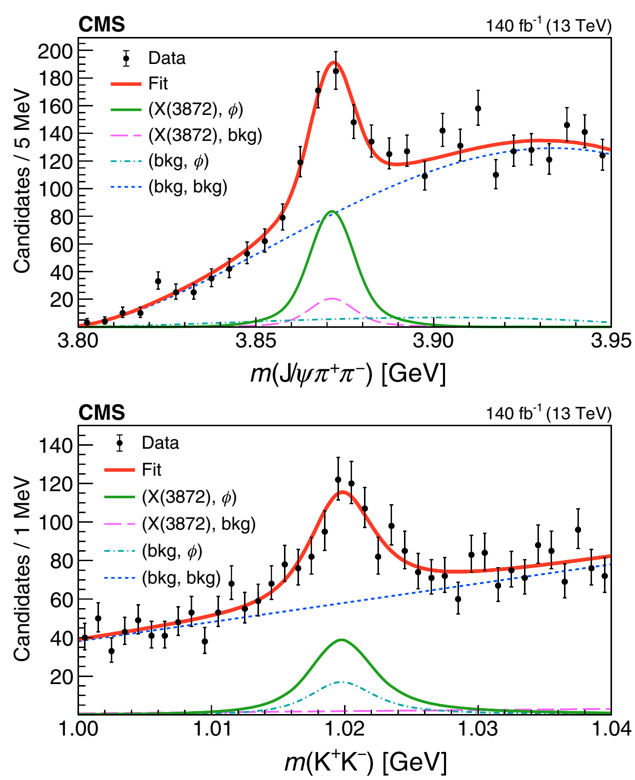

FIG. 2. The observed $J/\psi\pi^+\pi^-$ (upper) and K^+K^- (lower) invariant mass distributions for the $B_s^0 \to X(3872)\phi$ candidates are shown by the points, with the vertical bars representing the statistical uncertainties. The projections of the 2D fit and its various components are shown by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

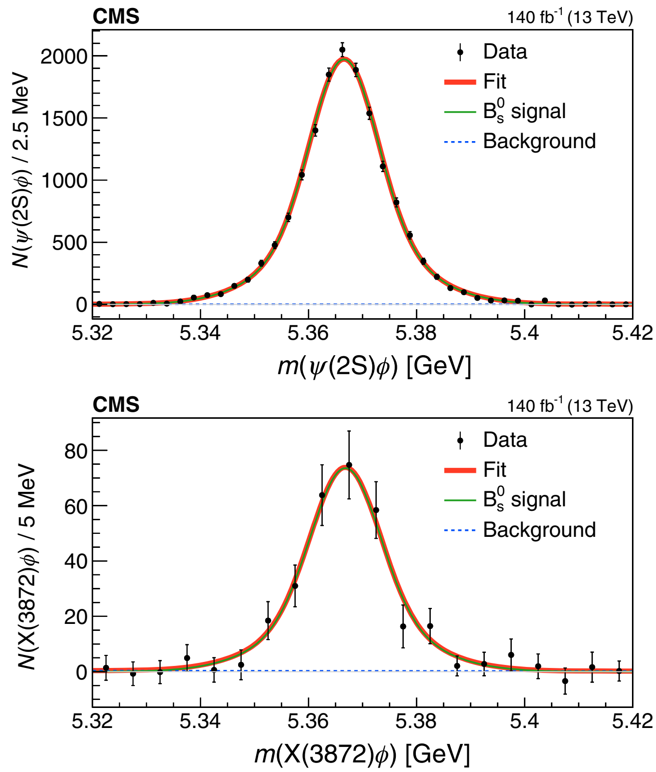

FIG. 3. Background-subtracted $\psi(2S)\phi$ (upper) and $X(3872)\phi$ (lower) invariant mass distributions obtained by $_s\mathcal{P}$lot weighting. The result of each fit and its components are shown by the lines.

$5.32 < m(\psi(2S)\phi) < 5.42$ GeV, the mass distribution of $\psi(2S)\phi$ is studied, as shown in Fig 3 (upper). The background-subtraction technique $_s\mathcal{P}$lot [34] is used, together with the 2D fit described above, to subtract backgrounds from the 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 (upper). The fit returns a non-B_s^0 background contribution of 0.5%. The same procedure is repeated in the $X(3872)\phi$ channel, shown in Fig. 3 (lower), and the measured contribution of the non-B_s^0 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 the non-B_s^0 production of $\psi(2S)\phi$ and $X(3872)\phi$ combinations. The significance of the $B_s^0 \to X(3872)\phi$ signal extracted from the binned fit to the background-subtracted $m(X(3872)\phi)$ distribution exceeds 10σ.

