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Observation of the $Y(4140)$ structure in the $J/\psi\,\phi$ Mass Spectrum in $B^{\pm} \rightarrow J/\psi\,\phi K^{\pm}$ Decays

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The observation of the $Y(4140)$ structure in $B^{\pm} \to J/\psi\,\phi K^{\pm}$ decays produced in $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV is reported with a statistical significance greater than 5 standard deviations. A fit to the $J/\psi\,\phi$ mass spectrum is performed assuming the presence of a Breit-Wigner resonance. The fit yields a signal of $19 \pm 6(\text{stat}) \pm 3(\text{syst})$ resonance events, and resonance mass and width of $4143.4^{+2.9}_{-3.0}(\text{stat}) \pm 0.6(\text{syst})$ MeV/c^2 and $15.3^{+10.4}_{-6.1}(\text{stat}) \pm 2.5(\text{syst})$ MeV/c^2 respectively. The parameters of this resonance-like structure are consistent with values reported from an earlier CDF analysis.

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The existence of exotic mesons beyond $q\bar{q}$ has been dis-

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cussed for many years [1], but evidence for such mesons has not been clearly established. The recent discoveries of states with charmonium-like decay modes [2–5] that do not fit into the overall charmonium system have introduced challenges to the conventional $q\bar{q}$ meson model. The possible interpretations beyond $q\bar{q}$ such as hybrid ($q\bar{q}g$) and four-quark states ($q\bar{q}q\bar{q}$) have revitalized interest in exotic mesons in the charm sector [6–11].

Recently, the CDF collaboration has reported evidence for a narrow structure near the $J/\psi\,\phi$ threshold in $B^+ \to J/\psi\,\phi K^+$ decays produced in $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV [12]. Charge conjugation is implied throughout this letter. Since the mass of this state, termed $Y(4140)$, is well beyond the threshold of open charm-pair production, the expected branching fraction into this channel for conventional charmonium is tiny. The structure is the first observed charmonium-like object decaying into a pair of quarkonium states ($c\bar{c}$ and $s\bar{s}$) with a relative narrow width, a possible signature for an exotic meson [7, 11, 13, 14]. The Belle collaboration has searched for this $J/\psi\,\phi$ structure without a firm conclusion near the $J/\psi\,\phi$ threshold [15].

In this Letter, we report a further study of the structures in the $J/\psi\,\phi$ system produced in exclusive $B^+ \to J/\psi\,\phi K^+$ decays with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$ reported in Ref. [12]. This analysis is based on a sample of $\bar{p}p$ collision data collected by the CDF II detector with an integrated luminosity of 6.0 fb^{-1}. This analysis includes the data used in, and supersedes the results of Ref. [12].

The CDF II detector has been described in detail elsewhere [16]. The important components for this analysis include the tracking, muon, and time-of-flight (TOF) systems. The tracking system is composed of a silicon-strip vertex detector surrounded by an open-cell drift chamber system (COT) located inside a solenoid with a 1.4 T magnetic field. The COT and silicon-strip vertex detector are used for the measurement of charged-particle trajectories and decay locations. In addition, the COT provides ionization energy loss information, dE/dx, used for kaon discrimination, while the TOF system provides complementary kaon discrimination information. The central muon identification system is located radially outside the electromagnetic and hadronic calorimeters and consists of two sets of drift chambers and scintillation counters. The central detector covers the pseudorapidity region $|\eta| \leq 0.6$ and detects muons with $p_T \geq 1.4$ GeV/c [17], and the outer part covers the region $0.6 < |\eta| < 1.0$ and detects muons with $p_T \geq 2.0$ GeV/c.

In this analysis, $J/\psi \to \mu^+\mu^-$ events are recorded using a dedicated three-level dimuon trigger. The first trigger level requires two muon candidates with two COT tracks that extrapolate to track segments in the muon detectors. The second level applies additional kinematic requirements to the muon pair candidate. The third level requires the invariant mass of the $\mu^+\mu^-$ pair to be within the mass range of 2.7 to 4.0 GeV/c^2. The trigger requirements are confirmed offline.

