

Evidence for a New Resonance and Search for the  $Y(4140)$  in the  $\gamma\gamma \rightarrow \phi J/\psi$  Process

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The process  $\gamma\gamma \rightarrow \phi J/\psi$  is measured using a data sample of  $825 \text{ fb}^{-1}$  collected with the Belle detector. A narrow peak of  $8.8_{-3.2}^{+4.2}$  events, with a significance of 3.2 standard deviations including systematic uncertainty, is observed. The mass and natural width of the structure [named  $X(4350)$ ] are measured to be  $[4350.6_{-5.1}^{+4.6}(\text{stat}) \pm 0.7(\text{syst})] \text{ MeV}/c^2$  and  $[13_{-9}^{+18}(\text{stat}) \pm 4(\text{syst})] \text{ MeV}$ , respectively. The product of its two-photon decay width and branching fraction to  $\phi J/\psi$  is  $[6.7_{-2.4}^{+3.2}(\text{stat}) \pm 1.1(\text{syst})] \text{ eV}$  for  $J^P = 0^+$ , or  $[1.5_{-0.6}^{+0.7}(\text{stat}) \pm 0.3(\text{syst})] \text{ eV}$  for  $J^P = 2^+$ . No signal for the  $Y(4140) \rightarrow \phi J/\psi$  structure reported by the CDF Collaboration in  $B \rightarrow K^+ \phi J/\psi$  decays is observed, and limits of  $\Gamma_{\gamma\gamma}(Y(4140))\mathcal{B}(Y(4140) \rightarrow \phi J/\psi) < 41 \text{ eV}$  for  $J^P = 0^+$  or  $< 6.0 \text{ eV}$  for  $J^P = 2^+$  are determined at the 90% C.L. This disfavors the scenario in which the  $Y(4140)$  is a  $D_s^{*+} D_s^{*-}$  molecule.

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In recent years, many new charmonia or charmonium-like states have been discovered. These states are not easily accommodated in the quark-model picture of hadrons [1]. In this Letter, we report the first investigation of the  $\phi J/\psi$  system produced in the two-photon process  $\gamma\gamma \rightarrow \phi J/\psi$  with the  $J/\psi$  decaying into lepton pairs and  $\phi \rightarrow K^+ K^-$ , to search for high mass states with  $J^{PC} = 0^{++}$  or  $2^{++}$ , such as the tetraquark states and molecular states that are predicted by various models [2–4]. We find an unexpected structure in  $\phi J/\psi$  mass near  $4350 \text{ MeV}/c^2$ .

In a related study of  $B^+ \rightarrow K^+ \phi J/\psi$  decays, the CDF Collaboration reported evidence of a state called  $Y(4140)$  with mass and width values of  $M = [4143.0 \pm 2.9(\text{stat}) \pm 1.2(\text{syst})] \text{ MeV}/c^2$  and  $\Gamma = [11.7_{-5.0}^{+8.3}(\text{stat}) \pm 3.7(\text{syst})] \text{ MeV}$  [5]. The Belle Collaboration searched for the  $Y(4140)$  using the same  $B$  mode with a sample of  $772 \times 10^6 B\bar{B}$  pairs [6]. No significant signal was found although the upper limit on the production rate does not contradict the CDF measurement.

There have been a number of different interpretations proposed for the  $Y(4140)$ , including a  $D_s^{*+} D_s^{*-}$  molecule [2,7–13], an exotic  $1^{-+}$  charmonium hybrid [9], a  $c\bar{c}s\bar{s}$  tetraquark state [3], or a natural consequence of the opening of the  $\phi J/\psi$  channel [14]. There are arguments against the interpretation of the  $Y(4140)$  as a conventional charmonium state, such as the  $\chi''_{c0}$  or  $\chi''_{c1}$  [15], or a scalar  $D_s^{*+} D_s^{*-}$  molecule since QCD sum rules [16,17] predict masses that are inconsistent with the observed value. Assuming that the  $Y(4140)$  is a  $D_s^{*+} D_s^{*-}$  molecule with quantum numbers  $J^{PC} = 0^{++}$  or  $2^{++}$ , Ref. [2] predicts its two-photon width to be of order 1 keV, which can be tested experimentally at Belle.

