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Observation of $\psi(3686) \to \Omega^- K^+ \bar{\Xi}^0 + \mathrm{c.c.}$

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Abstract: Using $(27.12 \pm 0.14) \times 10^8$ $\psi(3686)$ events collected with the BESIII detector at BEPCII, the decay of $\psi(3686) \to \Omega^- K^+ \bar{\Xi}^0 + \mathrm{c.c.}$ is observed for the first time. The branching fraction of this decay is measured to be $\mathcal{B}_{\psi(3686)\to\Omega^- K^+\bar{\Xi}^0+\mathrm{c.c.}} = (2.78 \pm 0.40 \pm 0.18) \times 10^{-6}$, where the first uncertainty is statistical and the second is systematic. Possible baryon excited states are searched for in this decay, but no evident intermediate state is observed with the current sample size.

Keywords: Branching fraction, e^+-e^- Experiments, QCD, Quarkonium

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1 Introduction

The discovery of the J/ψ and other $c\bar{c}$ bound states had a great impact on the development of the theory of strong interaction within the Standard Model (SM) [1, 2]. These states are multi-scale systems that probe a wide span of energy regimes in quantum chromodynamics (QCD): from the hard region, where expansions in the coupling constant are legitimate, to the low-energy region, where nonperturbative effects dominate [3]. Heavy quark-antiquark states remain an ideal laboratory where non-perturbative QCD and its interplay with perturbative QCD can be tested in a controlled framework.

The observation and study of a decay with three pairs of $s\bar{s}$ in the final state will expand our knowledge of the decay mechanism of charmonium and has the potential to improve of understanding of QCD [4, 5]. Experimental studies of hadronic decays of charmonium states provide important information for investigating many topics involving the strong interaction, such as the color octet and singlet contributions, the violation of helicity conservation, and SU(3) flavor symmetry breaking effects [3, 6].

Compared to the two-body final state, the theoretical analysis relevant to three-body decays of charmoniums is more difficult and the available experimental results are rather limited at present [7]. Recently, theoretical interest in final states containing baryons has been revived, stimulated by recent experimental discoveries, especially the phenomena of baryon-anitbaryon invariant mass enhancements near threshold [8–10].

The study of baryon spectroscopy played an important role in the development of the quark model and QCD [7, 11], although our knowledge of this subject is still limited. Due to the small production cross sections and the complicated topology of the final states, only a few Ξ^* and Ω^* states have been observed to date, and many of them lack a spin-parity determination. Until now, the most useful measurements have come from diffractive K^-p interactions [7, 12].

In this paper, the first observation of the decay $\psi(3686) \to \Omega^- K^+ \bar{\Xi}^0$ + c.c. is reported and the corresponding branching fraction is measured using $(27.12 \pm 0.14) \times 10^8$ $\psi(3686)$ events [13] collected with the BESIII detector. In addition, possible baryon excited states are also searched for in this decay. Throughout this paper, the charge conjugation decay mode is always implied.

2 BESIII detector and Monte Carlo simulation

The BESIII detector [14, 15] records e^+e^- collisions provided by the BEPCII storage ring [16], which operates with a peak luminosity of $1 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in the center-of-mass energy range from 2.00 to 4.95 GeV. The cylindrical core of the BESIII detector covers 93% of the full solid angle and consists of a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI (Tl) electromagnetic calorimeter (EMC), which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field [17]. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identification modules interleaved with steel. The charged-particle momentum resolution at $1\,\mathrm{GeV}/c$ is 0.5%, and the $\mathrm{d}E/\mathrm{d}x$ resolution is 6% for the electrons from Bhabha scattering at 1 GeV. The EMC measures photon energies with a resolution of 2.5% (5%) at 1 GeV in the barrel (end-cap) region. The time resolution of the TOF barrel part is 68 ps, while that of the end-cap part was 110 ps. The end-cap TOF system was upgraded in 2015 using multi-gap resistive plate chamber technology, providing a time resolution of 60 ps [18–20].