We apply the same requirements described in the previous analysis [12] to the current data. We form $B^+ \to J/\psi\,\phi K^+$ candidates by combining a $J/\psi \to \mu^+\mu^-$ candidate, a $\phi \to K^+K^-$ candidate, and an additional charged track, which are consistent with originating from a common point. The three hadronic tracks must be identified as kaon candidates by using a log-likelihood ratio estimator. This quantity reflects how well a candidate track can be positively identified as a kaon relative to other hadrons with its dE/dx and TOF information and must exceed 0.2 [18]. The reconstructed masses of the J/ψ and ϕ meson candidates must lie within 50 and 7 MeV/c^2 of their nominal values, respectively. In the final B^+ reconstruction the $\mu^+\mu^-$ mass is constrained to the known J/ψ mass [1], and the B^+ candidates must have $p_T > 4$ GeV/c. In addition, we require $L_{xy}(B^+) > 500$ μm for the $B^+ \to J/\psi\,\phi K^+$ candidate, where $L_{xy}(B^+)$ is the projection onto $\vec{p}_T(B^+)$ of the vector connecting the primary interaction point, determined for each event using prompt tracks, to the reconstructed B^+ decay point.

The invariant mass spectrum of the selected $J/\psi\,\phi K^+$ candidates is shown in Fig. 1(a). It is fit with a Gaussian signal function with its root-mean-square (RMS) width fixed to the mass resolution of 5.9 MeV/c^2 obtained from Monte Carlo (MC) simulation [19] and mean fixed to the nominal B^+ mass [1] and a linear background function. The B^+ yield is 115 ± 12(stat) events, a 53% increase over the previous analysis. This increase in yield, for an integrated luminosity increased by a factor of 2.2, is reduced by a trigger rate limitation at the higher instantaneous luminosities for the later data-taking period. The yield increase in the complementary mode $B^+ \to J/\psi\,\pi^+\pi^- K^+$ is 51.8 ± 2.4%, consistent with the yield increase in $B^+ \to J/\psi\,\phi K^+$ channel.

We then select B^+ signal candidates with a mass within ±3 RMS (±17.7 MeV/c^2) of the nominal B^+ mass. Events with a mass within $[-9, -6]$ RMS or $[+6, +9]$ RMS of the nominal B^+ mass are called B sideband events. They are normalized into the B^+ signal region assuming a linear background distribution. The J/ψ signal, checked by removing its mass constraint, contains almost no background. Figure 1(b) shows the invariant mass distribution of the K^+K^- pairs from $J/\psi\,K^+K^-K^+$ candidates inside the B mass window and in the B sidebands before applying the restriction on the K^+K^- mass. The clear ϕ signal inside the B mass window and almost featureless K^+K^- mass distribution in the B sideband indicate that the $B^+ \to J/\psi\,K^+K^-K^+$ final state is well described as $J/\psi\,\phi K^+$. In none of the candidate events do both K^+K^- combinations from the three-kaon final state fall into the ϕ mass window.

Fig. 2 shows the mass difference $\Delta M =$

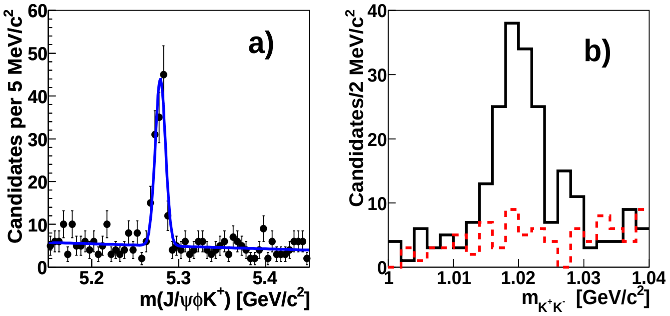

FIG. 1: (a) The mass distribution of $J/\psi\,\phi K^+$; the solid blue line is a fit to the data with a Gaussian signal function and linear background function. (b) The K^+K^- mass distributions inside the B mass window (black solid) and in the B sidebands (red dotted).

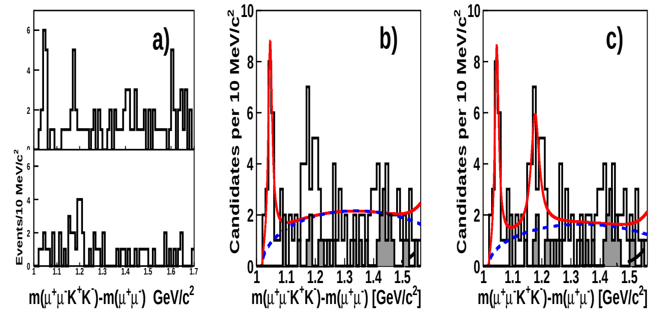

FIG. 2: (a) The mass difference, ΔM, between $\mu^+\mu^-K^+K^-$ and $\mu^+\mu^-$, in the B^+ mass window. Top–data from Ref. [12], bottom–new data. (b) A fit to the combined data assuming $Y(4140)$ only. (c) A fit to the combined data assuming two structures. This fit, including the second peak, lowers the 3–body phase space background under the first peak and increases its yield and significance with negligible effect on its resonance parameters. The shaded histogram is the data from the B sideband. The dotted blue curve is the predicted background contribution, the dash-dotted black curve is the predicted B^0_s contamination, and the solid red curve is the total unbinned fit.