This analysis of  $\gamma\gamma \rightarrow \phi J/\psi$  is based on a  $825 \text{ fb}^{-1}$  data sample collected with the Belle detector [18] operat-

ing at the KEKB asymmetric-energy  $e^+e^-$  collider [19]. About 90% of the data were collected at the  $Y(nS)$  ( $n = 1, 3, 4, 5$ ) resonances, and about 10% were taken at a center-of-mass (c.m.) energy that is 60 MeV below the  $Y(4S)$  peak.

The detector is described in detail elsewhere [18]. 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  $K_L^0$  mesons and to identify muons (KLM).

We use the program TREPS [20] to generate signal Monte Carlo (MC) events. In this generator, the two-photon luminosity function is calculated, and simulated events are generated at a specified fixed  $\gamma\gamma$  c.m. energy ( $W_{\gamma\gamma}$ ) using the equivalent photon approximation [21]. The efficiency for detecting  $\gamma\gamma \rightarrow X \rightarrow \phi J/\psi \rightarrow K^+ K^- \ell^+ \ell^-$  ( $\ell = e, \mu$ ) is determined by assuming  $J^P = 0^+$  or  $2^+$  and a zero intrinsic width for the  $X$ .

We require four reconstructed charged tracks with zero net charge. For these tracks, the impact parameters perpendicular to and along the beam direction with respect to the interaction point are required to be less than 0.5 and 4 cm, respectively, and the transverse momentum in the laboratory frame is restricted to be higher than 0.1 GeV/c. For each charged track, information from different detector subsystems is combined to form a likelihood  $\mathcal{L}_i$  for each particle species [22]. Tracks with  $\mathcal{R}_K = \frac{\mathcal{L}_K}{\mathcal{L}_K + \mathcal{L}_\pi} > 0.6$  are identified as kaons with an efficiency of about 97% for the

tracks of interest; about 0.4% are misidentified  $\pi$  tracks [22]. 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 nonelectron, respectively, determined using the ratio of the energy deposit in the ECL to the momentum measured in the SVD and CDC, the shower shape in the ECL, the matching between the position of charged track trajectory and the cluster position in the ECL, the hit information from the ACC, and the  $dE/dx$  information in the CDC [23]. 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 hypotheses, respectively, based on the matching quality and penetration depth of associated hits in the KLM [24]. For electrons (muons) from  $J/\psi$  decay, both of the tracks should have  $\mathcal{R}_e(\mathcal{R}_\mu) > 0.1$ . The lepton ID efficiency is about 99% for  $J/\psi \rightarrow e^+e^-$  and 90% for  $J/\psi \rightarrow \mu^+\mu^-$ . There are a few background events due to photon conversions with the conversion leptons misidentified as kaon candidates in the  $e^+e^-$  mode; these are removed by requiring  $\mathcal{R}_e < 0.75$  for the kaon candidates.

The magnitude of the vector sum of the four tracks' transverse momenta in the c.m. frame,  $|\sum \vec{P}_t^*|$ , which approximates the transverse momentum of the two-photon-collision system, is required to be less than 0.2 GeV/c in order to reduce backgrounds from non-two-photon processes and two-photon processes with extra particles other than  $\phi$  and  $J/\psi$  in the final states. Figure 1 shows the  $|\sum \vec{P}_t^*|$  distributions from the data and a MC signal simulation before the  $|\sum \vec{P}_t^*|$  requirement. Here, the  $K^+K^-$  and  $\ell^+\ell^-$  invariant masses are required to be within the  $\phi$  and  $J/\psi$  signal regions, respectively.

A scatter plot of  $M(\ell^+\ell^-)$  versus  $M(K^+K^-)$  for the selected  $K^+K^-\ell^+\ell^-$  events is shown in Fig. 2, where we can see clear  $J/\psi$  and  $\phi$  signals. A partial correction for final-state radiation and bremsstrahlung energy loss is performed by including the four-momentum of every photon detected within a 50 mrad cone around the electron and positron direction in the  $e^+e^-$  invariant mass calculation. We define a  $J/\psi$  signal region as  $3.077 \text{ GeV}/c^2 < m_{\ell^+\ell^-} < 3.117 \text{ GeV}/c^2$  (the mass resolution is about  $10 \text{ MeV}/c^2$ ), and  $J/\psi$  mass sidebands as  $3.0 \text{ GeV}/c^2 < m_{\ell^+\ell^-} < 3.06 \text{ GeV}/c^2$  or  $3.14 \text{ GeV}/c^2 < m_{\ell^+\ell^-} < 3.20 \text{ GeV}/c^2$ . We also define a  $\phi$  signal region as  $1.01 \text{ GeV}/c^2 < m_{K^+K^-} < 1.03 \text{ GeV}/c^2$  [the full width at half maximum (FWHM) of the  $\phi$  signal is  $5.9 \text{ MeV}/c^2$ ], and  $\phi$  mass sidebands as  $1.00 \text{ GeV}/c^2 < m_{K^+K^-} < 1.01 \text{ GeV}/c^2$  or  $1.03 \text{ GeV}/c^2 < m_{K^+K^-} < 1.08 \text{ GeV}/c^2$ .

