Measurement of $e^+e^- \to \omega\pi^0$, $K^*(892)\bar{K}$ and $K_2^*(1430)\bar{K}$ at $\sqrt{s}$ near 10.6 GeV

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Abstract

Using data samples of 89 fb^{-1}, 703 fb^{-1}, and 121 fb^{-1} collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider at center-of-mass energies 10.52 GeV, 10.58 GeV, and 10.876 GeV, respectively, we study the exclusive reactions $e^+e^- \to \omega\pi^0$, $K^*(892)\bar{K}$, and $K_2^*(1430)\bar{K}$ (Charge-conjugate modes are included implicitly). Significant signals of $\omega\pi^0$, $K^*(892)^0\bar{K}^0$, and $K_2^*(1430)^-K^+$ are observed for the first time at these energies, and the energy dependencies of the cross sections are presented. On the other hand, no significant excesses for $K^*(892)^-K^+$ and $K_2^*(1430)^0\bar{K}^0$ are found, and we set limits on the cross section ratios $R_{\rm VP} = \frac{\sigma_B(e^+e^-\to K^*(892)^0\bar{K}^0)}{\sigma_B(e^+e^-\to K^*(892)^-K^+)} > 4.3$, 20.0, and 5.4, and $R_{\rm TP} = \frac{\sigma_B(e^+e^-\to K_2^*(1430)^0\bar{K}^0)}{\sigma_B(e^+e^-\to K_2^*(1430)^-K^+)} < 1.1$, 0.4, and 0.6, for center-of-mass energies of 10.52 GeV, 10.58 GeV, and 10.876 GeV, respectively, at the 90% C.L.

PACS numbers: 13.66.Bc, 13.25.Jx, 13.40.Gp, 14.40.Df

Large data samples collected at the B-factories provide an opportunity to explore rare two-meson production in e^+e^- annihilation, which allows us to investigate the energy dependence of various meson form factors and shed light on hadron structure and hence the strong interaction. These studies also supply information on the wave function of hadrons.

For a center-of-mass (CM) energy $\sqrt{s}$ much larger than resonance masses, one expects that the proportions of the cross sections of $\omega\pi^0$: $K^*(892)^0\bar{K}^0$: $K^*(892)^-K^+$ production equal 9:8:2 [1] if SU(3) flavor symmetry is exact. However, this relation was found to be violated severely at $\sqrt{s}$ = 3.67 GeV and 3.773 GeV by the CLEO experiment [2], with the $\omega\pi^0$ cross sections smaller than those of the $K^*(892)^0\bar{K}^0$, and the ratio $R_{\rm VP} = \frac{\sigma_B(e^+e^-\to K^*(892)^0\bar{K}^0)}{\sigma_B(e^+e^-\to K^*(892)^-K^+)}$ greater than 9 and 33 at $\sqrt{s}$ = 3.67 GeV and 3.773 GeV, respectively, at the 90% confidence level (C.L.) [3].

By taking into account SU(3)$_{\rm f}$ symmetry breaking and the transverse momentum distribution of partons in the light cone wave functions of mesons, a pQCD calculation [4] can reproduce most of the CLEO measurements with reasonable input parameters, and the corresponding cross sections at $\sqrt{s}$ = 10.58 GeV are predicted. The calculation predicts $R_{\rm VP}$ = 6.0, which is far below the CLEO lower limits and may indicate deficiencies in the model assumptions. The same calculation also predicts that the cross sections of $e^+e^-\to$ vector-pseudoscalar (VP) vary as $1/s^3$ rather than $1/s^2$ in Ref. [5] or $1/s^4$ in Refs. [6–8]; this can also be tested by combining the measurements from CLEO and the B-factories. At Belle, the cross sections of $e^+e^-\to\phi\eta,\ \phi\eta',\ \rho\eta,\ \rho\eta'$ have been measured at $\sqrt{s}$ = 10.58 GeV; however, no definite conclusion about the energy dependence of $e^+e^-\to VP$ can be drawn [9].

In the quark model, the tensor states $K_2^*(1430)$ have the same quark content as the vector states $K^*(892)$; thus, one may naively expect the same ratio between the neutral and charged $K_2^*(1430)\bar{K}$ production in e^+e^- annihilation as in the VP case, i.e., $R_{\rm TP} = \frac{\sigma_B(e^+e^-\to K_2^*(1430)^0\bar{K}^0)}{\sigma_B(e^+e^-\to K_2^*(1430)^-K^+)} = R_{\rm VP}$. This has never been tested.

In this paper, we report the cross sections of the exclusive reactions $e^+e^-\to\omega\pi^0$, $K^*(892)\bar{K}$, and $K_2^*(1430)\bar{K}$, based on data samples of 89 fb^{-1}, 703 fb^{-1}, and 121 fb^{-1} collected at $\sqrt{s}$ =10.52, 10.58 ($\Upsilon(4S)$ peak), and 10.876 GeV ($\Upsilon(5S)$ peak), respectively. The data were collected with the Belle detector [10] operating at the KEKB asymmetric-energy e^+e^- collider [11]. The final states are $\pi^+\pi^-\pi^0\pi^0$ and $K_S^0K^+\pi^-$, in which the K_S^0 is reconstructed from $\pi^+\pi^-$. The generator MCGPJ, developed according to the calculations in

Ref. [12], is used to generate Monte Carlo (MC) events with the exact next-to-leading order radiative corrections applied to all the studied processes. Generic $e^+e^- \to u\bar{u}/d\bar{d}/s\bar{s}$ MC events, produced using PYTHIA [13], are used to check background contributions.

The Belle detector is described in detail elsewhere [10]. It is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux return located outside of the coil is instrumented to detect K^0_L mesons and to identify muons (KLM).

