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

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Observation is reported for a 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 with a statistical significance of beyond 5 standard deviations. There are 19 ± 6 events observed for this structure at a mass of $4143.4^{+2.9}_{-3.0}(\text{stat}) \pm 0.6(\text{syst})$ MeV/c^2 and a width of $15.3^{+10.4}_{-6.1}(\text{stat}) \pm 2.5(\text{syst})$ MeV/c^2, which are consistent with the previous measurements reported as evidence of the $Y(4140)$.

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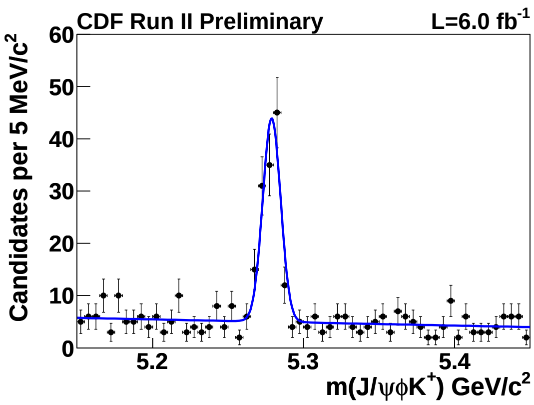

Figure 1: The mass distribution of $J/\psi\phi K^+$; the solid line is a fit to the data with a Gaussian signal function and linear background function.

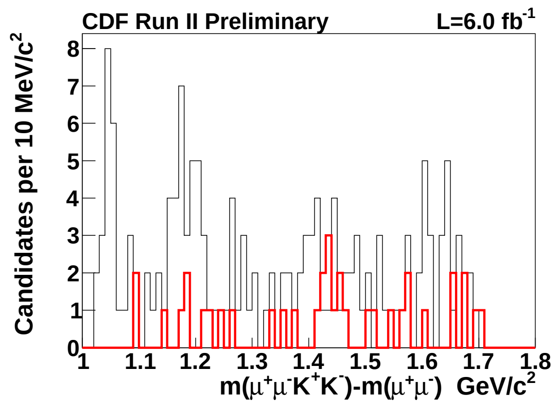

Figure 2: The mass difference, ΔM, between $\mu^+\mu^-K^+K^-$ and $\mu^+\mu^-$, in the B^+ mass window is shown as the black histogram. The red histogram is the ΔM distribution from the data in the B sideband.

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 $115 \pm 12(\text{stat})$ 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, $\Delta M = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$, for events in the B^+ mass window as well as in the B sideband in our data sample. The comparison of the 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

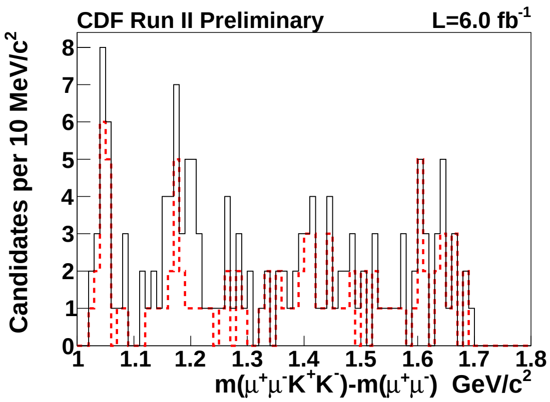

Figure 3: The ΔM distribution in the B mass window for the data used in the current analysis (6.0 fb^{-1}) is shown as the black histogram, and the same distribution for the data in the previous analysis(2.7 fb^{-1} [1])is shown as the red dashed histogram.

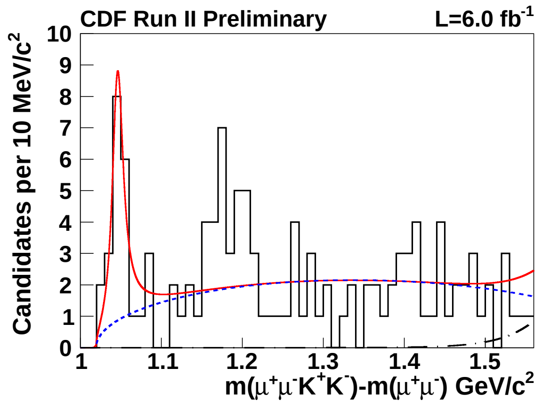

Figure 4: The mass difference, ΔM, between $\mu^+\mu^-K^+K^-$ and $\mu^+\mu^-$, in the B^+ mass window is shown as a solid black histogram for the data. The dotted curve is the predicted three-body phase space background contribution, the dash-dotted curve is the predicted B_s contamination (fixed to 3.3), and the solid red curve is the total unbinned fit where the signal PDF is an S-wave Breit-Wigner convoluted with the resolution (1.7 MeV/c^2).