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 $\epsilon_{B_s^0\to\psi(2S)\phi}/\epsilon_{B_s^0\to X(3872)\phi} = 1.136 \pm 0.026$. It is larger than unity due to a tighter requirement on the dipion mass $m(\pi^+\pi^-) > 0.7$ GeV applied in the $X(3872)$ channel. The reported 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 are tested. Uncertainties related to the choice of the signal and background models are calculated separately.

The systematic uncertainty in the modeling of the $\phi \to K^+K^-$ signal is estimated by varying the ϕ 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 [35] 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_s^0 background is estimated using the $_s\mathcal{P}$lot technique to subtract the contributions from nonresonant K^+K^- and $J/\psi\pi^+\pi^-$ combinations from the $m(B_s^0)$ 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 I summarizes the systematic uncertainties described above, together with the total systematic

TABLE I. Relative systematic uncertainties in the ratio R.

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_s^0 background	1.2
Simulated sample size	2.2
Total	7.7

uncertainty, obtained by adding the effects from the different sources in quadrature.

Using Eq. (1), together with the measured signal yields of the $B_s^0 \to X(3872)\phi$ and $B_s^0 \to \psi(2S)\phi$ decays and the corresponding efficiency ratio, the product of the branching fractions, with respect to that of the $B_s^0 \to \psi(2S)\phi$ decay, is measured to be

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

Multiplying the measured ratio R by the known branching fractions $\mathcal{B}[B_s^0 \to \psi(2S)\phi]$ and $\mathcal{B}[\psi(2S) \to J/\psi\pi^+\pi^-]$ [4], we obtain $\mathcal{B}[B_s^0 \to X(3872)\phi]\mathcal{B}[X(3872) \to J/\psi\pi^+\pi^-] = (4.14 \pm 0.54(\mathrm{stat}) \pm 0.32(\mathrm{syst}) \pm 0.46(\mathcal{B})) \times 10^{-6}$, 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]: $\mathcal{B}[B^0 \to X(3872)\bar{K}^0]\mathcal{B}[X(3872) \to J/\psi\pi^+\pi^-] = (4.3 \pm 1.3) \times 10^{-6}$ and $\mathcal{B}[B^+ \to X(3872)K^+]\mathcal{B}[X(3872) \to J/\psi\pi^+\pi^-] = (8.6 \pm 0.8) \times 10^{-6}$. The measured value for B_s^0 is consistent with that for B^0 but about two times smaller than the one for B^+: $\mathcal{B}[B_s^0 \to X(3872)\phi]/\mathcal{B}[B^+ \to X(3872)K^+] = 0.482 \pm 0.063(\mathrm{stat}) \pm 0.037(\mathrm{syst}) \pm 0.070(\mathcal{B})$. This ratio is significantly lower than the corresponding one for decays to the charmonium state $\psi(2S)$ of $\mathcal{B}[B_s^0 \to \psi(2S)\phi]/\mathcal{B}[B^+ \to \psi(2S)K^+] = 0.87 \pm 0.10$ [4]. While this work was in the journal review, an explanation of the observed difference in the decay branching fractions has been proposed [36] within the tetraquark model of the $X(3872)$ state.

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 $B_s^0 \to X(3872)\phi$ 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, supporting similar conclusions derived from other experimental measurements [2,5,9–13]. This observation may shed new light on the nature of the $X(3872)$ particle.