For each charged track except those from K^0_S decays, the impact parameters perpendicular to and along the beam direction with respect to the interaction point are required to be less than 0.5 cm and 4 cm, respectively, and the transverse momentum must exceed 0.1 GeV/c in the laboratory frame. Well-measured charged tracks are selected and the numbers of such charged tracks are two for the $\pi^+\pi^-\pi^0\pi^0$ final state and four for the $K^0_S K^+\pi^-$ final state. For each charged track, we combine information from several detector subsystems to form a likelihood $\mathcal{L}_i$ for each particle species [14]. A track with $\mathcal{R}_K = \frac{\mathcal{L}_K}{\mathcal{L}_K+\mathcal{L}_\pi} > 0.6$ is identified as a kaon, while a track with $\mathcal{R}_K < 0.4$ is treated as a pion. With this selection, the kaon (pion) identification efficiency is about 85% (89%), while 6% (9%) of kaons (pions) are misidentified as pions (kaons). For electron identification, the likelihood ratio is defined as $\mathcal{R}_e = \frac{\mathcal{L}_e}{\mathcal{L}_e+\mathcal{L}_x}$, where $\mathcal{L}_e$ and $\mathcal{L}_x$ are the likelihoods for electron and non-electron, respectively. These are determined using the ratio of the energy deposited in the ECL to the momentum measured in the SVD and CDC, the shower shape in the ECL, position matching between the charged track trajectory and the cluster position in the ECL, hit information from the ACC, and specific ionization (dE/dx) information in the CDC [15]. For muon identification, the likelihood ratio is defined as $\mathcal{R}_\mu = \frac{\mathcal{L}_\mu}{\mathcal{L}_\mu+\mathcal{L}_\pi+\mathcal{L}_K}$, where $\mathcal{L}_\mu$, $\mathcal{L}_\pi$, and $\mathcal{L}_K$ are the likelihoods for muon, pion, and kaon, respectively. These are based on track matching quality and penetration depth of associated hits in the KLM [16].

Except for the $\pi^+\pi^-$ pair from K^0_S decay, all charged tracks are required to be positively identified as pions or kaons. The requirements $\mathcal{R}_\mu < 0.95$ and $\mathcal{R}_e < 0.95$ for the charged tracks remove 9.3% of the backgrounds for $K^0_S K^+\pi^-$ with negligible loss in efficiency.

For K^0_S candidates decaying into $\pi^+\pi^-$ in the $K^0_S K^+\pi^-$ mode, we require that the invariant mass of the $\pi^+\pi^-$ pair lie within a ± 8 MeV/c^2 interval around the K^0_S nominal mass, which contains around 95% of the signal according to MC simulation, and that the pair have a displaced vertex and flight direction consistent with a K^0_S originating from the IP [17].

An energy cluster in the electromagnetic calorimeter is reconstructed as a photon if it does not match the extrapolated position of any charged track. A π^0 candidate is reconstructed from a pair of photons whose energies exceed 100 MeV in the laboratory frame. We perform a mass-constrained fit to the selected π^0 candidate and require $\chi^2 < 15$. To suppress background from the Initial-State-Radiative (ISR) process $e^+e^- \to \gamma_{\rm ISR}\omega \to \gamma_{\rm ISR}\pi^+\pi^-\pi^0$, the requirement of $|(E_1-E_2)/(E_1+E_2)| < 0.65$ is imposed for the primary π^0 of $e^+e^- \to \omega\pi^0$, where E_1 and E_2 are the energies in the laboratory frame of the photons forming the higher-momentum π^0 candidate.

We define an energy conservation variable $X_T = \Sigma_h E_h/\sqrt{s}$, where E_h is the energy of the final-state particle h in the e^+e^- CM frame. For the signal candidates, X_T should be around 1. After the application of all the above selection requirements, Fig. 1 shows the X_T distributions for the final candidate events of $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ (top row) and $K^0_S K^+\pi^-$ (bottom row) from the $\sqrt{s} = 10.52$ GeV, 10.58 GeV, and 10.876 GeV data samples, respectively. Clear $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ and $K^0_S K^+\pi^-$ signals are observed. We require $|X_T - 1| < 0.025$ for $\pi^+\pi^-\pi^0\pi^0$ and $|X_T - 1| < 0.02$ for $K^0_S K^+\pi^-$, as indicated by the dotted lines in Fig. 1.

The distributions of $M(\pi^+\pi^-\pi^0_l)$ versus $M(\pi^+\pi^-\pi^0_h)$ for the $\pi^+\pi^-\pi^0_h\pi^0_l$ final state and $M(K^0_S\pi^-)$ versus $M(K^+\pi^-)$ for the $K^0_S K^+\pi^-$ final state are shown in Fig. 2. Here, π^0_h and π^0_l represent the π^0 candidates with higher and lower momentum, respectively, in the laboratory system. According to MC-simulated $e^+e^- \to \omega\pi^0$ signal events, most of the π^0s ($> 97\%$) from ω decays have lower momentum and there is only one $\pi^+\pi^-\pi^0$ combination in the ω mass region. In the $K^0_S K^+\pi^-$ mode, we see clearly the intermediate states $K^*(892)\bar{K}$, $K^*_2(1430)\bar{K}$ and possibly $a_2(1320)\pi$.