Monte Carlo (MC) simulated data samples produced with a GEANT4 [21] based software package, which includes the geometric description of the BESIII detector and the detector response, are used to optimize the event selection criteria, estimate the signal efficiency and background level. The simulation models the beam-energy spread and initial-state radiation in the e^+e^- annihilation using the generator KKMC [22]. The inclusive MC sample includes the production of the $\psi(3686)$ resonance, the initial-state radiation production of the J/ψ meson, and the continuum processes incorporated in KKMC [22]. Particle decays are generated by EVTGEN [23, 24] for the known decay modes with branching fractions taken from the Particle Data Group [7] and LUNDCHARM [25, 26] for the remaining unknown ones. Final-state radiation from charged final-state particles is included using the PHOTOS package [27]. To determine the detection efficiency, a signal MC sample of the whole decay chain of $\psi(3686) \to \Omega^- K^+ \bar{\Xi}^0$, $\Omega^- \to \Lambda(\to p\pi^-)K^-$ is generated uniformly in phase space (PHSP), along with generic $\bar{\Xi}^0$ decays. An inclusive $\psi(3686)$ MC sample, consisting of 27.12×10^8 events, is used to estimate potential backgrounds. The data sample collected at the center-of-mass energy of 3.650, 3.682, 3.773 GeV and 9 energy points from 3.58 to 3.71 GeV, corresponding to total integrated luminosities of $410\,\mathrm{pb}^{-1}$, $404\,\mathrm{pb}^{-1}$, $7.93\,\mathrm{fb}^{-1}$ and $503\,\mathrm{pb}^{-1}$, respectively, are used to estimate the contamination from the continuum processes.

3 Event selection

The cascade decay of interest is $\psi(3686) \to \Omega^- K^+ \bar{\Xi}^0$, with $\Omega^- \to \Lambda K^-$, $\Lambda \to p\pi^-$. As the full reconstruction method suffers from low detection efficiency, a partial-reconstruction

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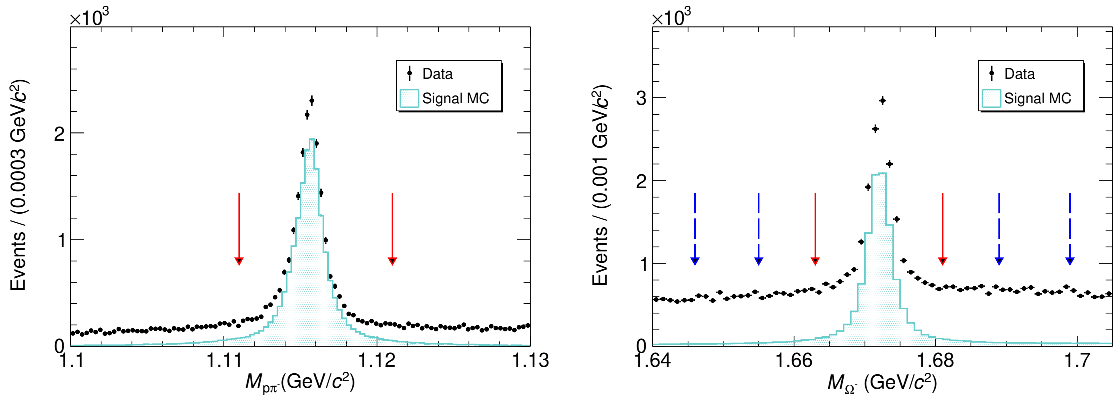
strategy is applied, in which only the Ω^-K^+ is reconstructed, with no attempt made to identify the $\bar{\Xi}^0$. The charged tracks in the MDC are required to have a polar angle θ with respect to the beam direction within the MDC acceptance $|\cos\theta| < 0.93$. For each charged track, particle identification (PID) is performed, combining measurements of the $\mathrm{d}E/\mathrm{d}x$ in the MDC and the flight time in the TOF to form particle identification (PID) confidence levels CL_h for each hadron h hypothesis. The charged tracks are identified as protons with the requirement of $\mathrm{CL}_p > \mathrm{CL}_K$, $\mathrm{CL}_p > \mathrm{CL}_\pi$ and $\mathrm{CL}_p > 0.001$, and kaons with $\mathrm{CL}_K > \mathrm{CL}_\pi$ and $\mathrm{CL}_K > 0$. The remaining charged tracks are assigned to be pions. If there is more than one K^+ candidate, the K^+ with the highest CL_K is assumed to be from the interaction point (IP), i.e. the K^+ is further required to have a distance of closest approach to the IP less than 10 cm along the z-axis and less than 1 cm in the transverse plane.