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Paganis,[134] A. Psallidas,[134] A. Steen,[134] E. Yazgan,[134] B. Asavapibhop,[135] C. Asawatangtrakuldee,[135] N. Srimanobhas,[135] F. Boran,[136] S. Damarseckin,[136,iii] Z. S. Demiroglu,[136] F. Dolek,[136] C. Dozen,[136,jjj] I. Dumanoglu,[136,kkk] E. Eskut,[136] G. Gokbulut,[136] Y. Guler,[136] E. Gurpinar Guler,[136,lll] I. Hos,[136,mmm] C. Isik,[136] E. E. Kangal,[136,nnn] O. Kara,[136] A. Kayis Topaksu,[136] U. Kiminsu,[136] G. Onengut,[136] K. Ozdemir,[136,ooo] A. Polatoz,[136] A. E. Simsek,[136] B. Tali,[136,ppp] U. G. Tok,[136] S. Turkcapar,[136] I. S. Zorbakir,[136] C. Zorbilmez,[136] B. Isildak,[137,qqq] G. Karapinar,[137,rrr] K. Ocalan,[137,sss] M. Yalvac,[137,ttt] I. O. Atakisi,[138] E. Gülmez,[138] M. Kaya,[138,uuu] O. Kaya,[138,vvv] Ö. Özçelik,[138] S. Tekten,[138,www] E. A. Yetkin,[138,xxx] A. Cakir,[139] K. Cankocak,[139,kkk] Y. Komurcu,[139] S. Sen,[139,yyy] F. Aydogmus Sen,[140] S. Cerci,[140,ppp] B. Kaynak,[140] S. Ozkorucuklu,[140] D. Sunar Cerci,[140,ppp] B. Grynyov,[141] L. Levchuk,[142] E. Bhal,[143] S. Bologna,[143] J. J. Brooke,[143] E. Clement,[143] D. Cussans,[143] H. Flacher,[143] J. Goldstein,[143] G. P. Heath,[143] H. F. Heath,[143] L. Kreczko,[143] B. Krikler,[143] S. Paramesvaran,[143] T. Sakuma,[143] S. Seif El Nasr-Storey,[143] V. J. Smith,[143] J. Taylor,[143] A. Titterton,[143] K. W. Bell,[144] A. Belyaev,[144,zzz] C. Brew,[144] R. M. Brown,[144] D. J. A. Cockerill,[144] K. V. Ellis,[144] K. Harder,[144] S. Harper,[144] J. Linacre,[144] K. Manolopoulos,[144] D. M. Newbold,[144] E. Olaiya,[144] D. Petyt,[144] T. Reis,[144] T. Schuh,[144] C. H. Shepherd-Themistocleous,[144] A. Thea,[144] I. R. Tomalin,[144] T. Williams,[144] R. Bainbridge,[145] P. Bloch,[145] S. Bonomally,[145] J. Borg,[145] S. Breeze,[145] O. Buchmuller,[145] A. Bundock,[145] V. Cepaitis,[145] G. S. Chahal,[145,aaaa] D. Colling,[145] P. Dauncey,[145] G. Davies,[145] M. Della Negra,[145] P. Everaerts,[145] G. Fedi,[145] G. Hall,[145] G. Iles,[145] J. 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Arcaro,[150] C. Cosby,[150] Z. Demiragli,[150] D. Gastler,[150] C. Richardson,[150] J. Rohlf,[150] K. Salyer,[150] D. Sperka,[150] D. Spitzbart,[150] I. Suarez,[150] S. Yuan,[150] D. Zou,[150] G. Benelli,[151] B. Burkle,[151] X. Coubez,[151,t] D. Cutts,[151] Y. t. Duh,[151] M. Hadley,[151] U. Heintz,[151] J. M. Hogan,[151,cccc] K. H. M. Kwok,[151] E. Laird,[151] G. Landsberg,[151] K. T. Lau,[151] J. Lee,[151] M. Narain,[151] S. Sagir,[151,dddd] R. Syarif,[151] E. Usai,[151] W. Y. Wong,[151] D. Yu,[151] W. Zhang,[151] R. Band,[152] C. Brainerd,[152] R. Breedon,[152] M. Calderon De La Barca Sanchez,[152] M. Chertok,[152] J. Conway,[152] R. Conway,[152] P. T. Cox,[152] R. Erbacher,[152] C. Flores,[152] G. Funk,[152] F. Jensen,[152] W. Ko,[152,a] O. Kukral,[152] R. Lander,[152] M. Mulhearn,[152] D. Pellett,[152] J. Pilot,[152] M. Shi,[152] D. Taylor,[152] K. Tos,[152] M. Tripathi,[152] Y. Yao,[152] F. Zhang,[152] M. Bachtis,[153] R. Cousins,[153] A. Dasgupta,[153] A. Florent,[153] D. Hamilton,[153] J. Hauser,[153] M. Ignatenko,[153] T. Lam,[153] N. Mccoll,[153] W. A. Nash,[153] S. Regnard,[153] D. Saltzberg,[153] C. Schnaible,[153] B. Stone,[153] V. Valuev,[153] K. Burt,[154] Y. Chen,[154] R. Clare,[154] J. W. Gary,[154] S. M. A. Ghiasi Shirazi,[154] G. Hanson,[154] G. Karapostoli,[154] O. R. Long,[154] N. Manganelli,[154] M. Olmedo Negrete,[154] M. I. Paneva,[154] W. Si,[154] S. Wimpenny,[154] Y. Zhang,[154] J. G. Branson,[155] P. Chang,[155] S. Cittolin,[155] S. Cooperstein,[155] N. Deelen,[155] M. Derdzinski,[155] J. Duarte,[155] R. Gerosa,[155] D. Gilbert,[155] B. Hashemi,[155] D. Klein,[155] V. Krutelyov,[155] J. Letts,[155] M. Masciovecchio,[155] S. May,[155] S. Padhi,[155] M. Pieri,[155] V. Sharma,[155] M. Tadel,[155] F. Würthwein,[155] A. Yagil,[155] N. Amin,[156] C. Campagnari,[156] M. Citron,[156] A. Dorsett,[156] V. Dutta,[156] J. Incandela,[156] B. Marsh,[156] H. Mei,[156] A. Ovcharova,[156] H. Qu,[156] M. Quinnan,[156] J. Richman,[156] U. Sarica,[156] D. Stuart,[156] S. Wang,[156] D. Anderson,[157] A. Bornheim,[157] O. Cerri,[157] I. Dutta,[157] J. M. Lawhorn,[157] N. Lu,[157] J. Mao,[157] H. B. Newman,[157] T. Q. Nguyen,[157] J. Pata,[157] M. Spiropulu,[157] J. R. Vlimant,[157] S. Xie,[157] Z. Zhang,[157] R. Y. Zhu,[157] J. Alison,[158] M. B. Andrews,[158] T. Ferguson,[158] T. Mudholkar,[158] M. Paulini,[158] M. Sun,[158] I. Vorobiev,[158] J. P. Cumalat,[159] W. T. Ford,[159] E. MacDonald,[159] T. Mulholland,[159] R. Patel,[159] A. Perloff,[159] K. Stenson,[159] K. A. Ulmer,[159] S. R. Wagner,[159] J. Alexander,[160] Y. Cheng,[160] J. Chu,[160] D. J. Cranshaw,[160] A. Datta,[160] A. Frankenthal,[160] K. Mcdermott,[160] J. Monroy,[160]

