Experimental Review of Structures in the $J/\psi\phi$ Mass Spectrum

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The discovery of numerous new charmonium-like structures since 2003 have revitalized interest in exotic meson spectroscopy. These structures do not fit easily into the conventional charmonium model, and proposals like four-quark states, hybrids, and re-scattering effects have been suggested as explanations. Since 2009, several new structures were reported in the $J/\psi\phi$ mass spectrum with the following characteristics: they are the first ones reported decaying into two heavy mesons which contain both a $c\bar{c}$ pair and an $s\bar{s}$ pair; and their masses are well beyond the open charm pair threshold. Conventional $c\bar{c}$ states with a mass beyond the $J/\psi\phi$ threshold are not expected to decay into this channel and the width is expected to be large, thus they are good candidates for exotic mesons. My focus in this article is to review the recent developments on the structures in the $J/\psi\phi$ mass spectrum from CDF, Belle and LHCb.

Keywords: exotic hadron; charmonium; exotic quantum number.

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1. Introduction

The $q\bar{q}$ (meson) and $qqq$ (baryon) states predicted by the quark model have been well established experimentally. All ground-state mesons have been observed since the discovery of the $B_c$ by CDF in 1998.

Hadrons beyond the $q\bar{q}$ and $qqq$ constructions are called exotic states. The possibility of $qqq$ and $qqqq$ states was already suggested by Gell-Mann at the very birth of the quark model. With the development of QCD, the existence of extra exotic mesons such as glueballs (consisting purely of gluons) and hybrids (mixtures of valance gluons and quarks) was also proposed. There are a few candidates for exotic states in the light quark sector but none of them has been established convincingly. There has also been considerable theoretical work on exotic mesons in the heavy quark sector, especially since the discovery of the $X(3872)$ by Belle in 2003.
1.1. Recent Developments of Charmonium-like Structures

In the charm sector, the charmonium potential model successfully explained and predicted the properties of charmonium states below the open charm threshold. This model starts with a phenomenological potential which includes a Coulomb-like component and a linear increasing component for quark confinement. It can be further extended to include spin-dependent terms and relativistic corrections. This model had been very successful for explaining the masses and widths for observed charmonium states—until the observation of the so-called charmonium-like states. The latter are superficially like a charmonium state but do not quite fit into the charmonium model, for instance, their masses, widths, or decay rates deviate from charmonium expectations. Thus some of these structures are proposed as candidates for various exotic mesons.

A possible experimental indication for the existence of exotic charmonium-like states surfaced back in 1994 when the CDF collaboration reported a $\psi(2S)$ production rate that was a factor of about 30 larger than the theoretical expectation. It was soon suggested that an important part of this excess rate could be from contributions due to hybrid charmonium states. However, the color octet production mechanism is believed to be an important factor contributing to the excess. Even though the feed-down from possible hybrids and other exotic states is not the dominant factor, it remains an open question whether exotics might make a substantial contribution to inclusive charmonium production at hadron colliders. It has also been proposed that the observed large branching fraction for non-charm $B$ decays may indicate a sizeable non-conventional charmonium production, such as hybrid charmonium, in $B$ decays since the dominant decay channel for conventional charmonium is open charm pair if the mass is above threshold.

The discovery of the $X(3872)$ by Belle in 2003 opened a new chapter for exotic mesons and subsequent discoveries provide more candidates for exotic charmonium. The $X(3872)$ was discovered decaying into $J/\psi \pi^+ \pi^-$, with a mass close to $D\bar{D}^*$ threshold. It was natural to consider it a candidate for the missing $D_s^2$ charmonium state. However, Belle searched further for the $D_s^2$ in its favored channel $J/\psi \gamma$, and found no signal. As pointed out in Belle’s paper, the observed mass is higher than the theoretical prediction for the $D_s^2$, and the closeness of its mass to the $D\bar{D}^*$ threshold motivated speculation that this structure is some kind of exotic meson—perhaps a loosely bound ‘molecular’ structure. It is now ten years since the discovery of the $X(3872)$ and its nature is still not really resolved despite a very large body of experimental work, including: observation of a number of different decay modes, precision mass measurements, studies of the $\pi^+ \pi^-$ system in $J/\psi \pi^+ \pi^-$ decays, determination of its $J^{PC}$ as $1^{++}$ and production characteristics.

Many more charmonium-like states have been claimed since the $X(3872)$, a recent review of the $X(3872)$ and the other 15 observations can be found in Table 2 in Ref. This spectroscopic bounty raises the question: are there in fact too many...
of the so-called X/Y/Z candidates, either as conventional or exotic charmonium? Most of these reported structures need confirmation, and probably not all of them will survive further experimental tests, as pointed out, for example, in Ref.\cite{47} Among those to be confirmed are structures like the $Z(4430)^+$ and the most recently reported $Z_c(3900)^+$\cite{48-50} which would be prima facie smoking-guns for exotic states because no charmonium state can, of course, be charged. Charmonium hybrids are also not an option for these observations due to their charges and they are likely to be a four-quark state. However, they need to be first confirmed as resonance states and their neutral partners need to be established before settling on a four-quark interpretation.