Λ candidates are reconstructed using common vertex fits [28] on $p\pi^-$ pairs with the requirement $\chi^2 < 200$. If there is more than one $p\pi^-$ combination, the pair corresponding to the minimum χ^2 from the vertex fit is retained. The $p\pi^-$ invariant mass ($M_{p\pi^-}$) must be within the Λ signal region, $M_{p\pi^-} \in [1.111, 1.121]\,\mathrm{GeV}/c^2$, as shown in figure 1(a). The Ω^- decay is reconstructed with a Λ candidate and a K^- by implementing another common vertex fit for which $\chi^2 < 200$ is again required. The reduced mass for the Ω^- candidates, $M_{\Omega^-} = M_{\Lambda K^-} - M_{p\pi^-} + M_\Lambda^{\mathrm{PDG}}$, is used to improve the mass resolution of the Ω^- candidate, where M_Λ^{PDG} is the known mass of the Λ baryon [7]. If there is more than one Ω^- candidate, the one with the minimum $|M_{\Omega^-} - M_{\Omega^-}^{\mathrm{PDG}}|$ is chosen, where $M_{\Omega^-}^{\mathrm{PDG}}$ is the known mass of the Ω^- [7]. Based on the MC study, the probability of occurrence of multiple Ω^- candidates is about 1.7%. With our method of selecting the best Ω^- candidate, only less than four percent of them would select the incorrect Ω^- candidate, which means the potential bias of best Ω^- candidate selection is negligible. The distribution of M_{Ω^-} is shown in figure 1(b). The signal region defined as $M_{\Omega^-} \in [1.663, 1.681]\,\mathrm{GeV}/c^2$, corresponding to six times the mass resolution, is imposed to select Ω^- candidates. The sideband regions defined as $M_{\Omega^-} \in ([1.646, 1.655] \cup [1.689, 1.699])\,\mathrm{GeV}/c^2$ are used to estimate the background. The two-dimensional (2-D) distributions of $M_{p\pi^-}$ versus M_{Ω^-} for signal MC sample and data are shown in figure 2. Signal events manifest themselves through a $\bar{\Xi}^0$ peak in the spectrum of the invaritant mass recoiling against the Ω^-K^+ pair ($RM_{\Omega^-K^+}$). The $RM_{\Omega^-K^+}$ spectrum for MC sample and data are shown in figure 3. The $\bar{\Xi}^0$ signal region is defined as $RM_{\Omega^-K^+} \in [1.282, 1.352]\,\mathrm{GeV}/c^2$, corresponding to approximately $\pm 3\sigma$ around the nominal $\bar{\Xi}^0$ mass, where σ is the mass resolution of $RM_{\Omega^-K^+}$ from the signal MC sample.