For the selected events, Fig. 3 shows the $\pi^+\pi^-\pi^0$, $K^+\pi^-$, and $K^0_S\pi^-$ invariant mass distributions for the $\pi^+\pi^-\pi^0\pi^0$ and $K^0_S K^+\pi^-$ final states from the $\sqrt{s} = 10.52$ GeV, 10.58 GeV, and 10.876 GeV data samples. For charge-conjugate modes the numbers of selected candidate events are consistent within one standard deviation. The dots with error bars are from data and the light shaded histograms are from the normalized $e^+e^- \to u\bar{u}/d\bar{d}/s\bar{s}$ backgrounds. In the $\pi^+\pi^-\pi^0$ invariant mass distributions, the dark shaded histograms in the

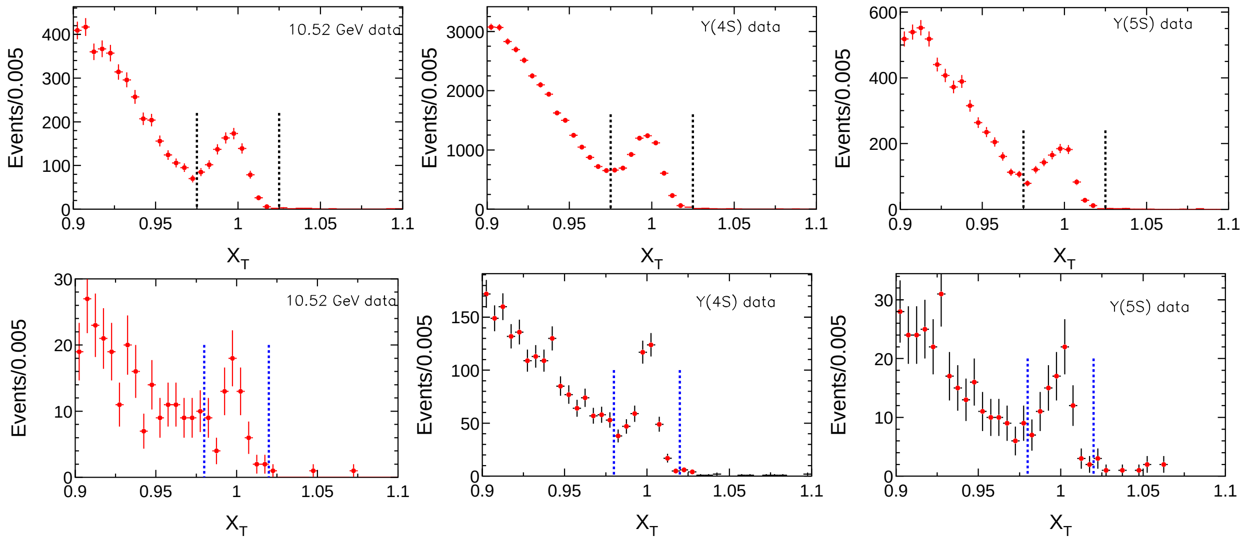

FIG. 1: The scaled total energy X_T distributions for the selected $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ (top row) and $K_S^0K^+\pi^-$ (bottom row) candidate events from the $\sqrt{s}$ = 10.52 GeV, 10.58 GeV, and 10.876 GeV data samples. The signal region is between the dotted lines.

ω and ϕ mass regions are from the normalized $e^+e^- \to \gamma_{\rm ISR}\omega/\phi \to \gamma_{\rm ISR}\pi^+\pi^-\pi^0$ backgrounds. In the normalization, the expected ISR events are calculated with $N^{\rm prod} = \mathcal{L} \times \sigma^{\rm prod}$, where $\mathcal{L}$ is the integrated luminosity and $\sigma^{\rm prod}$ is the production cross section. The production cross sections are calculated to be $\sigma^{\rm prod}(e^+e^- \to \gamma_{\rm ISR}\omega)$ = 15.1 pb, 14.9 pb, and 14.2 pb, and $\sigma^{\rm prod}(e^+e^- \to \gamma_{\rm ISR}\phi)$ = 25.4 pb, 25.2 pb, and 23.9 pb, for $\sqrt{s}$ = 10.52 GeV, 10.58 GeV, and 10.876 GeV, respectively [18]. ISR MC events of $e^+e^- \to \gamma_{\rm ISR}\omega/\phi \to \gamma_{\rm ISR}\pi^+\pi^-\pi^0$ are simulated using the PHOKHARA generator [19], which simulates ISR process at the next-to-leading order accuracy. In the $K^+\pi^-$ and $K_S^0\pi^-$ invariant mass distributions, we observe clear $K^*(892)^0$ and $K_2^*(1430)^-$ signals, while almost no signals for $K_2^*(1430)^0$ and $K^*(892)^-$ can be seen.

We perform unbinned maximum likelihood fits to these mass distributions, as shown in Fig. 3. The signal shapes of ω, $K^*(892)$, and $K_2^*(1430)$ are obtained directly from MC simulated signal samples [20]. The combinatorial backgrounds are modeled by a second-order Chebyshev polynomial and the additional normalized backgrounds from $e^+e^- \to \gamma_{\rm ISR}\omega/\phi \to \gamma_{\rm ISR}\pi^+\pi^-\pi^0$ are fixed in the $\pi^+\pi^-\pi^0$ mass spectrum fit. The fitted results are shown in Fig. 3 and listed in Table I.