The structures reported in the $J/\psi$ mass spectrum are also striking. Their widths are relatively narrow and their masses are well beyond the open charm pair threshold, to which conventional charmonium of such high mass should overwhelmingly prefer to decay into\cite{26-28} and thus these also strongly imply an exotic nature. They are also the first structures reported which decay into two heavy mesons that contain both a $c\bar{c}$ pair and an $s\bar{s}$ pair. Interestingly, the $J/\psi$ system has positive C parity—since the two decay daughters both have $J^{PC} = 1^{+}$—which keeps the door open for this state to be manifestly exotic, i.e. $J^{PC} = 1^{-+}$ is forbidden for conventional $c\bar{c}$. A recent lattice calculation for a $1^{-+}$ charmed hybrid predicts a mass of $4.30 \pm 0.05$ GeV, which also places these reported structures in the right mass range.\cite{51} A $1^{-+}$ charmonium-like state would therefore also provide a smoking-gun for an exotic meson.

In a word, we are in exciting times for heavy-quark exotic spectroscopy, many exotic candidates have been observed but none of them can be declared as conclusive yet. Besides the observed charmonium-like structures, there are also bottomonium-like structures observed\cite{33} and all these together provide us rich opportunity to understand exotic mesons. In this article I review recent developments on the structures in the $J/\psi$ mass spectrum from CDF, Belle and LHCb.

### 1.2. The Currently Reported Structures in the $J/\psi$ Spectrum

| Production Process | Experiment | Mass (MeV) | Width (MeV) |
|--------------------|------------|------------|-------------|
| $B^+ \rightarrow J/\psi K^+$ | CDF | $4143.4^{+2.9}_{-3.0}$(stat) $\pm 0.6$(syst) | $15.3^{+10.4}_{-6.1}$(stat) $\pm 2.5$(syst) |
| $B^+ \rightarrow J/\psi K^+$ | CDF | $4274.4^{+5.4}_{-4.7}$(stat) $\pm 1.9$(syst) | $32.3^{+21.9}_{-15.3}$(stat) $\pm 7.6$(syst) |
| $e^+e^- \rightarrow \gamma\gamma e^+e^-$ | Belle | $4350.6^{+4.6}_{-5.1}$(stat) $\pm 0.7$(syst) | $13^{+18}_{-9}$ (stat) $\pm 4$(syst) |

The CDF collaboration reported the first evidence of a new structure near the $J/\psi$ threshold, the $Y(4140)$, in 2009 through exclusive $B^+ \rightarrow J/\psi K^+$ decays.\cite{52} In a subsequent report CDF placed the significance of the structure as exceeding $5\sigma$.\cite{53} In addition to this structure, CDF also reported evidence for a second one around $4.28$ GeV, which is curiously about one pion mass above the reported
Y(4140). In 2010 the Belle collaboration reported evidence for a structure around 4.35 GeV in a search through two-photon processes. The situation in $J/\psi \phi$ structures became murkier in 2011 when LHCb reported a null search for the $Y(4140)$ in conflict with CDF’s report. However, in 2012, the CMS collaboration reported preliminary observations of two structures in the $J/\psi \phi$ spectrum from exclusive $B^+ \to J/\psi \phi K^+$ decays. The lower mass structure from CMS provides the first confirmation of the existence of the $Y(4140)$. CMS’s second structure is close to CDF’s $Y(4274)$, but the difference in mass is large enough, given the quoted errors, such that it does not obviously support equating the two structures. The properties of these structures are summarized in Table 1.

1.3. Production of Possible $J/\psi \phi$ Structures

The $J/\psi \phi$ system consists of two $1^{-+}$ states, $J/\psi$ and $\phi$, and therefore depending on the orbital angular momentum configuration the system can have the following $J^{PC}$: $0^{++}$, $1^{++}$, and $2^{++}$ for $s$-wave coupling; and $0^{-+}$, $1^{-+}$, $2^{-+}$, and $3^{-+}$ for $p$-wave. As noted above, the $J/\psi \phi$ system always carries positive C-parity, and therefore it cannot be produced through processes that carry negative C-parity, such as Initial State Radiation (ISR) in an $e^+e^-$ collider where either electron or positron radiate a photon before the electron-positron annihilation. The $J/\psi \phi$ system is mainly accessible in the following processes: exclusive $B$ decays ($b \to c\bar{c}s$ transition), two-photon process, and prompt production in $p\bar{p}/pp$ interactions.

**Exclusive $B \to J/\psi \phi K$ decays:** For the exclusive $B \to J/\psi \phi K$ decay, the creation of an $ss$ from the vacuum is needed, so the branching fraction is suppressed ($OZI$ rule). Supposing that there is no structure in any two-body sub-system ($J/\psi \phi$, $J/\psi K^+$, $\phi K^+$), the decay of $B \to J/\psi \phi K$ will be simply kinematically constrained so that the $J/\psi \phi$ mass spectrum will be just phase space. Other sorts of production, such as possible hybrid charmonium or tetra-quark states, appear as structures on top of phase space. A reasonable production rate of exotic states can be prominent over a small phase space background, thus making this decay a promising channel for exotic states searches. The long $B$ lifetime provides an additional experimental handle to obtain a clean $B$ signal. Compared to inclusive production, which will be discussed below, the narrow $B$ signal and its sideband can provide constraints on possible reflections from partially reconstructed or mis-reconstructions of other $B$ hadrons. The latter is because the partial reconstruction or mis-reconstruction of other $B$ hadrons are expected to extend well into $B$ sideband.

