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

The CMS Collaboration*

Abstract

Using a data sample of proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$, corresponding to an integrated luminosity of $140\,\text{fb}^{-1}$ 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 $(2.21 \pm 0.29\,(\text{stat}) \pm 0.17\,(\text{syst}))\%$. 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 $D\overline{D}$ 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 $D\overline{D}$ 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 $D\overline{D}$ threshold. Its world-average mass is 3871.69 ± 0.17 MeV, which is extremely close to the $\overline{D}^0D^{*0}$ threshold of 3872.68 ± 0.07 MeV [4]. With this mass and a total width less than 1.2 MeV [5], 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 [4, 6]. At hadron colliders, prompt processes were found to be the dominant $X(3872)$ production mechanism [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 ($J^{PC} = 1^{++}$) [10–12]. The studies of the dipion mass spectrum [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 $\mathcal{B}(B \to X(3872)h)$ 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 [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 [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 μs. 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/ψ 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 $B_s^0 \to X(3872)\phi$ and $B_s^0 \to \psi(2S)\phi$ 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 EVTGEN 1.6.0 [17], where the final-state photon radiation is included using PHOTOS 3.61 [18, 19]. Generated events are then passed to a detailed 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/ψ mass [4], $m_{J/\psi}^{PDG}$. 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 [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 $m_{J/\psi}^{PDG}$ 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 $m(B_s^0) = m(J/\psi K^+K^-\pi^+\pi^-) - m(J/\psi\pi^+\pi^-) + m_{\psi(2S)\,/\,X(3872)}^{PDG}$, where $m_{\psi(2S)}^{PDG}$ and $m_{X(3872)}^{PDG}$ 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:

- $3.60 < m(J/\psi\pi^+\pi^-) < 3.95\,\text{GeV}$,
- $1.00 < m(K^+K^-) < 1.04\,\text{GeV}$,
- $5.32 < m(B_s^0) < 5.42\,\text{GeV}$,
- 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 $B_s^0 \to X(3872)\phi$ simulated sample is used to measure the signal efficiency. The resulting selection criteria are: $p_T(B_s^0) > 10\,\text{GeV}$, vertex χ^2 fit probability $P_{vtx}(B_s^0) > 7\%$, $p_T(\pi^\pm) > 0.7\,\text{GeV}$, $\min(p_T(K^\pm)) > 1.5\,\text{GeV}$, $\max(p_T(K^\pm)) > 2.2\,\text{GeV}$, 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 $\cos(\vec{p}_T, \vec{L}_{xy}) > 0.999$, 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 $m(\mathrm{J}/\psi\pi^+\pi^-)$ and $m(\mathrm{K}^+\mathrm{K}^-)$ distributions for B_s^0 candidates in the range $5.32 < m(\mathrm{B}_\mathrm{s}^0) < 5.42\,\mathrm{GeV}$. The numbers of $X(3872)\phi$ and $\psi(2\mathrm{S})\phi$ 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 $m(\mathrm{J}/\psi\pi^+\pi^-)$ (left) and $m(\mathrm{K}^+\mathrm{K}^-)$ (right) invariant mass distributions for the $\psi(2\mathrm{S})\phi$ candidates with $3.60 < m(\mathrm{J}/\psi\pi^+\pi^-) < 3.75\,\mathrm{GeV}$. Overlaid are the projections of the 2D fit function, which consists of the following four components:

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

Each component is a product of two one-dimensional functions. For the $\phi \to \mathrm{K}^+\mathrm{K}^-$ signal, a relativistic Breit–Wigner function 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 $\mathrm{K}^+\mathrm{K}^-$ mass distribution is modeled with a threshold function multiplied by a first-order polynomial: $(m(\mathrm{K}^+\mathrm{K}^-) - x_0)^\alpha Pol_1(m(\mathrm{K}^+\mathrm{K}^-))$, where x_0 is the threshold value equal to twice the kaon mass and α is a free parameter. The $\psi(2\mathrm{S}) \to \mathrm{J}/\psi\pi^+\pi^-$ signal is described with a double-Gaussian (DG) function with all parameters left free. The background in the $m(\mathrm{J}/\psi\pi^+\pi^-)$ distribution is modeled with a modified threshold function: $(m(\mathrm{J}/\psi\pi^+\pi^-) - y_0)^\beta Pol_1(m(\mathrm{J}/\psi\pi^+\pi^-))$, where y_0 is the threshold value equal to $m_{\mathrm{J}/\psi}^{\mathrm{PDG}} + 0.45\,\mathrm{GeV}$ (corresponding to the requirement $m(\pi^+\pi^-) > 0.45\,\mathrm{GeV}$), and β is a free parameter.