the yield to 3.3, scaled from the $B_s \to J/\psi\phi$ yield in data. An unbinned likelihood fit to the ΔM distribution, as shown in Fig. 4, returns a yield of 19 ± 6 events, a ΔM 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 $\sqrt{-2\ln(\mathscr{L}_0/\mathscr{L}_{max})}$ value greater than or equal to the value obtained in the data (5.9), as shown in Fig. 5, where $\mathscr{L}_0$ and $\mathscr{L}_{max}$ are the likelihood values for the null hypothesis fit and signal hypothesis fit. The resulting p-value is 2.3×10^{-7}, corresponding to a significance of greater than 5.0σ.

The mass of this structure, including systematic uncertainty, is measured as $4143.4^{+2.9}_{-3.0}(\text{stat})\pm 0.6(\text{syst})$ MeV/c^2 after including the world-average J/ψ 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 $0.149\pm0.039(\text{stat})\pm0.024(\text{syst})$.

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 5σ, we fit to the data assuming two structures at ΔM 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 ± 5 events, a ΔM 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 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 around ΔM of 1.18 GeV/c^2 . The significance of the second structure, determined by a similar simulation is 3.1σ.

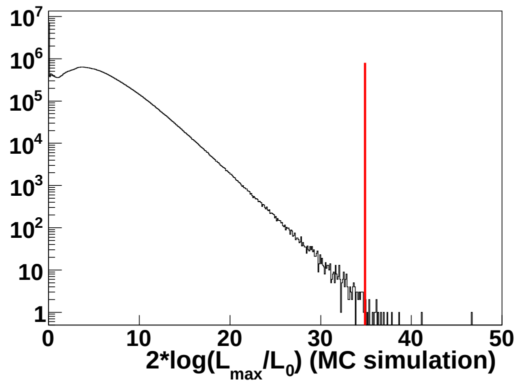

Figure 5: Distribution of $-2\ln(\mathscr{L}_0/\mathscr{L}_{max})$ for 84 million simulation trials. The p-value obtained from counting is 2.3×10^{-7}, corresponding to a significance of 5.0σ.

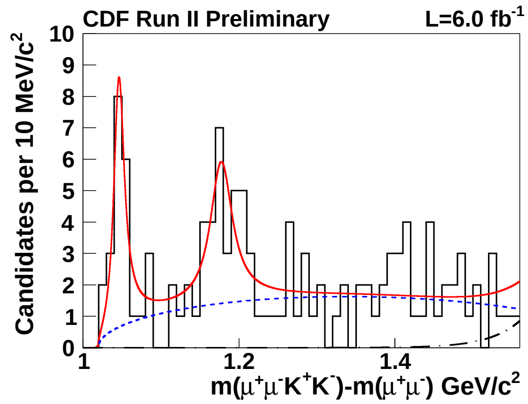

Figure 6: The mass difference, ΔM, between $\mu^+\mu^-K^+K^-$ and $\mu^+\mu^-$, in the B^+ mass window. The dotted curve is the background contribution, the dash-dotted curve is the B_s contamination, and the red solid curve is the total unbinned fit assuming two structures.

In summary, the growing $B^+\to J/\psi\phi K^+$ sample at CDF enables us to observe the $Y(4140)$ structure [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 $4143.4^{+2.9}_{-3.0}(\mathrm{stat})\pm0.6(\mathrm{syst})$ MeV/c^2 and $15.3^{+10.4}_{-6.1}(\mathrm{stat})\pm2.5(\mathrm{syst})$ MeV/c^2, respectively. 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 $0.149\pm0.039(\mathrm{stat})\pm0.024(\mathrm{syst})$. We also find evidence at 3.1σ level for a second structure with a mass of $4274.4^{+8.4}_{-6.7}(\mathrm{stat})$ MeV/c^2, a width of $32.3^{+21.9}_{-15.3}(\mathrm{stat})$ MeV/c^2 and a yield of 22 ± 8.

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

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