**Two-photon processes:** In $e^+e^-$ collisions the electron and positron can each radiate a photon which interact with each other to produce new particles. The mass spectrum of $J/\psi \phi$ from $\gamma\gamma$ interactions can be used to search for the states otherwise inaccessible to $e^+e^-$ annihilation. Normally, these events are selected by requiring a very low transverse momentum of the system being searched for, which provides a very clean signal. However, producing a state of $3^{-+}$ as well as states with $J = 1$ states are forbidden in this process by Yang’s Theorem.
Prompt production from $p\bar{p}/pp$ interactions: All $J^{PC}$ states are allowed in this process. Depending on the prompt production rate and the width of the possible structures, inclusive searches in prompt production can be important in $p\bar{p}/pp$ interactions—e.g., the first confirmation of the $X(3872)$ by CDF. However, it is in general difficult to deal with large prompt backgrounds, and the lack of constraints can make it difficult to understand possible reflections.

2. Observation of $B \to J/\psi\phi K$

The first reports of exclusive $B^+ \to J/\psi\phi K^+$ and $B^0 \to J/\psi\phi K^0_S$ signals were from the CLEO collaboration in 1999 with 9.1 fb$^{-1}$ of $e^+e^-$ data. Figure 1 (left and middle) shows the $\Delta E$ vs $M(B)$ distributions reported by CLEO, where $\Delta E$ is defined as $E(J/\psi) + E(\phi) + E(K) - E_{\text{beam}}$ and $M(B)$ is $\sqrt{E_{\text{beam}}^2 - p^2(B)}$. The Dalitz plot for the selected $B$ signal events is shown in Fig. 1 (right). There was no discussion on possible structures in the $J/\psi\phi$ mass spectrum due to low statistics even though in hindsight it seems that those 10 events do concentrate in two clusters. Furthermore, as pointed out in CLEO’s report, their reconstruction efficiency was close to zero near the edge of phase space, and thus they were not sensitive to possible structures in the low $J/\psi\phi$ mass region below the $DD^*$ threshold.

The BaBar collaboration reported more significant $B^+ \to J/\psi\phi K^+$ (23 events) and $B^0 \to J/\psi\phi K^0_S$ (13 events) signals with 50.9 fb$^{-1}$ of data. The $\Delta E$ vs $m_{ES}$ [i.e. $M(B)$] distribution and the projections for both $B^+$ and $B^0$ are shown in Fig. 2. There was again no report on the examination of the $J/\psi\phi$ mass spectrum due to the low statistics.

Four other experiments have also observed significant $B \to J/\psi\phi K$ signals, but these reports are intimately involved in the matter of positive evidence for structures.
in the $J/\psi\phi$ mass distribution and are the topic of the next section.

3. Evidence of Structures in the $J/\psi\phi$ Mass Spectrum

In this section we discuss the evidence of structures in the $J/\psi\phi$ mass spectrum from exclusive $B$ decays, and from two-photon process, based on reports by CDF, Belle, and LHCb—but first we briefly review the detectors involved.

3.1. The CDF, Belle and LHCb Detectors

3.1.1. The CDF Detector

CDF collected data at the Tevatron, a $p\bar{p}$ collider at a center-of-mass energy of 2 TeV, with an instantaneous luminosity ranging from the initial $10^{31}$ to $4.3 \times 10^{32}$ cm$^{-2}$ sec$^{-1}$ at the end of its program. The cross section for $B$ hadron production at the Tevatron is very large, around 20 $\mu$b in the kinematic region of interest. CDF II was a general purpose solenoidal detector which combines precision charged particle tracking with fast projective calorimetry and fine grained muon detection. It was nearly cylindrically symmetric with respect to the beamline, and forward-backward symmetric with respect to the nominal interaction point. The tracking system was in a 1.4 T axial magnetic field provided by a superconducting solenoid. Charged particles created in the $p\bar{p}$ collision had their momentum and charge measured by the tracking system. The sub-tracking system, the Central-Outer-Tracker (COT), measured $dE/dx$ for charged particles which could be used for hadron particle identification. Right outside the tracking system, there was a Time-of-Flight

![Fig. 2](image-url) The $\Delta E$ and $m_{ES}$ distributions for $B^+ \to J/\psi\phi K^+$ (left set) and $B^0 \to J/\psi\phi K_S^0$ (right set) from BaBar. For each respective mode, the $\Delta E$ vs $m_{ES}$ event distribution is shown in (a) with a small rectangle as the signal box. The $\Delta E$ projection of the $m_{ES}$ signal region selection is shown in (b). The $m_{ES}$ projection of the $\Delta E$ signal region selection is shown in (c). The red solid lines in (c) of both left and right plots are fits to the data with background and signal.
detector which was of further aid in hadron particle identification, especially for studying $J/\psi \phi$ system. The muon chamber system was the outermost part of CDF, and was used to trigger and identify muons. A crucial component of the system for $B$ studies was the Silicon Vertex Detector, which made it possible to reconstruct the $B$ signal with excellent mass resolution and isolate the $B$ signal from large prompt background using its excellent vertex resolution. The typical mass resolution for $B$ hadrons was 5-10 MeV, and the typical vertex resolution was about 20-30 $\mu$m.