Figure 3 shows the  $\phi J/\psi$  invariant mass distribution [25], together with the background estimated from the normalized  $J/\psi$  and  $\phi$  mass sidebands. No  $Y(4140)$  signal is evident. Assuming that there is no background within the  $Y(4140)$  mass region and the number of signal events follows a Poisson distribution with a uniform prior probability density function, a Bayesian upper limit on the

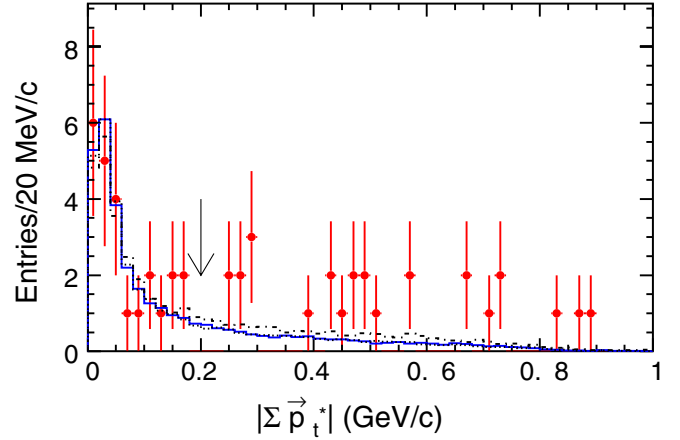


FIG. 1 (color online). The magnitude of the vector sum of  $\phi J/\psi$  transverse momenta with respect to the beam direction in the  $e^+e^-$  c.m. frame for the selected  $\phi J/\psi$  events. Points with error bars are data. The dot-dashed, solid, and dotted histograms are MC simulations for  $\gamma\gamma \rightarrow \phi J/\psi$  with the  $\phi J/\psi$  mass fixed at 4.20, 4.35, and 4.50  $\text{GeV}/c^2$ , respectively (normalized to the number of events with  $|\sum \vec{P}_t^*| < 0.2 \text{ GeV}/c$ ). The arrow shows the position of the  $|\sum \vec{P}_t^*|$  requirement.

number of the  $Y(4140)$  signal events is estimated to be 2.3 at the 90% C.L. [26]. However, there is a clear enhancement at 4.35  $\text{GeV}/c^2$ , where the background level estimated from the normalized  $J/\psi$  and  $\phi$  mass sidebands is very low. Other possible backgrounds that are not included in the sidebands, such as  $\gamma\gamma \rightarrow \phi J/\psi + X$  and  $e^+e^- \rightarrow \phi J/\psi + X$  where  $X$  may indicate one or more particles, and  $\gamma\gamma \rightarrow \phi J/\psi$  with the  $J/\psi$  and  $\phi$  decaying into final states other than lepton pairs and  $K^+K^-$ , are found to be very small after applying all of the event selection criteria.

In order to obtain resonance parameters for the structure at 4.35  $\text{GeV}/c^2$ , an unbinned extended maximum likelihood method is applied to the  $\phi J/\psi$  mass spectrum in Fig. 3. The distribution is fitted in the range 4.2 to 5.0  $\text{GeV}/c^2$  with an acceptance-corrected Breit-Wigner (BW) function convoluted with a double Gaussian resolu-