J. R. Patterson,[160] D. Quach,[160] A. Ryd,[160] W. Sun,[160] S. M. Tan,[160] Z. Tao,[160] J. Thom,[160] P. Wittich,[160] M. Zientek,[160] S. Abdullin,[161] M. Albrow,[161] M. Alyari,[161] G. Apollinari,[161] A. Apresyan,[161] A. Apyan,[161] S. Banerjee,[161] L. A. T. Bauerdick,[161] A. Beretvas,[161] D. Berry,[161] J. Berryhill,[161] P. C. Bhat,[161] K. Burkett,[161] J. N. Butler,[161] A. Canepa,[161] G. B. Cerati,[161] H. W. K. Cheung,[161] F. Chlebana,[161] M. Cremonesi,[161] V. D. Elvira,[161] J. Freeman,[161] Z. Gecse,[161] E. Gottschalk,[161] L. Gray,[161] D. Green,[161] S. Grünendahl,[161] O. Gutsche,[161] R. M. Harris,[161] S. Hasegawa,[161] R. Heller,[161] T. C. Herwig,[161] J. Hirschauer,[161] B. Jayatilaka,[161] S. Jindariani,[161] M. Johnson,[161] U. Joshi,[161] P. Klabbers,[161] T. Klijnsma,[161] B. Klima,[161] M. J. Kortelainen,[161] S. Lammel,[161] D. Lincoln,[161] R. Lipton,[161] M. Liu,[161] T. Liu,[161] J. Lykken,[161] K. Maeshima,[161] D. Mason,[161] P. 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Meng,[180] K. Mohrman,[180] Y. Musienko,[180,rr] R. Ruchti,[180] P. Siddireddy,[180] S. Taroni,[180] M. Wayne,[180] A. Wightman,[180] M. Wolf,[180] L. Zygala,[180] J. Alimena,[181] B. Bylsma,[181] B. Cardwell,[181] L. S. Durkin,[181] B. Francis,[181] C. Hill,[181] A. Lefeld,[181] B. L. Winer,[181] B. R. Yates,[181] G. Dezoort,[182] P. Elmer,[182] B. Greenberg,[182] N. Haubrich,[182] S. Higginbotham,[182] A. Kalogeropoulos,[182] G. Kopp,[182] S. Kwan,[182] D. Lange,[182] M. T. Lucchini,[182] J. Luo,[182] D. Marlow,[182] K. Mei,[182] I. Ojalvo,[182] J. Olsen,[182] C. Palmer,[182] P. Piroué,[182] D. Stickland,[182] C. Tully,[182] S. Malik,[183]