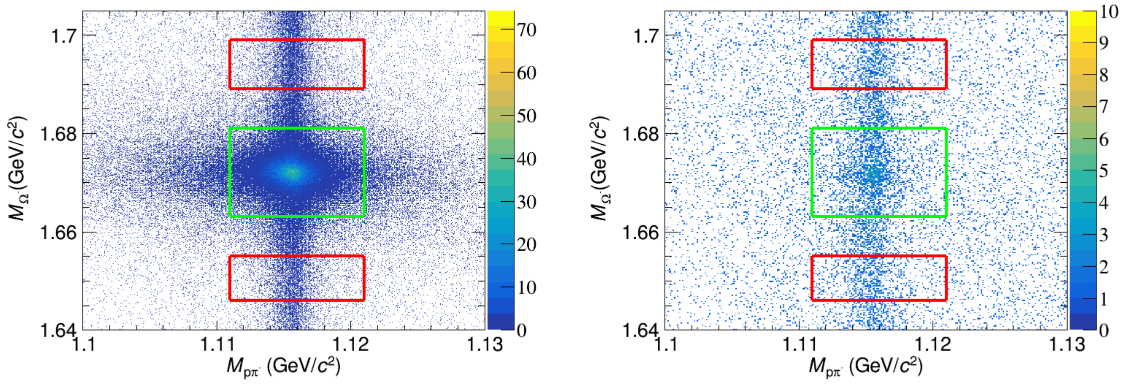
4 Detection efficiency determination

The detection efficiency is determined with MC simulation. Thus, it is necessary to assess the potential impact of intermediate states. Based on the known excited states of Ω^- and Ξ^0 [7], under the limitation of the PHSP, the only possible excited states in this channel is $\Xi(2250)^0(\to \Omega^-K^+)$. As a further test to ensure we are not sensitive to intermediate resonances, we combine the signal MC sample with the inclusive MC sample, based on the measured branching fraction of this decay (which can be found in section 6), and verify its consistency with the data. The distributions of $M_{\Omega^-K^+}$ between data and MC simulations in figure 4 show acceptable agreement, and no intermediate state is evident in the data sample.



(a) (b)

Figure 1. The distributions of $M_{p\pi^-}$ and M_{Ω^-}. The red arrows show the signal region, and the blue dashed arrows show the sideband regions.



(a) (b)

Figure 2. The 2-D distributions of $M_{p\pi^-}$ and M_{Ω^-} for signal MC sample (a) and data (b). The green box denotes the signal region and the red boxes denote the sideband regions.

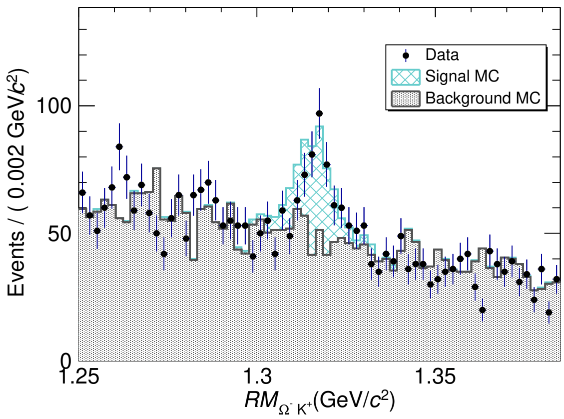


Figure 3. The distribution of $RM_{\Omega^- K^+}$.

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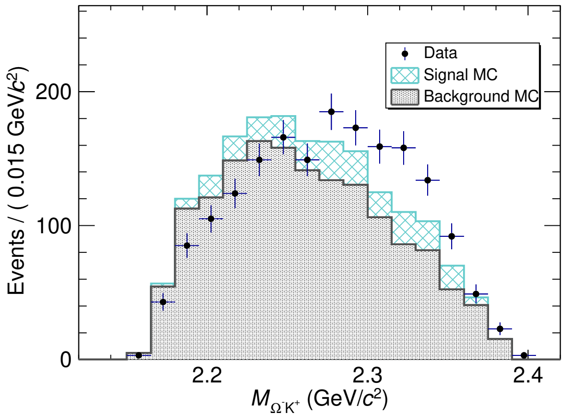

Figure 4. The distribution of $M_{\Omega^-K^+}$.

5 Background study

The $\psi(3686)$ inclusive MC sample is analysed with a generic event-type examination tool, TopoAna [29], to identify potential backgrounds. Further studies are performed of the surviving events in the $\bar{\Xi}^0$ signal region from the inclusive MC sample, and the events in the Ω^- mass sideband regions from data, respectively. These investigations indicate that there is no significant source of peaking background in the $RM_{\Omega^-K^+}$ spectrum.