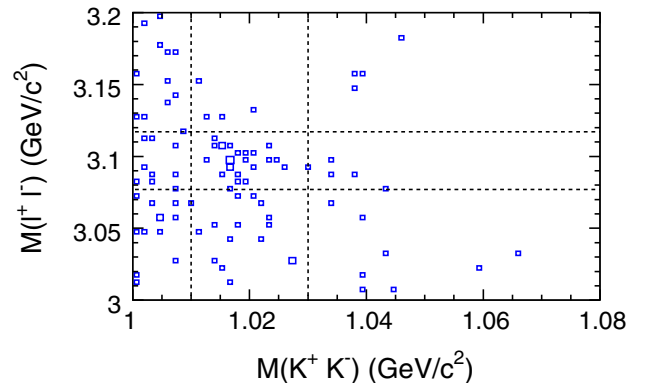


FIG. 2 (color online). A scatter plot of  $M(\ell^+\ell^-)$  versus  $M(K^+K^-)$  for the selected  $K^+K^-\ell^+\ell^-$  events. The size of the boxes is proportional to the number of events.

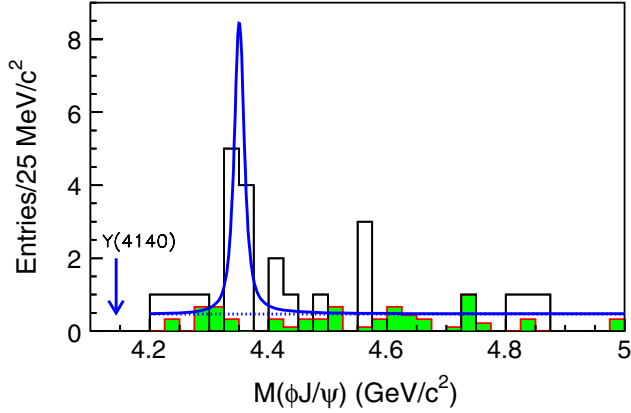


FIG. 3 (color online). The  $\phi J/\psi$  invariant mass distribution of the final candidate events. The open histogram shows the experimental data. The fit to the  $\phi J/\psi$  invariant mass distribution from 4.2 to 5.0  $\text{GeV}/c^2$  is described in the text. The solid curve is the best fit, the dashed curve is the background, and the shaded histogram is from normalized  $\phi$  and  $J/\psi$  mass sidebands. The arrow shows the expected position of the  $Y(4140)$ .

tion function as the signal shape and a constant term as the background shape. The shape of the double Gaussian resolution function is obtained from MC simulation.

From the fit, we obtain  $8.8^{+4.2}_{-3.2}$  signal events, with a mass  $m = (4350.6^{+4.6}_{-5.1}) \text{ MeV}/c^2$  and a width  $\Gamma = (13^{+18}_-9) \text{ MeV}$ . The statistical significance of this structure is estimated to be  $3.9\sigma$ , from the difference of the logarithmic likelihoods,  $-2\ln(L_0/L_{\max}) = 21$ , taking the difference in the number of degrees of freedom ( $\Delta\text{ndf} = 3$ ) in the fits into account, where  $L_0$  and  $L_{\max}$  are the likelihoods of the fits with and without a resonance component, respectively. In the following, we refer to it as the  $X(4350)$ . The significance of the signal decreases to  $3.2\sigma$  if a linear function is used to model the background shape in the fit.

We use an ensemble of simulated experiments to estimate the probability that background fluctuations alone would produce signals as significant as that seen in the data. We generate  $\phi J/\psi$  mass spectra based on a uniform distribution alone with 24 events, the same as observed in data, and search for the most significant fluctuation in each spectrum in the mass range from 4.2 to 5.0  $\text{GeV}/c^2$ , with widths in a range between 3 MeV (half of the resolution) and 130 MeV (10 times the observed width). From these spectra, we obtain the distribution for  $-2\ln(L_0/L_{\max})$  in pure background samples, and compare it with the signal in the data. We performed a total of  $0.5 \times 10^6$  simulations and found 65 trials with a  $-2\ln(L_0/L_{\max})$  value greater than or equal to the value obtained in the data. The resulting  $p$  value is  $1.3 \times 10^{-4}$ , corresponding to a significance of  $3.8\sigma$ . Generating events in a wider  $\phi J/\psi$  mass range, or fitting with different width range, would change the resulting significance, but the dependence is weak for a signal as narrow as the  $X(4350)$ .