The trigger system plays a crucial role in a hadron collider experiments because the interaction rate is so high that each collision can not be read out and recorded. The data must be filtered to obtain interesting events. Storage capacity limited the trigger rate to about 75 Hz. The online physics event selection at CDF was achieved by a three-layer trigger. The CDF trigger relevant to $J/\psi \rightarrow \mu^+\mu^-$ required two oppositely charged online muon tracks with $p_T > 1.5$ or $p_T > 2.0$ GeV, depending on the part of the muon system involved, and the dimuon mass was required to be in the range from 2.7 to 4.0 GeV. This trigger was dynamically pre-scaled due to its high rate.

Due to the transverse momentum requirement in the trigger system and the centrality of the detector, the $B \rightarrow J/\psi \phi K$ hadrons were highly boosted (the typical $B$ transverse momentum was above 4 GeV), thus providing high efficiency for $B$ events even near the edge of their decay phase space. This is an important characteristic of a central hadron-collider detector and a significant factor in searching for structures in the near-threshold region in the $J/\psi \phi$ mass spectrum.

3.1.2. The Belle Detector

The Belle detector is installed at an asymmetric $e^+e^-$ collider operating at the $\Upsilon(4S)$ resonance, the KEK-B-factory. It is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect $K_S^0$ mesons and to identify muons (KLM).

The trigger system at Belle is almost 100% efficient for $B$ mesons. The Belle detector has excellent mass resolution, quite similar to CDF’s. Belle’s particle identification is intrinsically very powerful for the low transverse momentum tracks from $B$ decays.

3.1.3. The LHCb Detector

The LHCb detector is running at the Large Hadron Collider (LHC), which provides $pp$ collisions at a center-of-mass energy up to 8 TeV (so far). It is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, which includes
a high precision silicon tracking system and straw drift-tubes. The dipole magnet provides 1.4 T magnetic field. The combined tracking system has momentum resolution $\Delta p/p$ that varies from 0.4% at 5 GeV and to 0.6% at 100 GeV, and an impact parameter (IP) resolution of 20 $\mu$m for tracks with high transverse momentum. Charged hadrons are identified using two ring-imaging Cherenkov detectors. Photon, electron, and hadron candidates are identified by a calorimeter system consisting of scintillating-pad and pre-shower detectors, an electromagnetic calorimeter (ECAL), and a hadronic calorimeter (HCAL). Muons are identified by a muon system (MUON) composed of alternating layers of iron and multi-wire proportional chambers. The MUON, ECAL, and HCAL provide the capability for first-level hardware triggering. The single and dimuon hardware triggers provide good efficiency for $B$ hadrons. A single track trigger and dimuon trigger are used in the analysis discussed here. At the final stage, they either require a $J/\psi \rightarrow \mu^+\mu^-$ with $p_T > 1.5$ GeV or a muon-track pair with significant IP.

The LHCb detector has excellent mass resolution and excellent hadron particle identification ability. The mass resolutions of $B^+ \rightarrow J/\psi \phi K^+$ for both CDF and LHCb are both between 5 and 6 MeV, while the Belle experiment obtains better resolution due to the beam energy constraint. The LHCb experiment handles a very high data rate with an open trigger which enables them to collect a very broad spectrum of hadronic $B$ decays. However, as a result the LHCb experiment runs at a relatively low instantaneous luminosity compared to the ATLAS and CMS experiments due to limitations on the trigger bandwidth. Different from most other detectors, which measure the transverse momentum of tracks, LHCb mainly measures a track’s longitudinal momentum.

### 3.2. Structures in the $J/\psi \phi$ Mass Spectrum: CDF

The CDF collaboration reported evidence of a structure near the $J/\psi \phi$ threshold in exclusive $B^+ \rightarrow J/\psi \phi K^+$ using 2.7 fb$^{-1}$ of data in 2009. The CDF analysis first reconstructed a $J/\psi \rightarrow \mu^+\mu^-$ candidate by forming the dimuon tracks into a common vertex, and then required the $B$ meson to be 500 $\mu$m away from the primary vertex in the transverse plane, which reduces the background by a factor of 200 and keeps the signal with a efficiency of 60%. The track $dE/dx$ and Time-of-flight information is summarized in a log-likelihood ratio, which reflects how well a candidate track can be positively identified as a kaon relative to a pion. The requirement of minimum log-likelihood ratio of 0.2 for all three kaon candidates reduces the non-$B$ background by a factor of 100 with an efficiency of about 40%. The mass distribution of $J/\psi \phi K^+$ after all selections is shown in Fig. 3 a) with 75 $\pm$ 10 $B$ signals, and the $B$ signal purity is about 80% with a mass resolution of 6 MeV. Figure 3 b) shows the $B^+$ sideband-subtracted mass distribution of $K^+ K^-$ without the $\phi$ mass-window requirement. A fit was done to the $K^+ K^-$ distribution using a Breit-Wigner function only and it returns a mass and width compatible with the $\phi$ meson, which shows that $J/\psi \phi K^+$ dominates the observed $B$ signal.
Figure 4 a) shows the Dalitz plot for those events in the $B$ mass window. There is a cluster around the $m^2(J/\psi \phi)$ of 17 GeV$^2$, and there may be another cluster around 18 GeV$^2$.

