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 $4143^{+2.9}_{-3.0}$(stat) $\pm 0.6$(syst) MeV/$c^2$ and a width of $15.3^{+10.4}_{-6.1}$(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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the phase space [6] to describe the background shape. Even though we exclude the high mass region to 

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used in the previous analysis (2.7 fb^{-1})

events. Fig. 2 shows the mass difference, \( \Delta M \), between \( \mu^+\mu^-K^+K^- \) and \( \mu^+\mu^- \), in the \( B^+ \) mass window is shown as the black histogram. The red histogram is the \( \Delta M \) distribution from the data in the B sideband.

Recently, evidence has been reported by CDF for a narrow structure near the \( J/\psi \phi \) threshold, named \( Y(4140) \), in \( B^+ \to J/\psi \phi K^+ \) 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 \( J/\psi \phi \) system produced in exclusive \( B^+ \to J/\psi \phi K^+ \) decays with \( J/\psi \to \mu^+\mu^- \) and \( \phi \to K^+K^- \). 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, \( J/\psi \to \mu^+\mu^- \) events are recorded using a dedicated three-level dimuon trigger.

The invariant mass of \( J/\psi \phi K^+ \) 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/c^2 obtained from Monte Carlo (MC) simulation [4] and a linear background function to the mass spectrum of \( J/\psi \phi K^+ \) 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 \( 3\sigma \) (17.7 MeV/c^2) of the nominal \( B^+ \) mass. We define those events with a mass within \([-9,-6]\)\( \sigma \) or \([6,9]\)\( \sigma \) of nominal \( B \) mass as B sideband events. Fig. 2 shows the mass difference, \( \Delta M = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-) \), for events in the \( B^+ \) mass window as well as in the B sideband in our data sample. The comparison of the \( \Delta M \) 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 \( \Delta M \) shape from \( B_s \) contamination and fix the \( \Delta M \) shape obtained from \( B_s \) MC simulation,
the yield to 3.3, scaled from the $B_s \to J/\psi \phi$ yield in data. An unbinned likelihood fit to the $\Delta M$ distribution, as shown in Fig. 4, returns a yield of $19 \pm 6$ 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. 5, 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 5.0$\sigma$.

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

An further excess above the three-body phase space background shape appears at approximately 1.18 GeV/$c^2$ in Fig. 1 (b). Since the significance of $Y(4140)$ is greater than 5$\sigma$, we fit to the data assuming two structures at $\Delta M$ of 1.05 and 1.18 GeV/$c^2$ as shown in Fig. 6. The fit to the data with the same requirements as in the previous paper [1] returns a yield of $20 \pm 5$ 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 $22 \pm 8$ events, a $\Delta M$ 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 around $\Delta M$ of 1.18 GeV/$c^2$. The significance of the second structure, determined by a similar simulation is 3.1$\sigma$.
In summary, the growing $B^+ \rightarrow J/\psi K^+$ sample at CDF enables us to observe the $Y(4140)$ structure [1] with a significance greater than 5$\sigma$. Assuming an S-wave relativistic BW, the mass and width of this structure, including systematic uncertainties, are measured to be $4143.4^{+2.9}_{-3.0}$(stat) $\pm$ 0.6(syst) MeV/$c^2$ and $15.3^{+10.4}_{-6.1}$(stat) $\pm$ 2.5(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(stat) $\pm$ 0.024(syst). We also find evidence at 3.1$\sigma$ level for a second structure with a mass of $4274.4^{+8.4}_{-6.7}$(stat) MeV/$c^2$, a width of $32.3^{+21.9}_{-15.3}$(stat) MeV/$c^2$ and a yield of 22 $\pm$ 8.

References

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