The product of the two-photon decay width and branching fraction is obtained using the formula:  $\Gamma_{\gamma\gamma}(R)\mathcal{B}(R \rightarrow$

final state) =  $N/[(2J+1)\epsilon\mathcal{K}\mathcal{L}_{\text{int}}]$ , where  $N$  is the number of observed events,  $\epsilon$  is the efficiency,  $J$  is the spin of the resonance, and  $\mathcal{L}_{\text{int}}$  is the integrated luminosity.  $\mathcal{K}$  is a factor that is calculated from the two-photon luminosity function  $\mathcal{L}_{\gamma\gamma}(M_R)$  for a resonance with mass  $M_R$  using the relation:  $\mathcal{K} = 4\pi^2\mathcal{L}_{\gamma\gamma}(M_R)/M_R^2$ , which is valid when the resonance width is small compared to its mass [widths are smaller than 1% of the masses in the  $Y(4140)$  and  $X(4350)$  cases]. The  $\mathcal{K}$  parameter is calculated to be 0.46 fb/eV and 0.36 fb/eV for the  $Y(4140)$  and the  $X(4350)$ , respectively, using TREPS [20]. The efficiencies are 0.30% and 0.41% for  $J^P = 0^+$  and  $2^+$ , respectively, at 4.143  $\text{GeV}/c^2$ , and 7.90% and 6.98% for  $J^P = 0^+$  and  $2^+$ , respectively, at 4.35  $\text{GeV}/c^2$ . From the above values, we obtain  $\Gamma_{\gamma\gamma}(Y(4140))\mathcal{B}[Y(4140) \rightarrow \phi J/\psi] < 36 \text{ eV}$  for  $J^P = 0^+$ , or  $< 5.3 \text{ eV}$  for  $J^P = 2^+$ , at the 90% C.L., and  $\Gamma_{\gamma\gamma}(X(4350))\mathcal{B}[X(4350) \rightarrow \phi J/\psi] = (6.7^{+3.2}_{-2.4}) \text{ eV}$  for  $J^P = 0^+$ , or  $(1.5^{+0.7}_{-0.6}) \text{ eV}$  for  $J^P = 2^+$ , where the errors are statistical only.

There are several sources of systematic errors for the measurements of the products of the two-photon decay width and branching fractions. The particle identification uncertainties are 1.2%/kaon and 0.8%/lepton. The uncertainty in the tracking efficiency for tracks from  $J/\psi$  decays is 1% per track, while that for kaon tracks from  $\phi$  decays range from 2.4% to 1% per track as the average transverse momentum increases from 0.15 to 0.3  $\text{GeV}/c$ . The efficiency uncertainties associated with the  $J/\psi$  and  $\phi$  mass requirements are determined from the studies of the very pure  $e^+e^- \rightarrow \psi' \rightarrow \pi^+\pi^- J/\psi$  [27] and  $e^+e^- \rightarrow \phi\pi^+\pi^-$  [28] event samples. The detection efficiencies for  $J/\psi$  and  $\phi$  mesons are lower than those inferred from the MC simulations by  $(2.5 \pm 0.4)\%$  and  $(2.0 \pm 0.5)\%$  relatively, respectively. We take 0.96 as the efficiency correction factor, and 0.7% is included in the systematic error due to the  $J/\psi$  and  $\phi$  mass requirements. The statistical errors in the MC samples are 2.3% and 0.9% for  $Y(4140) \rightarrow \phi J/\psi$  and  $X(4350) \rightarrow \phi J/\psi$ , respectively. The accuracy of the two-photon luminosity function calculated by the TREPS generator is estimated to be about 5% including the error from neglecting radiative corrections (2%), the uncertainty from the form factor effect (2%), and the uncertainty in the total integrated luminosity (1.4%) [20]. The trigger efficiency for four charged track events is rather high because of the redundancy of the Belle first level multitrack trigger. According to the MC simulation, the trigger and preselection efficiency for the final state has little dependence on the  $\phi J/\psi$  invariant mass, with an uncertainty that is smaller than 5%. From Ref. [26], the uncertainty in the world average values for  $\mathcal{B}(\phi \rightarrow K^+K^-)$  is 1.2%, and that for  $\mathcal{B}(J/\psi \rightarrow \ell^+\ell^-) = \mathcal{B}(J/\psi \rightarrow e^+e^-) + \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)$  is 1% where we have added the errors of the  $e^+e^-$  and  $\mu^+\mu^-$  modes linearly. The uncertainty in the yield of  $X(4350)$  signal events due to the  $\phi J/\psi$  mass spectrum fit is estimated to be 15% by varying the order of the back-

ground polynomial (14%), resonance parameterization (0.5%), and the  $\phi J/\psi$  mass resolution (0.9%). Assuming that all the sources are independent and adding all uncertainties in quadrature, we obtain the total systematic errors on  $\Gamma_{\gamma\gamma}(Y(4140))\mathcal{B}(Y(4140) \rightarrow \phi J/\psi)$  and  $\Gamma_{\gamma\gamma}(X(4350))\mathcal{B}(X(4350) \rightarrow \phi J/\psi)$  to be 12% and 17%, respectively.