S. Norberg,[183] V. E. Barnes,[184] R. Chawla,[184] S. Das,[184] L. Gutay,[184] M. Jones,[184] A. W. Jung,[184] B. Mahakud,[184] G. Negro,[184] N. Neumeister,[184] C. C. Peng,[184] S. Piperov,[184] H. Qiu,[184] J. F. Schulte,[184] N. Trevisani,[184] F. Wang,[184] R. Xiao,[184] W. Xie,[184] T. Cheng,[185] J. Dolen,[185] N. Parashar,[185] M. Stojanovic,[185] A. Baty,[186] S. Dildick,[186] K. M. Ecklund,[186] S. Freed,[186] F. J. M. Geurts,[186] M. Kilpatrick,[186] A. Kumar,[186] W. Li,[186] B. P. Padley,[186] R. Redjimi,[186] J. Roberts,[186,a] J. Rorie,[186] W. Shi,[186] A. G. Stahl Leiton,[186] A. Zhang,[186] A. Bodek,[187] P. de Barbaro,[187] R. Demina,[187] J. L. Dulemba,[187] C. Fallon,[187] T. Ferbel,[187] M. Galanti,[187] A. Garcia-Bellido,[187] O. Hindrichs,[187] A. Khukhunaishvili,[187] E. Ranken,[187] R. Taus,[187] B. Chiarito,[188] J. P. Chou,[188] A. Gandrakota,[188] Y. Gershtein,[188] E. Halkiadakis,[188] A. Hart,[188] M. Heindl,[188] E. Hughes,[188] S. Kaplan,[188] O. Karacheban,[188,w] I. Laflotte,[188] A. Lath,[188] R. Montalvo,[188] K. Nash,[188] M. Osherson,[188] S. Salur,[188] S. Schnetzer,[188] S. Somalwar,[188] R. Stone,[188] S. A. Thayil,[188] S. Thomas,[188] H. Wang,[188] H. Acharya,[189] A. G. Delannoy,[189] S. Spanier,[189] O. Bouhali,[190,jjjj] M. Dalchenko,[190] A. Delgado,[190] R. Eusebi,[190] J. Gilmore,[190] T. Huang,[190] T. Kamon,[190,kkkk] H. Kim,[190] S. Luo,[190] S. Malhotra,[190] R. Mueller,[190] D. Overton,[190] L. Perniè,[190] D. Rathjens,[190] A. Safonov,[190] J. Sturdy,[190] N. Akchurin,[191] J. Damgov,[191] V. Hegde,[191] S. Kunori,[191] K. Lamichhane,[191] S. W. Lee,[191] T. Mengke,[191] S. Muthumuni,[191] T. Peltola,[191] S. Undleeb,[191] I. Volobouev,[191] Z. Wang,[191] A. Whitbeck,[191] E. Appelt,[192] S. Greene,[192] A. Gurrola,[192] R. Janjam,[192] W. Johns,[192] C. Maguire,[192] A. Melo,[192] H. Ni,[192] K. Padeken,[192] F. Romeo,[192] P. Sheldon,[192] S. Tuo,[192] J. Velkovska,[192] M. Verweij,[192] L. Ang,[193] M. W. Arenton,[193] B. Cox,[193] G. Cummings,[193] J. Hakala,[193] R. Hirosky,[193] M. Joyce,[193] A. Ledovskoy,[193] C. Neu,[193] B. Tannenwald,[193] Y. Wang,[193] E. Wolfe,[193] F. Xia,[193] P. E. Karchin,[194] N. Poudyal,[194] P. Thapa,[194] K. Black,[195] T. Bose,[195] J. Buchanan,[195] C. Caillol,[195] S. Dasu,[195] I. De Bruyn,[195] C. Galloni,[195] H. He,[195] M. Herndon,[195] A. Hervé,[195] U. Hussain,[195] A. Lanaro,[195] A. Loeliger,[195] R. Loveless,[195] J. Madhusudanan Sreekala,[195] A. Mallampalli,[195] D. Pinna,[195] T. Ruggles,[195] A. Savin,[195] V. Shang,[195] V. Sharma,[195] W. H. Smith,[195] D. Teague,[195] S. Trembath-reichert,[195] and W. Vetens[195]

(CMS Collaboration)

[1]*Yerevan Physics Institute, Yerevan, Armenia*
[2]*Institut für Hochenergiephysik, Wien, Austria*
[3]*Institute for Nuclear Problems, Minsk, Belarus*
[4]*Universiteit Antwerpen, Antwerpen, Belgium*
[5]*Vrije Universiteit Brussel, Brussel, Belgium*
[6]*Université Libre de Bruxelles, Bruxelles, Belgium*
[7]*Ghent University, Ghent, Belgium*
[8]*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
[9]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*
[10]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[11a]*Universidade Estadual Paulista, São Paulo, Brazil*
[11b]*Universidade Federal do ABC, São Paulo, Brazil*
[12]*Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria*
[13]*University of Sofia, Sofia, Bulgaria*
[14]*Beihang University, Beijing, China*
[15]*Department of Physics, Tsinghua University, Beijing, China*
[16]*Institute of High Energy Physics, Beijing, China*
[17]*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[18]*Sun Yat-Sen University, Guangzhou, China*
[19]*Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE)—Fudan University, Shanghai, China*
[20]*Zhejiang University, Hangzhou, China*
[21]*Universidad de Los Andes, Bogota, Colombia*
[22]*Universidad de Antioquia, Medellin, Colombia*
[23]*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*
[24]*University of Split, Faculty of Science, Split, Croatia*
[25]*Institute Rudjer Boskovic, Zagreb, Croatia*
[26]*University of Cyprus, Nicosia, Cyprus*
[27]*Charles University, Prague, Czech Republic*
[28]*Escuela Politecnica Nacional, Quito, Ecuador*
[29]*Universidad San Francisco de Quito, Quito, Ecuador*