The significances and the upper limits listed in Table I are obtained by evaluating the

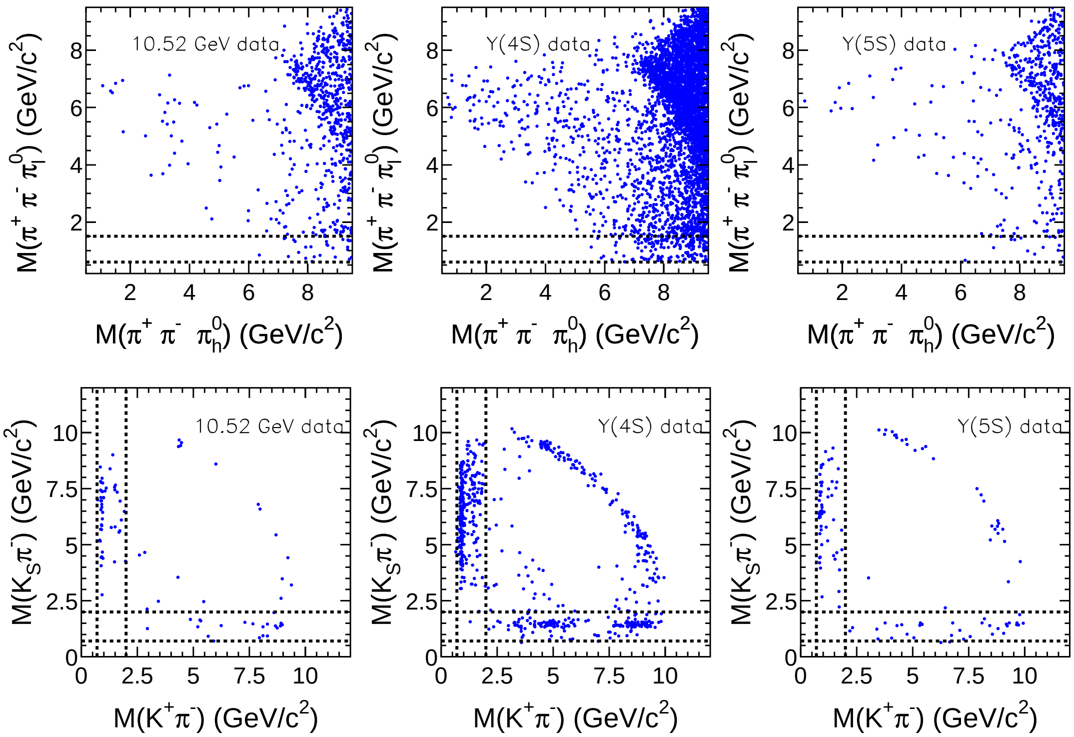

FIG. 2: Distributions of $M(\pi^+\pi^-\pi^0_l)$ versus $M(\pi^+\pi^-\pi^0_h)$ for the $\pi^+\pi^-\pi^0\pi^0$ (top row) and $M(K^0_S\pi^-)$ versus $M(K^+\pi^-)$ for the $K^0_S K^+\pi^-$ (bottom row) final states from the $\sqrt{s}$ = 10.52 GeV, 10.58 GeV, and 10.876 GeV data samples. In the $\pi^+\pi^-\pi^0\pi^0$ panels, π^0_h and π^0_l represent the pions with higher and lower momentum in the laboratory system, respectively. The events between the dotted lines will be selected to search for ω, K^* and K^*_2 signals.

likelihood profile. To take into account the systematic uncertainty, we convolve the likelihood function with a Gaussian whose width equals the total systematic uncertainty. The significance is obtained by comparing the likelihood values at maximum and at zero signal yield using $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\rm max})}$. The upper limit $N^{\rm UL}_{\rm sig}$ on $N_{\rm sig}$ at 90% C.L. is obtained by integrating the likelihood function from zero to the bound that gives 90% of the total area.

The observed cross section is determined according to the formula $\sigma^{\rm obs} = \frac{N}{L\,B_{V/T}\,B_P\,\epsilon}$, where N is the signal yield, L is the integrated luminosity, $B_{\rm V/T}$ and $B_{\rm P}$ are the branching fractions of the corresponding decay channels of the vector/tensor and pseudoscalar mesons including secondary branching fractions to reconstructed final states, respectively, and ϵ is the corresponding detection efficiency. The Born cross section is written as $\sigma_B = \frac{\sigma^{\rm obs}|1-\Pi(s)|^2}{(1+\delta)}$, where $1+\delta$ is the radiative correction factor and $|1-\Pi(s)|^2$ is the vacuum polarization factor. The radiative correction factors $1+\delta$ are 0.89, 0.88, and 0.88 for $\omega\pi^0$, $K^*(892)\bar{K}$,