$m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$ for events in the B^+ mass window. Events from reference [12] and from new data are shown in (a) top and bottom. In the $Y(4140)$ signal region ($\Delta M < 1.07\mathrm{GeV}/c^2$), the new data agree within 1σ of the expectation (6 events compared to 7.3 expected). Over the entire examined region the two data sets are consistent at the 7% probability level. We have investigated the consistency of particle ID for the two data sets using the $B^+ \to J/\psi\,K^+$ channel and see no discrepant effects. In (b) and (c), we display ΔM distributions for the events in the B signal and sideband in the combined data sample. We restrict our study to events with ΔM smaller than 1.56 GeV/c^2 to avoid appreciable combinatorial backgrounds from misidentified $B^0_s \to \psi(2S)\phi \to (J/\psi\,\pi^+\pi^-)\phi$ decays [12]. An enhancement is observed near the $J/\psi\,\phi$ threshold from the B^+ signal while there are no events in the ΔM range below 1.1 GeV/c^2 from the combinatorial background estimated from B sideband events.

We model the observed threshold structure by an S-wave relativistic Breit-Wigner (BW) function [21] convoluted with a Gaussian resolution function with the RMS fixed to 1.7 MeV/c^2 obtained from MC. Three–body phase space [1] is used to describe the background shape. There is still a small B^0_s contribution (3.3±1.0 events) in the ΔM distribution up to 1.56 GeV. The MC shape of the B^0_s contribution is normalized to this area and added to the three-body phase space. The parameters from an unbinned likelihood fit to the ΔM distribution, as shown in Fig. 2(b), are given in Table I. To test the hypothesis that the structure has zero width (weak decay), we also fit the ΔM distribution to a zero-width peak, using a single Gaussian with RMS given by the expected mass resolution (1.7 MeV/c^2), plus phase space background. The statistical significance for a non-zero width determined by the likelihood ratio between these two fits is 3.7σ, favoring a strong decay (non-zero width) rather than a weak decay for this structure.

The combinatorial background contains primarily misidentified ϕ candidates, as can be seen in Fig. 1 (b). These two tracks with a ϕ-like mass will be combined with a real J/ψ, and an additional kaon candidate, all having a common vertex and forming a B mass. We model this component with phase space. To check this assumption, we performed several studies in which we relaxed cuts that would not influence the mass-difference distribution of events from the B mass region: loosened vertex requirements or loosened L_{xy} cuts. These studies show that the combinatoric background from the B sideband region is consistent with 3–body phase space. We can now conclude that the flat background hypothesis used in the previous paper [12] was overly conservative.

We determine the significance of the structure at the $J/\psi\,\phi$ threshold based on simulation. We generated 8.4×10^7 mass spectra (119 events for each, corresponding to the number of observed events) drawn from a three–body phase-space-like distribution, and search for the most significant fluctuation in each spectrum in the mass range of 1.02 to 1.56 GeV/c^2, with widths in the range of resolution up to 120 MeV/c^2 [12]. We evaluate $2\Delta\ln\mathcal{L} = -2\ln(\mathcal{L}_0/\mathcal{L}_{max})$ value for each generated spectrum, where $\mathcal{L}_0$ and $\mathcal{L}_{max}$ are the likelihood values for the null hypothesis fit and signal hypothesis fit. Both fits use three-body phase space to describe the background. There are 19 generated spectra with a $2\Delta\ln\mathcal{L}$ value greater than or equal to the value (34.9 obtained in the data assuming the $Y(4140)$ structure only [23]) obtained in the data. The resulting p-value, taken as the fraction of the generated spectra with a $2\Delta\ln\mathcal{L}$ value greater than or equal to the value obtained in the data, is 2.3×10^{-7}, corresponding to a significance greater than 5.0σ [24].

The mass of this enhancement is $4143.4^{+2.9}_{-3.0}$ MeV/c^2 after adding the J/ψ mass [1] to the ΔM calculation. To study the systematic uncertainties of the mass, width, and yield, we repeat the fit to the ΔM distribution using a non–relativistic BW and P-wave relativistic BW for signal. Other systematic uncertainties were also considered, including assuming the existence of the second structure, varying the mass resolution and B_s^0 component amplitude, as well as the systematic uncertainty due to the particle identification. The resulting systematic uncertainties for the measured quantities are shown in Table I.

TABLE I: The fit results for $J/\psi\,\phi$ resonance near threshold. The first uncertainty is statistical, and the second one is systematic.