For the systematic errors in the  $X(4350)$  mass and width, the uncertainties in the mass resolution (0.1 MeV/ $c^2$  and 0.9 MeV), the parameterization of the resonance (0 MeV/ $c^2$  and 0.3 MeV), and the background shape (0.7 MeV/ $c^2$  and 3.9 MeV) are considered. Assuming that all the sources are independent and adding them in quadrature, we obtain the total systematic errors on the  $X(4350)$  mass and width to be 0.7 MeV/ $c^2$  and 4.1 MeV, respectively.

In summary, we report results of the first search for  $Y(4140) \rightarrow \phi J/\psi$  in the two-photon process  $\gamma\gamma \rightarrow \phi J/\psi$ . No  $Y(4140)$  signal is observed, and upper limits on the product of the two-photon decay width and branching fraction of  $Y(4140) \rightarrow \phi J/\psi$  are established to be  $\Gamma_{\gamma\gamma}(Y(4140))\mathcal{B}(Y(4140) \rightarrow \phi J/\psi) < 41$  eV for  $J^P = 0^+$ , or  $< 6.0$  eV for  $J^P = 2^+$  at the 90% C.L. In the determination of the  $\Gamma_{\gamma\gamma}(Y(4140))\mathcal{B}(Y(4140) \rightarrow \phi J/\psi)$  upper limits, the efficiencies have been lowered by a factor of  $1 - \sigma_{\text{sys}}$  to obtain a conservative estimate, where  $\sigma_{\text{sys}}$  is the total relative systematic error. The upper limit on  $\Gamma_{\gamma\gamma}(Y(4140))\mathcal{B}(Y(4140) \rightarrow \phi J/\psi)$  from this experiment is lower than the prediction of  $(176_{-93}^{+137})$  eV for  $J^{PC} = 0^{++}$ ,  $(189_{-100}^{+147})$  eV for  $J^{PC} = 2^{++}$  (calculated by us using the values in Ref. [2], and total width of the  $Y(4140)$  from CDF [5]). This disfavors the scenario in which the  $Y(4140)$  is a  $D_s^{*+}D_s^{*-}$  molecule with  $J^{PC} = 0^{++}$  or  $2^{++}$ .

We find evidence for an unexpected new narrow structure at 4.35 GeV/ $c^2$  in the  $\phi J/\psi$  mass spectrum with a significance of 3.2 standard deviations including systematic uncertainty. If this structure is interpreted as a resonance, its mass and width are  $[4350.6_{-5.1}^{+4.6}(\text{stat}) \pm 0.7(\text{syst})]$  MeV/ $c^2$  and  $[13_{-9}^{+18}(\text{stat}) \pm 4(\text{syst})]$  MeV, respectively. The product of its two-photon decay width and branching fraction to  $\phi J/\psi$  is measured to be  $\Gamma_{\gamma\gamma}(X(4350))\mathcal{B}(X(4350) \rightarrow \phi J/\psi) = [6.7_{-2.4}^{+3.2}(\text{stat}) \pm 1.1(\text{syst})]$  eV for  $J^P = 0^+$ , or  $[1.5_{-0.6}^{+0.7}(\text{stat}) \pm 0.3(\text{syst})]$  eV for  $J^P = 2^+$ . We note that the mass of this structure is consistent with the predicted values of a  $c\bar{c}s\bar{s}$  tetraquark state with  $J^{PC} = 2^{++}$  in Ref. [3] and a  $D_s^{*+}D_{s0}^{*-}$  molecular state in Ref. [4]. In a recent paper [29], the possibility that the  $X(4350)$  could be an excited  $P$ -wave charmonium state,  $\chi_{c2}''$ , was also discussed.

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