To investigate the contamination from continuum processes [13], the same selection criteria are applied to the control samples introduced in section 2. Peaking background events from the data sample at center-of-mass energy of 3.773 GeV are observed in figure 5(b) from section 6, while the background from the other continuum data samples are negligible.

6 Signal yield and BF

To determine the signal yield, an unbinned maximum-likelihood fit is performed on the $RM_{\Omega^-K^+}$ distribution. In the fit, the signal shape is described by the signal MC simulated shape convolved with a Gaussian function with free parameters, where the Gaussian function is used to compensate for the difference in mass resolution between data and MC simulation. The background shape is described by a second-order Chebyshev polynomial. The fit result is shown in figure 5(a). The signal yield from $\psi(3686)$ data in the signal region is determined to be $N_{\rm obs.} = 250 \pm 35$. The statistical significance of the $\bar{\Xi}^0$ signal is 8.3σ, which is determined from the change in the log-likelihood values and the corresponding change in the number of degrees of freedom with and without including the signal contribution in the fit.

The same fit procedure is performed on the continuum data at 3.773 GeV [30]. The parameters of the Gaussian function used for the convolution here are also floating. The result of the fit to the $RM_{\Omega^-K^+}$ distribution is shown in figure 5(b). The number of continuum background events fitted as signal in this sample is $N_{\rm cont.} = 21 \pm 11$, as shown in table 1. A scale factor f_c is defined as the ratio of the normalized number of continuum background

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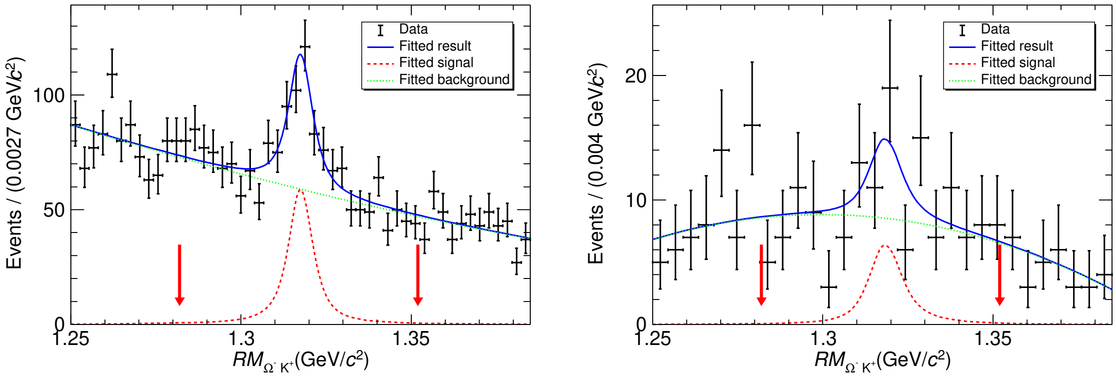

(a) (b)

Figure 5. Fits to the $RM_{\Omega^- K^+}$ distributions of the accepted candidates in $\psi(3686)$ data (a) and the continuum data at 3.773 GeV (b). The red arrows mark the $\bar{\Xi}^0$ signal region.

$\sqrt{s}$(GeV)	$\mathcal{L}$(fb^{-1})	ϵ(%)	$N_{\rm cont.}$	$f_{\rm c}$	$N_{\rm QED}$
3.686	4.08	7.43	21 ± 11	0.36	8 ± 4
3.773	7.93	11.09			

Table 1. The corresponding physical quantities in $f_{\rm c}$ factor and the estimated values of $f_{\rm c}$ and $N_{\rm QED}$.

events ($N_{\rm QED}$) to that in the data at 3.773 GeV, so that $N_{\rm QED} = f_c N_{\rm cont.}$, where

$$f_{\rm c} = \frac{\mathcal{L}_{\psi(3686)}}{\mathcal{L}_{\rm cont.}} \cdot \frac{s^n_{\rm cont.}}{s^n_{\psi(3686)}} \cdot \frac{\epsilon_{\psi(3686)}}{\epsilon_{\rm cont.}}. \tag{6.1}$$

Here, $\mathcal{L}$ [13], [31],[1] s, and ϵ refer to the integrated luminosity of data samples, the square of the center-of-mass energy, and the detection efficiency at the two center-of-mass energies, respectively. The index number n is assumed to be 1 for the baseline result, which corresponds to a $1/s$ dependence for the input cross sections. The impact of this assumption for n will be considered as a source of systematic uncertainty. The scale factor is calculated to be 0.36 and $N_{\rm QED}$ is 8 ± 4. All relevant numbers are listed in table 1.