Figure 4 b) shows the Dalitz projection onto $m(J/\psi \phi)$ but expressed as the mass difference $\Delta M = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$. A prominent structure appeared near the $J/\psi \phi$ threshold with a mass of $4143.0^{+2.9}_{-3.0}$ (stat) ± $1.2$ (syst) MeV and a width of $11.7^{+8.3}_{-5.0}$ (stat) ± $3.7$ (syst) MeV, which, following the pattern of other $X$ and $Y$ structures, was labeled the $Y(4140)$. With increased statistics over the original report, i.e. 6.0 fb$^{-1}$ of data and 115 ± 12 $B$ events, the statistical significance of the $Y(4140)$ exceeded 5$\sigma$ with $19\pm6$ signal events, assuming a relativistic BW for the signal and three-body phase space for the background as before. The $J/\psi \phi K^+$ invariant mass distribution and $\Delta M$ for the 6.0 fb$^{-1}$ are shown in Fig. 5. The mass and width of this structure are updated as $4143.4^{+2.9}_{-3.0}$ (stat) ± 0.6 (syst) MeV and $15.3^{+10.4}_{-6.1}$ (stat) ± 2.5 (syst) MeV. The relative branching fraction of $Y(4140)$ over inclusive $B^+ \rightarrow J/\psi \phi K^+$ decays $B_{rel} = B(B^+ \rightarrow Y(4140)K^+)\times B(Y(4140) \rightarrow J/\psi \phi)/B(B^+ \rightarrow J/\psi \phi K^+)$ including systematic uncertainties is measured as $0.149 \pm 0.039$ (stat) ± 0.024 (syst).

In addition, CDF also reported evidence for another structure in this larger data set around $\Delta M = 1.18$ GeV with a significance of 3.1$\sigma$ and a signal yield of $22\pm8$. The fitted mass difference and width are $1177.7^{+8.4}_{-6.7}$ MeV and $32.3^{+21.9}_{-15.3}$ MeV. Including systematics, the mass of this structure is $4274.4^{+8.4}_{-6.7}$ (stat) ± 1.9 (syst) MeV by adding the $J/\psi$ mass and including systematics, and the width is measured as $32.3^{+21.9}_{-15.3}$ (stat) ± 7.6 (syst) MeV.

![Fig. 3. (a) The mass distribution of $J/\psi \phi K^+$ from CDF with 2.7 fb$^{-1}$ of data; the solid line is a fit to the data with a Gaussian signal function and flat background function. (b) The $B^+$ sideband-subtracted mass distribution of $K^+K^-$ without the mass window requirement, where the solid curve is a P-wave relativistic Breit-Wigner fit to the data.](image-url)
3.3. Structures in the $J/\psi\phi$ Mass Spectrum: Belle

In 2009, the Belle collaboration promptly searched for the $Y(4140)$ structure through the same exclusive $B^+ \to J/\psi\phi K^+$ decays using 825 fb$^{-1}$ of $\Upsilon(4S)$ data. Belle found 7.5$^{+4.9}_{-4.4}$ signal candidates from 325 $\pm$ 21 $B$ events, corresponding to a significance of 1.9$\sigma$, by imposing the $Y(4140)$ parameters from CDF in their fit. This clearly cannot be counted as a confirmation. However, the efficiency near the $J/\psi\phi$ threshold is low and the Belle collaboration stated that they can

![Figure 4](image1.png)

**Fig. 4.** (a) The Dalitz plot of $m^2(\phi K^+)$ versus $m^2(J/\psi\phi)$ in the $B^+$ mass window from CDF with 2.7 fb$^{-1}$ of data. The boundary shows the kinematically allowed region. (b) The mass difference, $\Delta M$, between $\mu^+\mu^- K^+ K^-$ and $\mu^+\mu^-$, in the $B$ mass window from CDF. The dash-dotted curve is the background contribution and the red-solid curve is the result of the unbinned signal-plus-background fit assuming a single state.

![Figure 5](image2.png)

**Fig. 5.** (a) The mass distribution of $J/\psi\phi K^+$ from CDF with 6.0 fb$^{-1}$ of data; the solid line is a fit to the data with a Gaussian signal function and flat background. (b) The mass difference, $\Delta M$, between $\mu^+\mu^- K^+ K^-$ and $\mu^+\mu^-$, in the $B$ mass window from CDF with 6.0 fb$^{-1}$ of data. The dashed curve is the background contribution, the dashed-dotted curve is the contribution from the contamination from $B_s \to \psi(2S)\phi$ and the red-solid curve is the total unbinned fit incorporating two states.
neither confirm nor exclude the existence of the $Y(4140)$ with their current data.\cite{65}