[30]Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
[31]Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
[32]National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
[33]Department of Physics, University of Helsinki, Helsinki, Finland
[34]Helsinki Institute of Physics, Helsinki, Finland
[35]Lappeenranta University of Technology, Lappeenranta, Finland
[36]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
[37]Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, France
[38]Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
[39]Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
[40]Georgian Technical University, Tbilisi, Georgia
[41]RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
[42]RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[43]RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
[44]Deutsches Elektronen-Synchrotron, Hamburg, Germany
[45]University of Hamburg, Hamburg, Germany
[46]Karlsruher Institut fuer Technologie, Karlsruhe, Germany
[47]Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
[48]National and Kapodistrian University of Athens, Athens, Greece
[49]National Technical University of Athens, Athens, Greece
[50]University of Ioánnina, Ioánnina, Greece
[51]MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
[52]Wigner Research Centre for Physics, Budapest, Hungary
[53]Institute of Nuclear Research ATOMKI, Debrecen, Hungary
[54]Institute of Physics, University of Debrecen, Debrecen, Hungary
[55]Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary
[56]Indian Institute of Science (IISc), Bangalore, India
[57]National Institute of Science Education and Research, HBNI, Bhubaneswar, India
[58]Panjab University, Chandigarh, India
[59]University of Delhi, Delhi, India
[60]Saha Institute of Nuclear Physics, HBNI, Kolkata,India
[61]Indian Institute of Technology Madras, Madras, India
[62]Bhabha Atomic Research Centre, Mumbai, India
[63]Tata Institute of Fundamental Research-A, Mumbai, India
[64]Tata Institute of Fundamental Research-B, Mumbai, India
[65]Indian Institute of Science Education and Research (IISER), Pune, India
[66]Isfahan University of Technology, Isfahan, Iran
[67]Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
[68]University College Dublin, Dublin, Ireland
[69a]INFN Sezione di Bari
[69b]Università di Bari
[69c]Politecnico di Bari
[70a]INFN Sezione di Bologna, Bologna, Italy
[70b]Università di Bologna, Bologna, Italy
[71a]INFN Sezione di Catania, Catania, Italy
[71b]Università di Catania, Catania, Italy
[72a]INFN Sezione di Firenze, Firenze, Italy
[72b]Università di Firenze, Firenze, Italy
[73]INFN Laboratori Nazionali di Frascati, Frascati, Italy
[74a]INFN Sezione di Genova, Genova, Italy
[74b]Università di Genova, Genova, Italy
[75a]INFN Sezione di Milano-Bicocca, Milano, Italy
[75b]Università di Milano-Bicocca, Milano, Italy
[76a]INFN Sezione di Napoli, Napoli, Italy
[76b]Università di Napoli 'Federico II', Napoli, Italy
[76c]Università della Basilicata, Potenza, Italy
[76d]Università G. Marconi, Roma, Italy
[77a]INFN Sezione di Padova, Padova, Italy
[77b]Università di Padova, Padova, Italy

[77c]Università di Trento, Trento, Italy
[78a]INFN Sezione di Pavia
[78b]Università di Pavia
[79a]INFN Sezione di Perugia, Perugia, Italy
[79b]Università di Perugia, Perugia, Italy
[80a]INFN Sezione di Pisa, Pisa, Italy
[80b]Università di Pisa, Pisa, Italy
[80c]Scuola Normale Superiore di Pisa, Pisa, Italy
[81a]INFN Sezione di Roma, Rome, Italy
[81b]Sapienza Università di Roma, Rome, Italy
[82a]INFN Sezione di Torino, Torino, Italy
[82b]Università di Torino, Torino, Italy
[82c]Università del Piemonte Orientale, Novara, Italy
[83a]INFN Sezione di Trieste, Trieste, Italy
[83b]Università di Trieste, Trieste, Italy
[84]Kyungpook National University, Daegu, Korea
[85]Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
[86]Hanyang University, Seoul, Korea
[87]Korea University, Seoul, Korea
[88]Kyung Hee University, Department of Physics, Seoul, Republic of Korea
[89]Sejong University, Seoul, Korea
[90]Seoul National University, Seoul, Korea
[91]University of Seoul, Seoul, Korea
[92]Yonsei University, Department of Physics, Seoul, Korea
[93]Sungkyunkwan University, Suwon, Korea
[94]Riga Technical University, Riga, Latvia
[95]Vilnius University, Vilnius, Lithuania
[96]National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
[97]Universidad de Sonora (UNISON), Hermosillo, Mexico
[98]Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
[99]Universidad Iberoamericana, Mexico City, Mexico
[100]Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
[101]Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
[102]University of Montenegro, Podgorica, Montenegro
[103]University of Auckland, Auckland, New Zealand
[104]University of Canterbury, Christchurch, New Zealand
[105]National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
[106]AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
[107]National Centre for Nuclear Research, Swierk, Poland
[108]Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
[109]Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
[110]Joint Institute for Nuclear Research, Dubna, Russia
[111]Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
[112]Institute for Nuclear Research, Moscow, Russia
[113]Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia
[114]Moscow Institute of Physics and Technology, Moscow, Russia
[115]National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
[116]P.N. Lebedev Physical Institute, Moscow, Russia
[117]Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
[118]Novosibirsk State University (NSU), Novosibirsk, Russia
[119]Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia
[120]National Research Tomsk Polytechnic University, Tomsk, Russia
[121]Tomsk State University, Tomsk, Russia
[122]University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Serbia
[123]Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
[124]Universidad Autónoma de Madrid, Madrid, Spain
[125]Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
[126]Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
[127]University of Colombo, Colombo, Sri Lanka
[128]University of Ruhuna, Department of Physics, Matara, Sri Lanka

