Observation of a Narrow Near-Threshold Structure in the $J/\psi\phi$ Mass Spectrum in $B^+ \rightarrow J/\psi\phi K^+$ Decays

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Observation is reported for a structure near the $J/\psi\phi$ threshold in $B^+ \rightarrow J/\psi\phi K^+$ decays produced in $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV with a statistical significance of beyond 5 standard deviations. There are $19 \pm 6$ events observed for this structure at a mass of $4143.4^{+2.9}_{-3.0}$ (stat) $\pm 0.6$ (syst) MeV/c$^2$ and a width of $15.3^{+10.1}_{-6.1}$ (stat) $\pm 2.5$ (syst) MeV/c$^2$, which are consistent with the previous measurements reported as evidence of the $Y(4140)$. 

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Recently, evidence has been reported by CDF for a narrow structure near the $J/ψφ$ threshold, named $Y(4140)$, in $B^+ \rightarrow J/ψφK^+$ decays produced in $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV [1]. The structure is the first charmonium-like structure decaying into two heavy quarkonium states ($c\bar{c}$ and $s\bar{s}$) which is a candidate for exotic mesons [2]. In this note, we report an update on a search for structures in the $J/ψφ$ system produced in exclusive $B^+ \rightarrow J/ψφK^+$ decays with $J/ψ \rightarrow μ^+μ^−$ and $φ \rightarrow K^+K^−$. This analysis is based on a sample of $\bar{p}p$ collision data at $\sqrt{s} = 1.96$ TeV with an integrated luminosity of about 6.0 fb$^{-1}$ collected by the CDF II detector at the Tevatron. The CDF II detector has been described in detail elsewhere [3]. In this analysis, $J/ψ \rightarrow μ^+μ^−$ events are recorded using a dedicated three-level dimuon trigger.

The invariant mass of $J/ψφK^+$ in the current dataset, which includes those used in the previous analysis after applying the same requirements used in the previous analysis [1], is shown in Fig. 1. A fit with a Gaussian signal function with its rms fixed to the value 5.9 MeV obtained from Monte Carlo (MC) simulation [4] and a linear background function to the mass spectrum of $J/ψφK^+$ returns a $B^+$ signal of $115 \pm 12$ (stat) events. For a luminosity increase by a factor of 2.2, the yield increase was 1.53, reduced by trigger rate-limitation at higher average luminosity. We then select $B^+$ signal candidates with a mass within $3σ$ (17.7 MeV/c$^2$) of the nominal $B^+$ mass. We define those events with a mass within [-9,-6]σ or [6,9]σ of nominal $B$ mass as $B$ sideband events. Fig. 2 shows the mass difference, $ΔM = m(μ^+μ^-K^+K^-) - m(μ^+μ^-)$, for events in the $B^+$ mass window as well as in the $B$ sideband in our data sample. The comparison of the $ΔM$ distribution in the $B$ mass window for the dataset used in this analysis (6.0 fb$^{-1}$) and the dataset used in the previous analysis (2.7 fb$^{-1}$ [1]) is shown in Figure 3.

The same model is used to examine the $Y(4140)$ structure as described in reference [1]. We model the enhancement by an $S$-wave relativistic BW function [5] convoluted with a Gaussian resolution function with the r.m.s. fixed to 1.7 MeV/c$^2$ obtained from MC, and use three–body phase space [6] to describe the background shape. Even though we exclude the high mass region to avoid the $B_s$ contamination, there is still a small contribution in the region of interest. We obtained the $ΔM$ shape from $B_s$ contamination and fix the $ΔM$ shape obtained from $B_s$ MC simulation, and

Figure 1: The mass distribution of $J/ψφK^+$; the solid line is a fit to the data with a Gaussian signal function and linear background function.

Figure 2: The mass difference, $ΔM$, between $μ^+μ^-K^+K^-$ and $μ^+μ^-$, in the $B^+$ mass window is shown as the black histogram. The red histogram is the $ΔM$ distribution from the data in the $B$ sideband.
the yield to 3.3, scaled from the $B_s \rightarrow J/\psi \phi$ yield in data. An unbinned likelihood fit to the $\Delta M$ distribution, as shown in Fig. 3, returns a yield of 19 ± 6 events, a $\Delta M$ of 1046.7$^{+2.9}_{-3.0}$ MeV/$c^2$, and a width of 15.3$^{+10.4}_{-6.1}$ MeV/$c^2$.