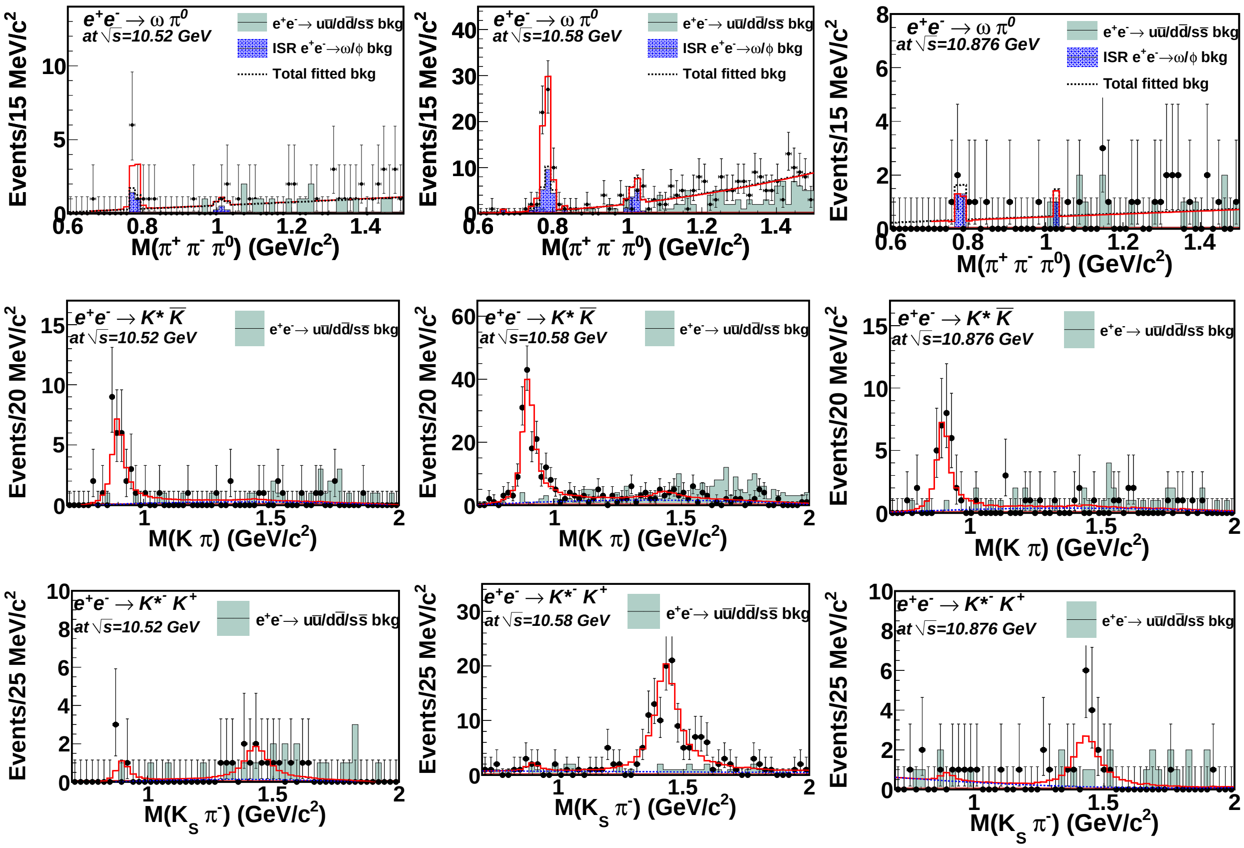

FIG. 3: The fits to the $\pi^+\pi^-\pi^0$ (top row), $K^+\pi^-$ (middle row) and $K^0_S\pi^-$ (bottom row) invariant mass distributions for the ω, $K^*(892)$, and $K^*_2(1430)$ meson candidates from $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ and $K^0_S K^+\pi^-$ events from the $\sqrt{s}$ = 10.52 GeV, 10.58 GeV, and 10.876 GeV data samples. The solid lines show the results of the fits described in the text, the dotted curves show the total background estimates, the dark shaded histograms are from the normalized ISR backgrounds $e^+e^- \to \gamma_{\rm ISR}\omega/\phi \to \gamma_{\rm ISR}\pi^+\pi^-\pi^0$ and the light shaded histograms are from the normalized $e^+e^- \to u\bar{u}/d\bar{d}/s\bar{s}$ backgrounds. The dotted curves are not significantly seen in the signal regions due to low background level.

and $K^*_2(1430)\bar{K}$, respectively, calculated with a limit on the energy of the radiated photon of 0.5 GeV [12]; the values of $|1-\Pi(s)|^2$ are 0.931, 0.930, and 0.929 [21] for $\sqrt{s}$ = 10.52 GeV, 10.58 GeV and 10.876 GeV, respectively.

There are several sources of systematic uncertainties for the cross section measurements. The uncertainty in the tracking efficiency for tracks with angles and momenta characteristic of signal events is about 0.35% per track and is additive. The uncertainty due to particle identification efficiency is 1.7% with an efficiency correction factor of 0.98 for each pion

TABLE I: Results for the Born cross sections, where $N_{\rm sig}$ is the number of fitted signal events, $N_{\rm sig}^{\rm UL}$ is the upper limit on the number of signal events, ϵ is the efficiency, Σ is the signal significance, σ_B is the Born cross section, $\sigma_B^{\rm UL}$ is the upper limit on the Born cross section. All the upper limits are given at the 90% C.L. The first uncertainty in σ_B is statistical, and the second systematic.

Channel	$\sqrt{s}$ (GeV)	$N_{\rm sig}$	$N_{\rm sig}^{\rm UL}$	ϵ (%)	Σ (σ)	σ_B (fb)	$\sigma_B^{\rm UL}$ (fb)
$\omega\pi^0$	10.52	$4.1^{+3.3}_{-2.6}$	9.9	1.25	1.6	$4.53^{+3.64}_{-2.88}\pm 0.50$	11
	10.58	$38.8^{+8.3}_{-7.6}$	—	1.10	6.7	$6.01^{+1.29}_{-1.18}\pm 0.57$	—
	10.876	$-0.7^{+2.9}_{-2.1}$	7.0	1.07	—	$-0.68^{+2.71}_{-1.97}\pm 0.20$	6.5
$K^*(892)^0\bar{K}^0$	10.52	$34.6^{+6.9}_{-6.1}$	—	16.49	7.4	$10.77^{+2.15}_{-1.90}\pm 0.77$	—
	10.58	187 ± 17	—	16.30	>10	$7.48\pm 0.67\pm 0.51$	—
	10.876	$34.6^{+7.5}_{-6.7}$	—	17.25	7.2	$7.58^{+1.64}_{-1.47}\pm 0.63$	—
$K^*(892)^-K^+$	10.52	$4.6^{+3.6}_{-2.7}$	9.3	20.40	1.4	$1.14^{+0.90}_{-0.67}\pm 0.15$	2.3
	10.58	$5.9^{+4.7}_{-3.8}$	14	21.03	1.5	$0.18^{+0.14}_{-0.12}\pm 0.02$	0.4
	10.876	$1.6^{+3.9}_{-3.0}$	8.5	21.29	0.3	$0.28^{+0.68}_{-0.52}\pm 0.10$	1.5
$K_2^*(1430)^0\bar{K}^0$	10.52	$1.3^{+4.3}_{-3.9}$	6.8	17.63	0.3	$0.76^{+2.53}_{-2.26}\pm 0.14$	4.0
	10.58	21^{+11}_{-10}	40	16.71	2.1	$1.65^{+0.86}_{-0.78}\pm 0.27$	3.1
	10.876	$1.0^{+4.5}_{-3.7}$	8.9	19.02	0.2	$0.38^{+1.79}_{-1.47}\pm 0.07$	3.5
$K_2^*(1430)^-K^+$	10.52	$12.0^{+6.2}_{-5.8}$	21	20.36	2.1	$6.06^{+3.13}_{-2.93}\pm 1.34$	11
	10.58	129 ± 15	—	20.17	>10	$8.36\pm 0.95\pm 0.62$	—
	10.876	$17.6^{+5.3}_{-4.6}$	—	21.50	4.5	$6.20^{+1.86}_{-1.63}\pm 0.64$	—