The Belle collaboration also extended their search in this channel to two-photon process using the same dataset.\cite{53} The $\mu^+\mu^-K^+K^-$ and $e^+e^-K^+K^-$ events with the four tracks pointing back to the interaction point are selected. Figure 6 (a) shows the magnitude of the sum of transverse momentum vectors making up the four-body system, with respect to the beam position, and a cluster of events around the zero value is observed. Those events with the magnitude of the sum of transverse momentum vectors to be less than 0.2 GeV are selected to be candidates from the two-photon process. Figure 6 (b) shows the invariant mass of the combined $\mu^+\mu^-K^+K^-$ and $e^+e^-K^+K^-$ system in the $J/\psi\phi$ signal region and its sideband regions for the selected events. They found no evidence of the $Y(4140)$ in two-photon process, however, they did find evidence for a new structure with a mass of $4350^{+6}_{-5}\,(\text{stat})\pm 0.7\,(\text{syst})$ MeV, and a width of $13^{+18}_{-9}\,(\text{stat})\pm 4\,(\text{syst})$ MeV called $X(4350)$ with a significance of 3.2\,$\sigma$. This structure cannot have $J=1$, being visible in the two-photon process and must have a positive charge parity. If confirmed, it is another good candidate for an exotic meson.

3.4. Structures in the $J/\psi\phi$ Mass Spectrum: LHCb

In 2011, the LHCb collaboration searched for the $Y(4140)$ through the exclusive $B^+ \rightarrow J/\psi\phi K^+$ channel as CDF, but using 370 pb$^{-1}$ of data collected from 7 TeV $pp$ collisions.\cite{69} At LHCb, they either require a $J/\psi \rightarrow \mu^+\mu^-$ with $p_T>1.5$ GeV or a muon-track pair with significant IP to confirm trigger requirements. In order to reduce beam related background, LHCb requires a minimum transverse momentum of 250 MeV for reconstructed kaon tracks. The forward position makes LHCb’s

![Fig. 6.](image)

Left: the magnitude of the vector sum of the $J/\psi\phi$ transverse momentum with respect to the beam direction in the $e^+e^-$ center-of-mass frame for 825 fb$^{-1}$ of Belle data, which are represented as points with error bars. MC simulation for $\gamma\gamma \rightarrow J/\psi\phi$ with a mass fixed at 4.20, 4.35, and 4.50 GeV are represented as dot-dashed, solid, and dotted histograms. The arrow shows the cut used. Right: the $J/\psi\phi$ invariant mass distribution after Belle’s final selection. Data are represented as the open histogram. The total fit of the data and background component are the solid and dashed curves respectively. The shaded histogram represents the background normalized from the $J/\psi$ and $\phi$ mass sidebands.
relative detection efficiency about 40% lower near the $J/\psi\phi$ threshold region where kaon tracks normally have low transverse momentum with lower efficiency. LHCb then combined other selection information into a likelihood ratio to select the $B$ signal events. They reconstructed $346\pm20$ $B^+$ events with a mass resolution of 5.2 MeV and negligible non-B background. The $J/\psi\phi K^+$ invariant mass distribution, the relative efficiency as a function of $\Delta M$, and the $\Delta M$ distribution in the $B$ mass window are shown in Fig. 7. The LHCb experiment has about three times CDF’s statistics, however, the sensitivity is reduced due to the efficiency drop (by 40%) near the $J/\psi\phi$ threshold. LHCb found no evidence for the $Y(4140)$ and they estimate that they are in $2.4\sigma$ disagreement with CDF’s report. An upper limit on its branching fraction relative to the exclusive $B^+ \to J/\psi\phi K^+$ is quoted to be $<0.07$ at 90% confidence level using the $Y(4140)$ parameters from CDF. Furthermore, they also set an upper limit for the second peak on the branching fraction relative to the exclusive $B^+ \to J/\psi\phi K^+$ to be $<0.08$ at 90% confidence level using the $Y(4274)$ parameters from CDF. The results from the LHCb and CDF stand in contention.

4. A New Kind of Spectroscopy in the $J/\psi\phi$ System?

4.1. The Status of the $J/\psi\phi$ Structures

There are at least three possible structures that have been experimentally claimed in the $J/\psi\phi$ mass spectrum, none of them are expected from the conventional charmonium states, and are thus good candidates for exotic mesons. Even though there has been contention between LHCb results and those of CDF, there are obvious activities around the $Y(4140)$ and $Y(4274)$ regions in the $J/\psi\phi$ mass spectrum. A paper from CMS on $J/\psi\phi$ structures based on the largest $B \to J/\psi\phi K^+$ sample in the world to date is expected to be submitted to Physics Letter B soon. LHCb also has ten times of more data to be analyzed, and thus we expect greater clarity in the near future.

To further examine the status of the $J/\psi\phi$ structures in exclusive $B$ decays, a display directly comparing the $J/\psi\phi$ or $\Delta M = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$ mass spectra from two of the experiments is shown in Fig. 8. Consider first the most significant structure originally reported by CDF, the $Y(4140)$ in 2009. The statistics for CDF’s report is low and it is difficult to determine the parameters of this structure, and confirmation from independent experiments was vital. The absence of any excesses in LHCb’s report in 2011 for CDF’s $Y(4140)$ is quite striking. The discrepancy can be understood quantitatively from the expected signal yields: the LHCb fitted yield using CDF parameters is $6.9\pm4.9$ candidates compared to an expected yield scaled from CDF’s of $35\pm9\pm6$ candidates, a $2.4\sigma$ disagreement.

\[a\] A recent unofficial result from LHCb using 1.0 fb$^{-1}$ seems supportive of the existence of the $Y(4140)$ structure, although no fit parameters were quoted to enable a quantitative comparisons.\[b\]
The ambiguous situation over the status of the $Y(4140)$ presented the usual dilemma of whether statistical fluctuations have confused the picture or unappreciated instrumental effects had struck? And if the latter, for which experiment?