Due to the limited sample size of the data taken in the vicinity of the $\psi(3686)$, the interference phase between the $\psi(3686)$ decay and the continuum production cannot be determined. Furthermore, the signal can be described well by the pure signal MC ($\psi(3686) \to \Omega^- K^+ \bar{\Xi}^0$) shape convolving with a Gaussian function as shown in figure 5(a), indicating that the potential interference is a subleading effect. Thus in this analysis, we do not consider the interference effect between the $\psi(3686) \to \Omega^- K^+ \bar{\Xi}^0$ decay and the continuum production $e^+e^- \to \Omega^- K^+ \bar{\Xi}^0$.

The branching fraction of the $\psi(3686) \to \Omega^- K^+ \bar{\Xi}^0$ decay is calculated as

$$\mathcal{B}_{\psi(3686)\to\Omega^- K^+ \bar{\Xi}^0 + {\rm c.c.}} = \frac{N_{\rm obs.} - N_{\rm QED}}{N_{\psi(3686)} \cdot \mathcal{B}_{\Omega^- \to \Lambda K^-} \cdot \mathcal{B}_{\Lambda \to p^+ \pi^-} \cdot \epsilon}, \tag{6.2}$$

[1]The integrated luminosity of the $\psi(3773)$ data samples collected in 2010, 2011 and 2022 is determined to be (7.93 ± 0.02) fb^{-1} as a preliminary result.

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where $N_{\rm obs.} - N_{\rm QED} = 242 \pm 35$ is the net number of signal events, $N_{\psi(3686)}$ is the total number of $\psi(3686)$ events [13], and $\epsilon = 7.43\%$ is the detection efficiency. $\mathcal{B}_{\Omega^- \to \Lambda K^-}$ and $\mathcal{B}_{\Lambda \to p^+\pi^-}$ are the branching fractions for $\Omega^- \to \Lambda K^-$, and $\Lambda \to p^+\pi^-$ decays, respectively, cited from the PDG [7]. With these inputs, the branching fraction of $\psi(3686) \to \Omega^- K^+ \bar{\Xi}^0 + \text{c.c.}$ is determined to be $(2.78 \pm 0.40) \times 10^{-6}$.

7 Systematic uncertainty

The systematic uncertainties in the $\mathcal{B}_{\psi(3686)\to\Omega^- K^+ \bar{\Xi}^0}$ measurement include contributions associated with the kaon-tracking efficiency, PID, Λ reconstruction, the requirement on M_{Ω^-}, signal and background shapes, $f_{\rm c}$ factor, MC generator, the sample size of the MC sample, the input branching fractions [7], and the total number of $\psi(3686)$ events [13].

The systematic uncertainties arising from the knowledge of the kaon-tracking and PID efficiencies are studied with the well understood decay of $e^+e^- \to K^+K^-$, and both assigned as 1.0% per track [32]. The systematic uncertainty associated with the Λ-reconstruction efficiency includes effects from the tracking (PID) efficiencies for proton and pion, and the requirement on $M_{p\pi^-}$. This uncertainty is estimated with a control sample of $J/\psi \to pK^-\bar{\Lambda} + \text{c.c.}$ decays [33]. The momentum-dependent ratios of the Λ reconstruction efficiencies between data and MC simulation are used to re-weight the MC sample. The difference between the baseline detection efficiency and that obtained after re-weighting, 4.1%, is taken as the systematic uncertainty.