and is 1.6% with an efficiency correction factor 0.97 for each kaon. The uncertainty in selecting π^0 is estimated using a control sample of $\tau^-\to\pi^-\pi^0\nu_\tau$. We introduce a 2.2% systematic uncertainty with efficiency correction factors of 0.94 for a low momentum π^0 and 0.97 for a high momentum one. In the $K_S^0K^+\pi^-$ mode, the K_S^0 reconstruction systematic uncertainty is estimated by comparing the ratio of the $D^+\to K_S^0\pi^+$ and $D^+\to K^-\pi^+\pi^+$ yields with the MC expectations; the difference between data and MC simulation is less than 4.9% [22]. Uncertainties on the branching fractions of the intermediate states are taken from the PDG listings [23]. According to MC simulation, the trigger efficiency is greater than 99% so the corresponding uncertainty is neglected. We estimate the systematic uncertainties associated with the fitting procedure by changing the shape of the background and the range of the fit and taking the differences in the fitted results, which are 1.0%-32% depending on the final state particles, as systematic uncertainties. The uncertainty due to limited MC statistics is at most 2.4%. The form factor dependence on s is assumed to be $\frac{1}{s}$ in the MCGPJ generator for the nominal results. The differences in the efficiency compared to the assumption of $\frac{1}{s^2}$ dependence for the form factor are taken as the systematic uncertainties due to the generator uncertainty, which are 1.5%, 0.9%, and 0.9% for the $\omega\pi^0$, $K^*(892)\bar{K}$, and $K_2^*(1430)\bar{K}$, respectively. We take 2% systematic uncertainty due to the uncertainty of the effect of soft and virtual photon emission in the generator [12]. The efficiency differences are 0.7% and 1.3% for $\omega\pi^0$ and $K_S^0 K^+\pi^-$ final states, respectively, when including or excluding final state radiation [24]; these are included into the uncertainty of the generator. Finally, the total luminosity is determined using wide angle Bhabha events with 1.4% precision. Assuming that all of these systematic uncertainty sources are independent, the total systematic uncertainty is 6.8%-33%, depending on the final state, as shown in Table II.

TABLE II: Relative systematic uncertainties (%) on the cross section. For the fit uncertainty and the total systematic uncertainty, the three values separated by slashes are for the CM energies 10.52 GeV, 10.58 GeV, and 10.876 GeV, respectively.

Source	$\omega\pi^0$	$K^*(892)^0\bar{K}^0$	$K^*(892)^-K^+$	$K_2^*(1430)^0\bar{K}^0$	$K_2^*(1430)^-K^+$
Tracking	0.7	0.7	0.7	0.7	0.7
PID	3.4	3.3	3.3	3.3	3.3
π^0 selection	4.4	—	—	—	—
K_S^0 selection	—	4.9	4.9	4.9	4.9
Branching fractions	0.8	0.1	0.1	2.4	2.4
Fit uncertainty	8.8/6.6/28	2.4/1.0/4.9	11/8.2/32	16/14/15	21/2.2/7.4
MC statistics	2.4	0.8	0.8	0.7	0.7
Generator	2.6	2.6	2.6	2.6	2.6
Luminosity	1.4	1.4	1.4	1.4	1.4
Sum in quadrature	11/9.5/29	7.1/6.8/8.3	13/11/33	18/16/17	22/7.4/11

Table I shows the results for the measured Born cross sections including the upper limits at 90% C.L. for the channels with a signal significance of less than 3σ. These are the first measurements of the cross sections and upper limits at CM energies 10.52 GeV, 10.58 GeV, and 10.876 GeV. The measured cross sections of $e^+e^- \to \omega\pi^0$ and $K^*(892)^0\bar{K}^0$ at $\sqrt{s}$ = 10.58 GeV are consistent within errors with the theoretical predictions that range from $(4.1^{+0.5}_{-0.3})$ fb to $(5.2^{+0.4}_{-0.3})$ fb for $\omega\pi^0$ and from $(5.6^{+0.2}_{-0.4})$ fb to (7.1 ± 0.4) fb for $K^*(892)^0\bar{K}^0$ in Ref. [4]. In contrast, we do not observe a significant signal for $e^+e^- \to K^*(892)^-K^+$ and the upper limit of the cross section at 10.58 GeV is much lower than the prediction from the same calculation [4]. The measured cross section of $e^+e^- \to \omega\pi^0$ is much smaller than the calculated value of about 240 fb using the theoretical formulae in Ref. [5].