The following parameters are free in the fit: numbers of events in the four components, ϕ and $\psi(2\mathrm{S})$ meson masses, $\psi(2\mathrm{S})$ resolution parameters, and background parameters of $m(\mathrm{K}^+\mathrm{K}^-)$ and $m(\mathrm{J}/\psi\pi^+\pi^-)$. The fitted yield for the $\psi(2\mathrm{S}) + \phi$ component is $N(\mathrm{B}_\mathrm{s}^0 \to \psi(2\mathrm{S})\phi) = 15\,359 \pm 171$.

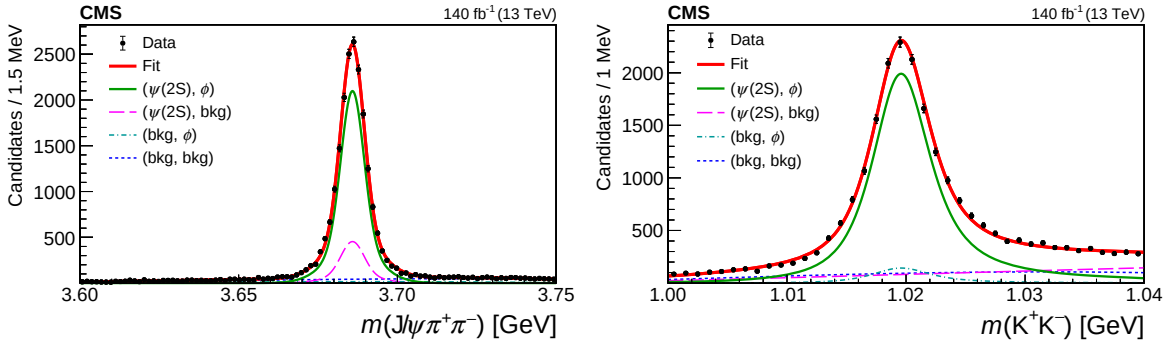

Figure 1: The observed $\mathrm{J}/\psi\pi^+\pi^-$ (left) and $\mathrm{K}^+\mathrm{K}^-$ (right) invariant mass distributions for the $\mathrm{B}_\mathrm{s}^0 \to \psi(2\mathrm{S})\phi$ candidates are shown by the points, with the vertical bars representing the statistical uncertainties. The projections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

For the $X(3872)$ mass region, defined as $3.80 < m(\mathrm{J}/\psi\pi^+\pi^-) < 3.95\,\mathrm{GeV}$, the same fit function is used as in the $\psi(2\mathrm{S})$ channel, but additional constraints are made because of the lower number of signal events. The shape of the $X(3872) \to \mathrm{J}/\psi\pi^+\pi^-$ signal is fixed to the one obtained in data for $\psi(2\mathrm{S}) \to \mathrm{J}/\psi\pi^+\pi^-$, 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 $m^{\mathrm{PDG}}_{\mathrm{J}/\psi} + 0.7\,\mathrm{GeV}$ 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 $N(\mathrm{B}^0_\mathrm{s} \to X(3872)\phi) = 299 \pm 39$.

The statistical significance of the $\mathrm{B}^0_\mathrm{s} \to X(3872)\phi$ 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 $\mathrm{B}^0_\mathrm{s} \to X(3872)\phi$ signal is over 6 standard deviations (σ), after accounting for the systematic uncertainties discussed later.