The systematic uncertainty associated with the requirement on M_{Ω^-} is studied with a control sample of $\psi(3686) \to \Omega^-\bar{\Omega}^+$ events, where Ω^- is fully reconstructed with $\Omega^- \to \Lambda K^-$, $\Lambda \to p\pi^-$. Details on the event selection can be found in ref. [34]. The signal yield is obtained by fitting the recoiling mass against the Ω^- (RM_{Ω^-}). In the baseline analysis, the requirement of $M_{\Omega^-} \in [1.663, 1.681]\,\text{GeV}/c^2$ is applied, which is about $\pm 3\sigma$ around the known Ω^- mass. We change the Ω^- mass window to be $[1.643, 1.700]\,\text{GeV}/c^2$, which contains almost all the signal events and retains a low background level. The change in the efficiency difference between data and MC simulation is taken as the systematic uncertainty, which is 0.6%.

The systematic uncertainty associated with the knowledge of the signal shape is caused by detection resolution effects in data, and is estimated by changing the MC shape convolved with a Gaussian function to the MC shape convolved with a double-Gaussian function. The relative difference in the branching fraction, 0.4%, is assigned as the uncertainty. The systematic uncertainty associated with the background shape is estimated by changing the background shape from a second-order Chebyshev polynomial to a third-order Chebyshev polynomial. The resulting difference to the original branching fraction, 0.4%, is assigned as the systematic uncertainty.

The systematic uncertainty related to the scale factor $f_{\rm c}$ is estimated by changing n from 1 to 2 and 3. The resulting largest difference to the original branching fraction, 0.3%, is assigned as the systematic uncertainty.

Similar to ref. [34], a event-by-event weighting method is used to study the systematic uncertainty related to the MC generator. The events of the signal MC sample are weighted in two dimensions according to the momentum distribution of K^+ and Ω^- in data. The

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Source	Uncertainty (%)
Kaon tracking	2.0
Kaon PID	2.0
Λ reconstruction	4.1
Mass window of M_{Ω^-}	0.6
Signal shape	0.4
Background shape	0.4
f_c factor	0.3
MC generator	3.9
MC sample size	0.2
$\mathcal{B}_{\Omega^- \to \Lambda K^-}$	1.0
$\mathcal{B}_{\Lambda \to p\pi^-}$	0.8
Number of $\psi(3686)$ events	0.5
Total	6.5

Table 2. Relative systematic uncertainties in the branching fraction measurement.

deviation between the nominal detection efficiency and that obtained after re-weighting, 3.9%, is taken as the systematic uncertainty.

The systematic uncertainty arising from the limited size of the MC sample is 0.2%. The uncertainty associated with the total number of $\psi(3686)$ events is 0.5% [13]. The uncertainties arising from the knowledge of the branching fractions for $\Omega^- \to \Lambda K^-$ and $\Lambda \to p\pi^-$ are 1.0% and 0.8% [7], respectively.

The systematic uncertainties are summarized in table 2. Assuming that all sources are independent, the total systematic uncertainty on the branching fraction of $\psi(3686) \to \Omega^- K^+ \bar{\Xi}^0$ is determined to be 6.5% by adding them in quadrature.

The signal significance is estimated to be 7.7σ after considering the systematic effects of the requirements of M_{Ω^-}, and the signal and background shapes in the fit to $RM_{\Omega^- K^+}$.

8 Summary

In summary, using the world's largest $\psi(3686)$ sample taken with the BESIII detector, we observe the $\psi(3686) \to \Omega^- K^+ \bar{\Xi}^0$ + c.c. decay for the first time by employing a partial reconstruction method. The measured branching fraction is $\mathcal{B}(\psi(3686) \to \Omega^- K^+ \bar{\Xi}^0 + \text{c.c.}) = (2.78 \pm 0.40 \pm 0.18) \times 10^{-6}$, where the first uncertainty is statistical and the second is systematic. This result provides useful information for understanding the dynamics of $\psi(3686)$ decays. With the current sample size, we do not observe any clear evidence of possible hyperon excited states. A larger data sample would be helpful for studying the decay dynamics of this process and explore the presence of potential excited baryon states.

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