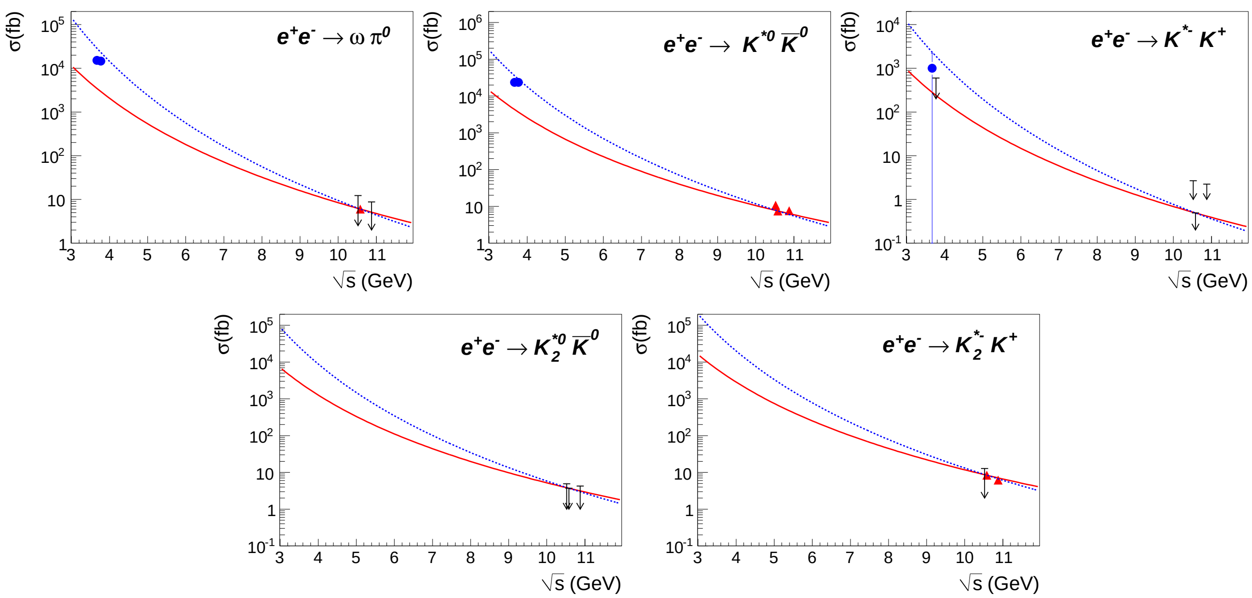

FIG. 4: The cross sections for $e^+e^- \to \omega\pi^0$, $K^*(892)\bar{K}$, and $K_2^*(1430)\bar{K}$. The data at $\sqrt{s} = 10.52$ GeV, 10.58 GeV, and 10.876 GeV are from our measurements. The data at $\sqrt{s} = 3.67$ GeV and 3.77 GeV, where shown, are from CLEO measurement [2]. Here, the uncertainties are the sum of the statistical and systematic uncertainties in quadrature. Upper limits are shown by the arrows. The solid line corresponds to a $1/s^3$ dependence and the dashed line to a $1/s^4$ dependence; the curves pass through the measured cross section at $\sqrt{s} = 10.58$ GeV.

Figure 4 shows the cross sections measured in our experiment at $\sqrt{s} = 10.52$ GeV, 10.58 GeV, and 10.876 GeV for $e^+e^- \to \omega\pi^0$, $K^*(892)\bar{K}$ and $K_2^*(1430)\bar{K}$, where the uncertainties are the sum in quadrature of the statistical and systematic uncertainties. Since the signal significance is greater than 5σ for $e^+e^- \to K^*(892)^0\bar{K}^0$ at all energies and for $e^+e^- \to \omega\pi^0$ at

$\sqrt{s} = 10.58$ GeV, we fit the $1/s^n$ dependence of the cross sections to our data and those from CLEO at $\sqrt{s} = 3.67$ GeV and 3.77 GeV [2]. The fit gives $n = 3.83 \pm 0.07$ and 3.75 ± 0.12 for $e^+e^- \to K^*(892)^0\bar{K}^0$ and $\omega\pi^0$ [25], respectively. These differ significantly from the $1/s^2$ [5] or $1/s^3$ [4] predictions and agree with $1/s^4$ [6–8] within 2.5σ. For other channels, no definite conclusion can be drawn from current results due to the large uncertainties.

In all the above discussions, we neglect possible small contributions from $\Upsilon(4S)$ and $\Upsilon(5S)$ resonance decays in the measured Born cross sections at $\sqrt{s} = 10.58$ GeV and 10.876 GeV. Since the signal significance exceeds 5σ for the $K^*(892)^0\bar{K}^0$ mode at the continuum energy $\sqrt{s} = 10.52$ GeV, we can estimate the continuum contributions at $\sqrt{s} = 10.58$ GeV and 10.876 GeV under the assumption that the continuum cross section varies as $1/s^4$. After subtracting the continuum contributions, the net contribution to the cross sections from $\Upsilon(4S)$ and $\Upsilon(5S)$ decays is determined to be (-4.5 ± 3.7) fb and (-0.8 ± 3.1) fb, respectively. Here, the errors are statistical and systematic combined and the common systematic errors are counted once. The efficiencies and the radiative correction factors are reevaluated assuming the events are from $\Upsilon(4S)$ or $\Upsilon(5S)$ decays, and possible interference between the continuum and resonant amplitudes is neglected. The total production cross sections of $\Upsilon(4S)$ and $\Upsilon(5S)$ are (2.06 ± 0.11) nb and (0.70 ± 0.39) nb, calculated with the world average values of their masses and partial widths to electron pairs [23]. By generating toy MC samples, assuming both the $K^*(892)^0\bar{K}^0$ and the total production cross sections follow Gaussian distributions (the mean values and standard deviations being set to the central values and corresponding errors of the cross sections, respectively), we obtain the distribution of the ratio of the two cross sections, from which the decay branching fraction upper limits $\mathcal{B}(\Upsilon(4S) \to K^*(892)^0\bar{K}^0) < 2.0 \times 10^{-6}$ and $\mathcal{B}(\Upsilon(5S) \to K^*(892)^0\bar{K}^0) < 1.0 \times 10^{-5}$ at 90% C.L. are determined. These results indicate that the contributions from $\Upsilon(4S)$ and $\Upsilon(5S)$ resonance decays are insignificant.