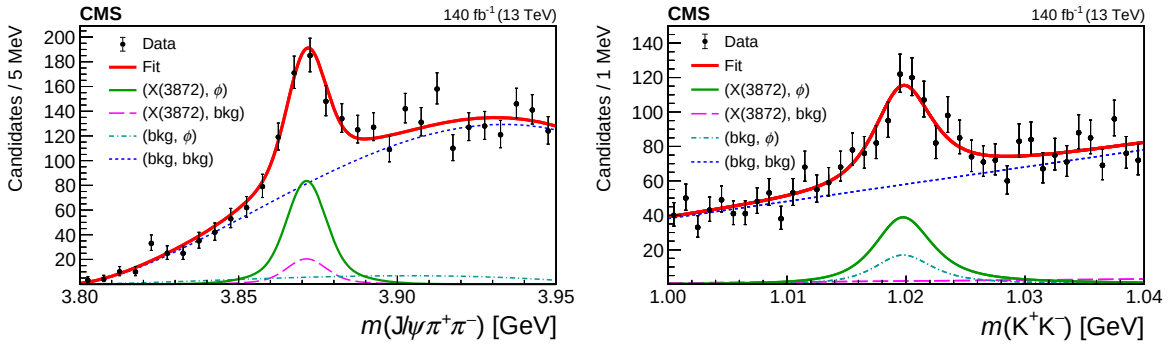

Figure 2: The observed $\mathrm{J}/\psi\,\pi^+\pi^-$ (left) and $\mathrm{K}^+\mathrm{K}^-$ (right) invariant mass distributions for the $\mathrm{B}^0_\mathrm{s} \to X(3872)\phi$ candidates are shown by the points, with the vertical bars representing the statistical uncertainties. The projections of the 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 $\psi(2\mathrm{S})\phi$ in the mass range $5.32 < m(\psi(2\mathrm{S})\phi) < 5.42\,\mathrm{GeV}$, the mass distribution of $\psi(2\mathrm{S})\phi$ is studied, as shown in Fig 3 (left). The background-subtraction technique ${}_s\mathcal{P}\mathrm{lot}$ [32] is used, together with the 2D fit described above, to subtract backgrounds from nonresonant $\mathrm{K}^+\mathrm{K}^-$ and $\mathrm{J}/\psi\,\pi^+\pi^-$ combinations. The observed $m(\psi(2\mathrm{S})\phi)$ 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 $X(3872)/\psi(2\mathrm{S})$ changes by 1.2% after accounting for this background from non-B^0_s production of $\psi(2\mathrm{S})\phi$ and $X(3872)\phi$ combinations. The significance of the $\mathrm{B}^0_\mathrm{s} \to X(3872)\phi$ 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 $\psi(2\mathrm{S})$ 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 $\epsilon_{\mathrm{B}^0_\mathrm{s}\to\psi(2\mathrm{S})\phi}/\epsilon_{\mathrm{B}^0_\mathrm{s}\to X(3872)\phi} = 1.136 \pm 0.026$, 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

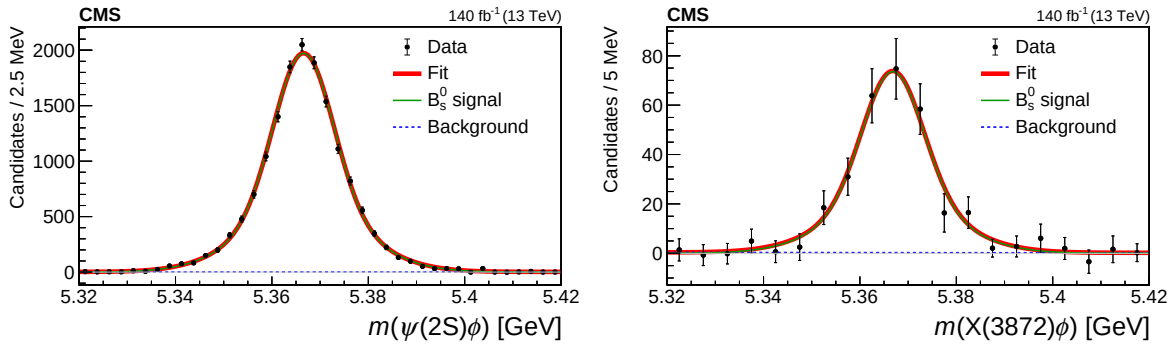

Figure 3: Background-subtracted $\psi(2S)\phi$ (left) and $X(3872)\phi$ (right) invariant mass distributions obtained by ${}_s\mathcal{P}$lot weighting. The result of each fit and its components are shown by the lines.

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

Table 1: 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

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

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

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

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

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]: $\mathcal{B}(B^0 \to X(3872)\overline{K}^0)\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (4.3 \pm 1.3) \times 10^{-6}$ 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^+:

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

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].

In summary, using a data sample corresponding to an integrated luminosity of $140\,\text{fb}^{-1}$ of proton-proton collisions collected by the CMS experiment at $\sqrt{s} = 13\,\text{TeV}$ 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 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.

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