![Mass distribution of $J/\psi \phi K^+$ at LHCb. A fit to the data with a Gaussian signal function and flat background function is shown as the solid red line. Top right: the relative efficiency for $J/\psi \phi$ as a function of the mass difference, $\Delta M$, between $\mu^+\mu^- K^+K^-$ and $\mu^+\mu^-$, for LHCb. Bottom: The $\Delta M$ distribution in the $B$ mass window (a) using three-body phase space background shape (b) using three-body phase space multiplied by a quadratic function at LHCb. The total fit is represented as the solid red curve and the dash-dotted blue curve shows the expected signals estimated from CDF results.](image)
On the other hand, there is in fact considerable consistency among experiments if one allows for the large uncertainty in ascertaining the properties of broad low-statistics structures above the near threshold region. One readily notices in Fig. 8 that there actually seems to be an excess around $\Delta M = 1.2$ GeV, or $m(J/\psi \phi) = 4.3$ GeV, among the two mass spectra even though they are of low significance and are not exactly aligned to the same position.

Fig. 8. A direct comparison of $J/\psi \phi$ mass or $\Delta M$ distributions among CDF, LHCb.
An excess seems quite pronounced at higher mass in the LHCb spectrum, which becomes visually more striking when their data is rebinned to 8 MeV, as shown in Fig. 9 (left). An estimation from my simple fit of this excess, shown in Fig. 9 (right), gives the rough parameters of a possible second structure as: mass $4.300 \pm 0.004$ GeV, width $20 \pm 10$ MeV, yield $36 \pm 12$, and a local significance of about $3\sigma$ (in each case with statistical uncertainties only). The simple model assumed here did not have the efficiency correction, and the mass resolution was assumed to be 2 MeV. The excess was represented by a Breit-Wigner convoluted with Gaussian resolution function, and the background was a three-body phase space shape. We are left with the intriguing prospect that there probably is evidence for this second $J/\psi\phi$ structure in LHCb data—although it is not in very good accord with CDF’s parameters. The latter fact helps explain LHCb’s negative report of a signal: because they imposed CDF parameters in their search the apparent yield was compatible with background. However, given the difficulties of extracting mass parameters for broad weak signals the poor consistency between CDF and LHCb may not be so surprising.

The width and relative BF for the second structure are consistent among the two experiments. However, the mass is about $2.4\sigma$ inconsistent between LHCb and CDF’s result assuming negligible systematic uncertainty from LHCb experiment.

Overall, there is obvious activity going on around $\Delta m = 1.2$ GeV or $m(J/\psi\phi) = 4.3$ GeV. However, the locations from various experiments are not in very good agreement, but yet they are not entirely inconsistent. More data from the LHC should fully resolve the situation.

4.2. Possible Interpretations and Outlook

Various explanations have been proposed for these structures in the $J/\psi\phi$ spectrum, but their nature is still not understood. Further joint experimental and theoretical effort is needed to completely understand their origin. I will summarize the
possible interpretations based on what is currently known including conventional charmonium, molecular, hybrid, non-resonance effects. Recently there was also a hadro-charmonium proposal which is a QCD analog of the van der Waals force. Hadro-charmonium is a new type of bound state formed by binding a relatively compact charmonium state inside an excited state of light hadronic matter. The charmonium state behaves like a compact sub-object inside the new state such that the loosely bound states decay into this charmonium and light mesons. However, there is no detailed calculations for $J/\psi \phi$ structures so far and I therefore pass over it in the following discussion.

$Y(4140)$ options. Conventional charmonium: The $Y(4140)$ mass is well beyond the open charm threshold, and thus it would be expected to decay dominantly into open charm pairs with a large width and to decay into $J/\psi \phi$ with a tiny branching fraction. For instance, the upper limit on the branching fraction of $Y(4140)$ as the second radial excitation of the $P$-wave charmoniums $\chi'_c(J = 0, 1)$ decaying into hidden charm is calculated to be in the order of $10^{-4}$ to $10^{-3}$. This implies that the $J/\psi \phi$ is not likely to be a discovery channel for these conventional $\chi$-states, and correspondingly, that the $Y(4140)$ is unlikely to be a conventional charmonium state.