[129]CERN, European Organization for Nuclear Research, Geneva, Switzerland
[130]Paul Scherrer Institut, Villigen, Switzerland
[131]ETH Zurich—Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
[132]Universität Zürich, Zurich, Switzerland
[133]National Central University, Chung-Li, Taiwan
[134]National Taiwan University (NTU), Taipei, Taiwan
[135]Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
[136]Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
[137]Middle East Technical University, Physics Department, Ankara, Turkey
[138]Bogazici University, Istanbul, Turkey
[139]Istanbul Technical University, Istanbul, Turkey
[140]Istanbul University, Istanbul, Turkey
[141]Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
[142]National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
[143]University of Bristol, Bristol, United Kingdom
[144]Rutherford Appleton Laboratory, Didcot, United Kingdom
[145]Imperial College, London, United Kingdom
[146]Brunel University, Uxbridge, United Kingdom
[147]Baylor University, Waco, Texas, USA
[148]Catholic University of America, Washington, DC, USA
[149]The University of Alabama, Tuscaloosa, Alabama, USA
[150]Boston University, Boston, Massachusetts, USA
[151]Brown University, Providence, Rhode Island, USA
[152]University of California, Davis, Davis, California, USA
[153]University of California, Los Angeles, California, USA
[154]University of California, Riverside, Riverside, California, USA
[155]University of California, San Diego, La Jolla, California, USA
[156]University of California, Santa Barbara—Department of Physics, Santa Barbara, California, USA
[157]California Institute of Technology, Pasadena, California, USA
[158]Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
[159]University of Colorado Boulder, Boulder, Colorado, USA
[160]Cornell University, Ithaca, New York, USA
[161]Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[162]University of Florida, Gainesville, Florida, USA
[163]Florida International University, Miami, Florida, USA
[164]Florida State University, Tallahassee, Florida, USA
[165]Florida Institute of Technology, Melbourne, Florida, USA
[166]University of Illinois at Chicago (UIC), Chicago, Illinois, USA
[167]The University of Iowa, Iowa City, Iowa, USA
[168]Johns Hopkins University, Baltimore, Maryland, USA
[169]The University of Kansas, Lawrence, Kansas, USA
[170]Kansas State University, Manhattan, Kansas, USA
[171]Lawrence Livermore National Laboratory, Livermore, California, USA
[172]University of Maryland, College Park, Maryland, USA
[173]Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
[174]University of Minnesota, Minneapolis, Minnesota, USA
[175]University of Mississippi, Oxford, Mississippi, USA
[176]University of Nebraska-Lincoln, Lincoln, Nebraska, USA
[177]State University of New York at Buffalo, Buffalo, New York, USA
[178]Northeastern University, Boston, Massachusetts, USA
[179]Northwestern University, Evanston, Illinois, USA
[180]University of Notre Dame, Notre Dame, Indiana, USA
[181]The Ohio State University, Columbus, Ohio, USA
[182]Princeton University, Princeton, New Jersey, USA
[183]University of Puerto Rico, Mayaguez, Puerto Rico, USA
[184]Purdue University, West Lafayette, Indiana, USA
[185]Purdue University Northwest, Hammond, Indiana, USA
[186]Rice University, Houston, Texas, USA
[187]University of Rochester, Rochester, New York, USA
[188]Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA

[189]University of Tennessee, Knoxville, Tennessee, USA
[190]Texas A&M University, College Station, Texas, USA
[191]Texas Tech University, Lubbock, Texas, USA
[192]Vanderbilt University, Nashville, Tennessee, USA
[193]University of Virginia, Charlottesville, Virginia, USA
[194]Wayne State University, Detroit, Michigan, USA
[195]University of Wisconsin—Madison, Madison, WI, Wisconsin, USA

[a]Deceased.
[b]Also at Vienna University of Technology, Vienna, Austria.
[c]Also at Department of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport.
[d]Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[e]Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.
[f]Also at Universidade Estadual de Campinas, Campinas, Brazil.
[g]Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
[h]Also at UFMS.
[i]Also at Universidade Federal de Pelotas, Pelotas, Brazil.
[j]Also at University of Chinese Academy of Sciences.
[k]Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia.
[l]Also at Joint Institute for Nuclear Research, Dubna, Russia.
[m]Also at Ain Shams University, Cairo, Egypt.
[n]Also at British University in Egypt, Cairo, Egypt.
[o]Also at Purdue University, West Lafayette, Indiana, USA.
[p]Also at Université de Haute Alsace, Mulhouse, France.
[q]Also at Ilia State University, Tbilisi, Georgia.
[r]Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
[s]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[t]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[u]Also at University of Hamburg, Hamburg, Germany.
[v]Also at Isfahan University of Technology, Isfahan, Iran.
[w]Also at Brandenburg University of Technology, Cottbus, Germany.
[x]Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
[y]Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
[z]Also at Physics Department, Faculty of Science, Assiut University.
[aa]Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[bb]Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[cc]Also at IIT Bhubaneswar, Bhubaneswar, India.
[dd]Also at Institute of Physics, Bhubaneswar, India.
[ee]Also at G.H.G. Khalsa College, Punjab, India.
[ff]Also at Shoolini University, Solan, India.
[gg]Also at University of Hyderabad, Hyderabad, India.
[hh]Also at University of Visva-Bharati, Santiniketan, India.
[ii]Also at Indian Institute of Technology (IIT), Mumbai, India.
[jj]Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
[kk]Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
[ll]Also at INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy.
[mm]Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development.
[nn]Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia.
[oo]Also at Riga Technical University, Riga, Latvia.
[pp]Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
[qq]Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
[rr]Also at Institute for Nuclear Research, Moscow, Russia.
[ss]Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
[tt]Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[uu]Also at University of Florida, Gainesville, Florida, USA.
[vv]Also at Imperial College, London, United Kingdom.
[ww]Also at P.N. Lebedev Physical Institute, Moscow, Russia.
[xx]Also at Moscow Institute of Physics and Technology, Moscow, Russia.
[yy]Also at California Institute of Technology, Pasadena, California, USA.

[zz]Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
[aaa]Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[bbb]Also at Università degli Studi di Siena, Siena, Italy.
[ccc]Also at Trincomalee Campus, Eastern University, Sri Lanka.
[ddd]Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy.
[eee]Also at National and Kapodistrian University of Athens, Athens, Greece.
[fff]Also at Universität Zürich, Zurich, Switzerland.
[ggg]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
[hhh]Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
[iii]Also at Şırnak University.
[jjj]Also at Department of Physics, Tsinghua University, Beijing, China.
[kkk]Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey.
[lll]Also at Beykent University, Istanbul, Turkey.
[mmm]Also at Istanbul Aydin University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies).
[nnn]Also at Mersin University, Mersin, Turkey.
[ooo]Also at Piri Reis University, Istanbul, Turkey.
[ppp]Also at Adiyaman University, Adiyaman, Turkey.
[qqq]Also at Ozyegin University, Istanbul, Turkey.
[rrr]Also at Izmir Institute of Technology, Izmir, Turkey.
[sss]Also at Necmettin Erbakan University, Konya, Turkey.
[ttt]Also at Bozok Universitetesi Rektörlügü.
[uuu]Also at Marmara University, Istanbul, Turkey.
[vvv]Also at Milli Savunma University.
[www]Also at Kafkas University, Kars, Turkey.
[xxx]Also at Istanbul Bilgi University, Istanbul, Turkey.
[yyy]Also at Hacettepe University, Ankara, Turkey.
[zzz]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[aaaa]Also at IPPP Durham University.
[bbbb]Also at Monash University, Faculty of Science, Clayton, Australia.
[cccc]Also at Bethel University, St. Paul, Minneapolis, USA.
[dddd]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[eeee]Also at Bingol University, Bingol, Turkey.
[ffff]Also at Georgian Technical University, Tbilisi, Georgia.
[gggg]Also at Sinop University, Sinop, Turkey.
[hhhh]Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[iiii]Also at Nanjing Normal University Department of Physics.
[jjjj]Also at Texas A&M University at Qatar, Doha, Qatar.
[kkkk]Also at Kyungpook National University, Daegu, Korea.