ΔM [MeV/c^2]	Width [MeV/c^2]	Yield
$1046.7^{+2.9}_{-3.0}\pm0.6$	$15.3^{+10.4}_{-6.1}\pm2.5$	$19\pm6\pm3$

The relative trigger and reconstruction efficiency $\epsilon(B^+\to Y(4140)K^+)\times\epsilon(Y(4140)\to J/\psi\,\phi)/\epsilon(B^+\to J/\psi\,\phi K^+)$ is determined to be 1.1, using an S-wave BW with mean and width values determined from data to represent the $Y(4140)$ structure and a three–body phase space kinematics for the $B^+\to J/\psi\,\phi K^+$ decay. Thus the relative branching fraction $\mathcal{B}_{rel}=\mathcal{B}(B^+\to Y(4140)K^+)\times\mathcal{B}(Y(4140)\to J/\psi\,\phi)/\mathcal{B}(B^+\to J/\psi\,\phi K^+)$ including systematic uncertainties is $0.149\pm0.039(\mathrm{stat})\pm0.024(\mathrm{syst})$.

An excess above the three-body phase space background shape appears at approximately 1.18 GeV/c^2 in Fig. 2 (b). Since the significance of $Y(4140)$ is greater than 5σ, we assume the existence of the $Y(4140)$ with the parameters given in Table I and background given by three–body phase space, and we test for the existence of a possible structure around 1.18 GeV/c^2 as shown in Fig. 2 (c). The signal PDF for the second structure is an S-wave relativistic BW function [21] convoluted with a Gaussian resolution function with the RMS fixed to 3.0 MeV/c^2 obtained from MC. For the second structure $-2\ln(\mathcal{L}_0/\mathcal{L}_{max})$ is 16.8, where $\mathcal{L}_0$ and $\mathcal{L}_{max}$ are the likelihood values for the null hypothesis fit assuming the $Y(4140)$-only and signal hypothesis fit assuming the $Y(4140)$ and a second structure near $\Delta M\simeq1.18$ GeV/c^2. The p-value determined by a simulation similar to the $Y(4140)$ investigation is 1.1×10^{-3}, which corresponds to a significance of 3.1σ. The fit returns a yield of 22 ± 8 events, a ΔM of $1177.7^{+8.4}_{-6.7}$ MeV/c^2, and a width of $32.3^{+21.9}_{-15.3}$ MeV/c^2 for the structure near $\Delta M\simeq1.18$ GeV/c^2. Refitting the ΔM distribution with a second structure produces negligible changes in the mass and width of the $Y(4140)$. The yield of the $Y(4140)$ increases by one event. We evaluated the systematic uncertainties for the second structure in the same way as for the $Y(4140)$ structure and found systematic uncertainties of 1.9 MeV/c^2 for the mass and 7.6 MeV/c^2 for the width. The mass of the second structure is $4274.4^{+8.4}_{-6.7}(\mathrm{stat})\pm1.9(\mathrm{syst})$ MeV/c^2 after including the world-average J/ψ mass.

In summary, the increased $B^+\to J/\psi\,\phi K^+$ sample at CDF enables us to observe the $Y(4140)$ structure with a significance greater than 5σ. Assuming an S-wave relativistic BW, the mass and width of this structure are measured to be $4143.4^{+2.9}_{-3.0}(\mathrm{stat})\pm0.6(\mathrm{syst})$ MeV/c^2 and $15.3^{+10.4}_{-6.1}(\mathrm{stat})\pm2.5(\mathrm{syst})$ MeV/c^2, respectively. They are consistent with the previous report ($m=4143.0\pm2.9(\mathrm{stat})\pm1.2(\mathrm{syst})$ MeV/c^2, $\Gamma=11.7^{+8.3}_{-5.0}(\mathrm{stat})\pm3.7(\mathrm{syst})$ MeV/c^2 [12]. The relative branching fraction is determined to be $\mathcal{B}_{rel}=0.149\pm0.039(\mathrm{stat})\pm0.024(\mathrm{syst})$. Light meson vector-vector threshold enhancements have been seen [22]. We do not know of any non-exotic mechanism for producing a threshold enhancement involving a pair of heavy quarkonium states, but we cannot exclude the possibility. We also find evidence for a second structure with a mass of $4274.4^{+8.4}_{-6.7}(\mathrm{stat})\pm1.9(\mathrm{syst})$ MeV/c^2, a width of $32.3^{+21.9}_{-15.3}(\mathrm{stat})\pm7.6(\mathrm{syst})$ MeV/c^2 and a yield of 22 ± 8 events. The significance of the second structure is estimated to be approximately 3.1σ.

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