Based on the likelihood curves of the cross section measurements, in which the relevant systematic uncertainties are convolved, we obtain:

$$R_{\mathrm{VP}} = \frac{\sigma_B(e^+e^- \to K^*(892)^0\bar{K}^0)}{\sigma_B(e^+e^- \to K^*(892)^-K^+)} > 4.3, \;\; 20.0, \;\; 5.4,$$

and

$$R_{\mathrm{TP}} = \frac{\sigma_B(e^+e^- \to K_2^*(1430)^0\bar{K}^0)}{\sigma_B(e^+e^- \to K_2^*(1430)^-K^+)} < 1.1, \;\; 0.4, \;\; 0.6,$$

for $\sqrt{s} = 10.52$ GeV, 10.58 GeV, and 10.876 GeV, respectively, at the 90% C.L. Assuming the cross section dependence on s is $1/s^n$ ($n = 3.83$) from our measurement of $K^*(892)^0\bar{K}^0$ and that this assumption is applicable to all the final states, we obtain the weighted average of the cross sections at a luminosity-weighted energy point of 10.61 GeV, which are $(7.86^{+0.72}_{-0.71})$ fb, $(0.54^{+0.13}_{-0.12})$ fb, $(1.36^{+0.77}_{-0.69})$ fb and $(7.81^{+0.96}_{-0.93})$ fb for $K^*(892)^0\bar{K}^0$, $K^*(892)^-K^+$, $K_2^*(1430)^0\bar{K}^0$ and $K_2^*(1430)^-K^+$, respectively. For $K_2^*(1430)^0\bar{K}^0$ and $K_2^*(1430)^-K^+$, based on the above weighted average of the cross sections at $\sqrt{s} = 10.61$ GeV and the assumption of the cross section dependence on s, we obtain $(3.8^{+2.1}_{-1.9})$ pb and $(21.6^{+2.7}_{-2.6})$ pb at $\sqrt{s} = 3.77$ GeV. The uncertainties are the sum in quadrature of the statistical and systematic uncertainties. We obtain the averaged ratios as $\bar{R}_{\rm VP} > 10.9$ and $\bar{R}_{\rm TP} < 0.3$ at the 90% C.L. Here, for the calculated ratios, the common systematic uncertainties cancel.

For $K^*(892)\bar{K}$, the ratio of the cross sections of $K^*(892)^0\bar{K}^0$ and $K^*(892)^-K^+$ at $\sqrt{s} =$ 10.58 GeV is much larger than the predictions from exact or broken SU(3) symmetry models. Conversely, for $K_2^*(1430)\bar{K}$, the ratio of the cross sections of $K_2^*(1430)^0\bar{K}^0$ and $K_2^*(1430)^-K^+$ is much smaller than the prediction from the SU(3) symmetry or with the SU(3) symmetry breaking effects considered.

In a naive quark model developed to explain the transition-rate difference between $K_2^*(1430)^0 \to K^0\gamma$ and $K_2^*(1430)^+ \to K^+\gamma$ [26], one obtains $R_{\rm TP} \ll 1$ by assuming the model can be extended to a time-like virtual-photon case; this extrapolation is justified since the same model predicted the ratio of $\frac{\Gamma(K_2^*(1430)^0 \to K^0\gamma)}{\Gamma(K_2^*(1430)^+ \to K^+\gamma)} = 0.054$, in rough agreement with the experimental measurement [26]. In the same model, however, the radiative transitions between $K^*(892)$ and K were also calculated, and a ratio $\frac{\Gamma(K^*(892)^0 \to K^0\gamma)}{\Gamma(K^*(892)^+ \to K^+\gamma)} = 1.7$ was obtained, which is very different from the measurements of $R_{\rm VP}$ from both this and CLEO [2] experiments.

In summary, we have measured for the first time the cross sections for the reactions $e^+e^- \to \omega\pi^0$, $K^*(892)\bar{K}$, and $K_2^*(1430)\bar{K}$ at CM energies between 10 and 11 GeV. The results are summarized in Table I. Significant signals of $\omega\pi^0$, $K^*(892)^0\bar{K}^0$, and $K_2^*(1430)^-K^+$ are observed, while no significant excess for $K^*(892)^-K^+$ and $K_2^*(1430)^0\bar{K}^0$ is found. The ratios $R_{\rm VP}$ and $R_{\rm TP}$ at the 90% C.L. are given.

We thank the KEKB group for excellent operation of the accelerator; the KEK cryogenics group for efficient solenoid operations; and the KEK computer group, the NII, and PNNL/EMSL for valuable computing and SINET4 network support. We acknowledge support from MEXT, JSPS and Nagoya's TLPRC (Japan); ARC and DIISR (Australia); FWF

(Austria); NSFC (China); MSMT (Czechia); CZF, DFG, and VS (Germany); DST (India); INFN (Italy); MEST, NRF, GSDC of KISTI, and WCU (Korea); MNiSW and NCN (Poland); MES and RFAAE (Russia); ARRS (Slovenia); IKERBASQUE and UPV/EHU (Spain); SNSF (Switzerland); NSC and MOE (Taiwan); and DOE and NSF (USA).

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