We use the same simulation process as in Reference [1], based on a pure three-body phase space background shape to determine the significance of the $Y(4140)$ structure. We performed a total of 84 million simulations and found 19 trials with a $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{max})}$ value greater than or equal to the value obtained in the data (5.9), as shown in Fig. 3, where $\mathcal{L}_0$ and $\mathcal{L}_{max}$ are the likelihood values for the null hypothesis fit and signal hypothesis fit. The resulting $p$-value is $2.3 \times 10^{-7}$, corresponding to a significance of greater than 5.0σ.

The mass of this structure, including systematic uncertainty, is measured as $4143.4^{+2.9}_{-3.0}(\text{stat}) \pm 0.6$(syst) MeV/$c^2$ after including the world-average $J/\psi$ mass. The relative efficiency between $B^+ \rightarrow Y(4140)K^+$, $Y(4140) \rightarrow J/\psi \phi$ and $B^+ \rightarrow J/\psi \phi K^+$ is 1.1 assuming $Y(4140)$ as an $S$-wave structure and $B^+$ phase space decays. Thus the relative branching fraction between $B^+ \rightarrow Y(4140)K^+$, $Y(4140) \rightarrow J/\psi \phi$ and $B^+ \rightarrow J/\psi \phi K^+$ including systematics is $0.149 \pm 0.039(\text{stat}) \pm 0.024(\text{syst})$.

An further excess above the three-body phase space background shape appears at approximately 1.18 GeV/$c^2$ in Fig. 3(b). Since the significance of $Y(4140)$ is greater than 5σ, we fit to the data assuming two structures at $\Delta M$ of 1.05 and 1.18 GeV/$c^2$ as shown in Fig. 3. The fit to the data with the same requirements as in the previous paper [1] returns a yield of 20 ± 5 events, a $\Delta M$ of 1046.7$^{+2.8}_{-2.9}$ MeV/$c^2$, and a width of 15.0$^{+8.5}_{-5.6}$ MeV/$c^2$ for the $Y(4140)$, which are consistent with the values returned from a $Y(4140)$-only signal fit. The fit returns a yield of 22 ± 8 events, a $\Delta M$ of 1177.7$^{+8.4}_{-6.7}$ MeV/$c^2$, and a width of 32.3$^{+21.3}_{-15.3}$ MeV/$c^2$ for the structure around $\Delta M$ of 1.18 GeV/$c^2$. The significance of the second structure, determined by a similar simulation is 3.1σ.
In summary, the growing $B^+ \rightarrow J/\psi \phi K^+$ sample at CDF enables us to observe the $Y(4140)$ structure \cite{1} with a significance greater than 5σ. Assuming an S-wave relativistic BW, the mass and width of this structure, including systematic uncertainties, are measured to be $4143.4^{+2.9}_{-3.0}\,(\text{stat}) \pm 0.6\,(\text{syst})$ MeV/$c^2$ and $15.3^{+10.4}_{-6.1}\,(\text{stat}) \pm 2.5\,(\text{syst})$ MeV/$c^2$, respectively. The relative branching fraction between $B^+ \rightarrow Y(4140)K^+$, $Y(4140) \rightarrow J/\psi \phi$ and $B^+ \rightarrow J/\psi \phi K^+$ including systematics is $0.149 \pm 0.039\,(\text{stat}) \pm 0.024\,(\text{syst})$. We also find evidence at $3.1\sigma$ level for a second structure with a mass of $4274.4^{+8.4}_{-6.7}\,(\text{stat})$ MeV/$c^2$, a width of $32.3^{+21.9}_{-15.3}\,(\text{stat})$ MeV/$c^2$ and a yield of $22 \pm 8$.

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[5] $\frac{dN}{dm} \propto \frac{m\Gamma(m)}{[m^2-m_0^2]^2+2m_0^2\Gamma^2(m)}$, where $\Gamma(m) = \Gamma_0 \frac{q_0}{q_0} \frac{m}{m}$, and the 0 subscript indicates the value at the peak mass.
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