Evidence for a Near-Threshold Structure in the \( J/\psi \phi \) channel from \( B^+ \to J/\psi \phi K^+ \)

Decays at CDF

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Evidence for a new particle in the \( J/\psi \phi \) mass spectrum is reported here. The new structure was found in 2.7 fb\(^{-1}\) of pp collision data collected with the CDF detector at Fermilab’s Tevatron accelerator at \( \sqrt{s} = 1960 \) GeV. The new state, \( Y(4140) \), has a mass of 4143.0 MeV/c\(^2\) and a width of 11.7 MeV/c\(^2\), with a statistical significance of at least 3.8 \( \sigma \).

Introduction

In recent years, several unusual and interesting charmonium-like mesons have been observed at BABAR, BELLE, CDF and D0\(^2,3,4,5\). The unusual properties of the X(3872), Y(3940), and Y(4260) mesons have led to speculations of exotic mesons such as hybrids or four-quark states.

These hints of exotic mesons have prompted searches for particles that could somehow be related. One such likely channel is the decay to \( J/\psi \phi \), for several reasons. The \( J/\psi \phi \) final state has positive C-parity and two \( J^{PC} = 1^{--} \) vector mesons (VV); the X(3872) and Y(3930) decay to VV states. The threshold for a particle decaying to \( J/\psi \phi \) is 4.116 GeV; the Y(3940) was observed near the \( J/\psi \omega \) threshold. Finally, a typical charmonium meson with a mass above 4.116 GeV/c\(^2\) has a very small predicted branching ratio to this channel; reconstructing an unexpected number would indicate something new.

From an experimental point of view, the \( J/\psi \phi \) channel is possible to reconstruct in a straightforward manner. To reduce combinatorial background the \( J/\psi \phi \) can be isolated by reconstructing the \( B^+ \) (charge conjugation is implied throughout) in the \( B^+ \to J/\psi \phi K^+ \) channel. Since b hadrons are copiously produced at the Tevatron, even rare processes can now be reconstructed in the large datasets available to CDF and D0; this CDF analysis searches 2.7 fb\(^{-1}\) of data, and nearly 5 fb\(^{-1}\) has been written to tape since the start of Run II. The b hadrons produced at the Tevatron are boosted, allowing near-threshold structure searches with a smooth acceptance. The CDF detector has excellent mass and vertex resolution, and analyses can take advantage of well-developed particle identification (PID) techniques. The CDF detector has been well described elsewhere\(^6\), and will not be discussed in detail here.

Analysis

The analysis strategy begins with reconstructing the \( B^+ \) in the \( B^+ \to J/\psi \phi K^+ \) decay channel, where the \( J/\psi \) decays to \( \mu^+ \mu^- \) and the \( \phi \) decays to \( K^+K^- \). Once this channel is isolated, the \( J/\psi \phi \) mass spectrum can be analyzed. In order to justify the choice of selection criteria, control channels of \( B_S \to J/\psi \phi \) (3000 events) and \( B^+ \to J/\psi K^+ \) (50,000 events) are selected.
Figure 1: The $B^+$ candidate mass spectrum before the $L_{xy}$ and kaon LLR cuts are applied.

Figure 2: The $B^+$ candidate mass spectrum after all selection criteria is applied.

The selection of the $B^+$ sample begins with the CDF dimuon trigger dataset, from which the $J/\psi$ is reconstructed using typical CDF selection criteria. Two kaon candidates whose invariant mass falls within a mass window defined by the $\phi$ mass and resolution are added, as well as an additional kaon to form the invariant mass of the five particles. The resulting $B^+$ candidate mass spectrum is shown in Figure 1. Two more selection criteria are added at this point. The vertex separation, $L_{xy}$, is the separation between the primary vertex and the secondary vertex formed by the reconstructed decay products of the candidate $B^+$. The $L_{xy}$ must be greater than 500 $\mu$m in this analysis. The CDF PID for kaons uses a log-likelihood ratio (LLR) to discriminate between kaons and pions. In this analysis, the kaon LLR must be greater than 0.2. The mass spectrum of the $B^+$ candidates is shown in Figure 2.

A phase-space Monte Carlo simulation was used to verify that no additional structures would be expected in the $B^+$ candidate mass spectrum of this analysis. The possibility of reflections was also considered; the decay $B_S \rightarrow \psi(2S)$ with $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ could be reconstructed in the $B^+$ mass window if one of the pions were misidentified as a kaon. This possible background was eliminated with a cut on the mass of the search window.

Additionally, a check of the $\phi$ mass spectrum was made to ensure that no component due to $f_0$ or $K^+K^-$ phase space was present. Looking at the $B^+$ candidate sample at the $\phi$ candidate
mass with a relaxed mass window, and subtracting the $B^+$ sidebands, yields the mass spectrum shown in Figure 3. Using a P-wave relativistic Breit-Wigner to fit the data yields a $\chi^2$ probability of 28%; there is little to no contamination of the $\phi$ sample.

Next, a search of the $J/\psi \phi$ mass spectrum is performed, and an enhancement at the threshold is present in the data, as shown in Figure 4, which shows the mass as $\Delta M$, or the difference between the mass of the $\mu^+\mu^-K^+K^-\tau$ and the mass of the $\mu^+\mu^-$. The data is fit with a signal hypothesis of an S-wave relativistic Breit-Wigner and a background hypothesis of three-body phase space, returning a signal yield of $14\pm5$, a width of $11.7 \pm 8.3 -5.0$ (stat) and a $\Delta M$ of $1046.3\pm2.9$ (stat) MeV/c$^2$.

A log-likelihood ratio (-2ln($L_0/L_{max}$)) is used to estimate the significance of the structure, where $L_0$ and $L_{max}$ are the likelihood values for the null hypothesis fit and the signal hypothesis fit. The significance of the structure in the $J/\psi \phi$ mass is $5.3\sigma$ if there were a priori predictions for mass and width of the new structure; however, in the absence of predictions the significance is found using a toy Monte Carlo technique to estimate the probability that the structure is due to a background fluctuation. The $\Delta M$ spectrum is modeled as a three-body phase space
decay. For each trial, the most significant fluctuation in the toy events is found anywhere in ΔM between 1.02 and 1.56 GeV/c², with a width between 1.7 MeV/c² (taken from resolution) and 120 MeV/c² (ten times the observed width). Then, the number of times that a fluctuation with a significance greater or equal to that found in the data is observed in the toy trials is counted, and a p-value is calculated. Using this method the significance drops from 5.3 σ to 4.3 σ. A further check is to vary the background model; using phase space and a flat background for non-B background yields a significance of 3.8 σ.

Conclusion

Evidence for a new structure in the J/ψφ mass spectrum has been found in 2.7 fb⁻¹ of data collected with the CDF detector at Fermilab. The signal yield is 14±5 events, with a width of 11.7 +8.3 -5.0 (statistical) ± 3.7 (systematic error) and a mass difference of 1046.3±2.9 (statistical) ± 1.2 (systematic error) MeV/c², giving a mass of 4143.0 MeV/c². The significance of this signal is 4.3 σ after taking the absence of a prediction for the mass and width into account. The width of this structure indicates that a strong decay is likely. The new structure is tentatively named the Y(4140).

References

2. S.-K. Choi et al. (Belle Collaboration),
3. S.-K. Choi et al. (Belle Collaboration),