$D_s^*+D_s^-$ molecule: Due to the similarity between $Y(4140)$ and $Y(3940)$, such as their decay channels and near threshold masses, the $D_s^*+D_s^-$ molecular state explanations to $Y(4140)$ and $Y(3940)$ were proposed in Ref.\textsuperscript{76} respectively. The $D_s^*+D_s^-$ threshold is about 80 MeV above the $Y(4140)$ mass, and thus the system would have a binding energy of 100 MeV. The $D_s^*+D_s^-$ molecule is bound together through attraction provided by meson exchange. It decays into two-body hidden-charm final states via the re-scattering of $D_s^*+D_s^-$ and into two-body open charm states via the exchange of light mesons, and it does so with roughly equal probability.\textsuperscript{82} Each sub-system in the molecule could decay into $DK$ pair, but it is not kinematically allowed (i.e. $DK$ mass is above $D_s^*$), thus the $D_s^*+D_s^-$ molecule has narrow natural width. To further test the molecular hypothesis of $Y(4140)$, the experimental measurement of the photon spectrum of $Y(4140) \rightarrow D_s^*+D_s^-\gamma, D_s^*+D_s^-\gamma$ are suggested. The $D_s^*+D_s^-$ molecule seems a viable interpretation of $Y(4140)$, but no concrete conclusion can be made. Furthermore, the two-photon partial width measured by Belle experiment\textsuperscript{53} disfavor the interpretation of $D_s^*+D_s^-\gamma$ with $J^{PC}= 0^{++}$ or $2^{++}$ for $Y(4140)$. $c\bar{c}q\bar{q}$ tetra-quark state: The $J/\psi \phi$ decay channel of $Y(4140)$ contains $c\bar{c}$ and $s\bar{s}$ components, thus it was also considered as a $c\bar{s}s\bar{s}$ tetra-quark state without sub-systems inside through rearrangement of the constitute quarks with a width of about 100 MeV, and about equal probabilities for both hidden and open-charm two-body decays. The observed width does not seems support this proposal. Charmonium hybrid state: Since the $Y(4140)$ mass is in the range of 4.1-4.4 GeV as predicted by various models for charmonium hybrid states, it is also considered as a charmonium hybrid candidate. The width of a hybrid is expected to be broad, however if it has exotic $J^{PC}$ of $1^{-+}$ and its mass lies below the threshold of $D^{(*)}D$, then its width can be narrow.\textsuperscript{83} This model predicts $D^*\bar{D}$ an an important decay. Non-resonance
Besides exotic resonance proposals, there are non-resonance proposals. For instance, a kinematical effect due to the opening of the $J/\psi\phi$ channel, with the creation of a $s\bar{s}$ pair and further forming a $\phi$ resonance surrounding the $c\bar{c}$ pair, the cross section rises and then falls rapidly to produce a peak-like structure, but this has nothing to do with being a resonance.

**Y(4274) options. Conventional charmonium:** The $Y(4274)$ mass is even further beyond the open charm threshold compared to $Y(4140)$, and thus it is also very unlikely to be conventional charmonium. $\bar{D}_sD^0(2317)$ molecule: Since the mass of $Y(4274)$ is close to $\bar{D}_sD^0(2317)$, like the proximity between $Y(4140)$ mass to the $D^+_sD^-_s\gamma$ and $Y(4274)\rightarrow D^+_sD^-_s\pi^0$ etc, which should be searched for. **Charmonium hybrid state:** Another possibility is that this structure can be a hybrid charmonium. A recent Lattice QCD calculation of hybrid charmonium with an exotic $J^{PC}$ of $1^{-+}$ yields a mass around the observed mass of this structure.

**X(4350) options. Conventional charmonium:** The $X(4350)\rightarrow J/\psi\omega$, similar to $X(3915)\rightarrow J/\psi\omega$, was discovered in the two-photon process, which is an abundant source of charmonium production via $\gamma\gamma$ fusion. The $J^{PC}$ possibilities of $1^{-+}$, $1^{++}$ and $3^{-+}$ are excluded due to Yang’s Theorem. Under the $P$-wave charmonium assignment to $X(3915)$ and $X(4350)$, the $J^{PC}$ quantum numbers of these two states must be $0^{++}$ and $2^{++}$ respectively, which shows that $X(3915)$ and $X(4350)$ can be as the second and third radial excitations of $\chi_{c0}$ and $\chi_{c2}$ respectively. And these authors found that the calculated mass spectrum and two-body OZI-allowed strong decay behavior are consistent with experimental results. $D^*_s\bar{D}_s^*$ molecule: The $X(4350)$ is also proposed as a $D^*_s\bar{D}^0_s$ molecular state\(^{59}\) as well as charmonium-virtual molecular ($c\bar{c}$-$D^*_s\bar{D}^*_s$) mixing state\(^{92}\). As this is only observed in two-photon process so far, the Belle II program would provide the large increase in yield that will make further investigations possible before it appears in other process at the LHC.

Finally, there are also a number of interesting phenomenological observations to be made. First, there are similar near threshold excesses which have already been observed in light vector mesons through radiative $J/\psi$ or exclusive $B$ decays: the near threshold enhancements for two isospin-0 vectors $\phi\phi$, $\omega\omega$, and $\omega\phi$\(^{93-99}\) and the near threshold enhancement for two isospin-1 vectors $\rho\rho$\(^{100,101}\). However, there has been no clear structure observed that decays into two vectors that one of them has isospin-1 and the other has isospin-0–$\phi\rho$ or $\omega\rho$\(^{102}\). These near threshold enhancements for two light isospin-0 vectors could possibly be connected to the $Y(3940)\rightarrow J/\psi\omega$ and $Y(4140)\rightarrow J/\psi\phi$ since both $J/\psi$ and $\phi$ have isospin-0 and are very close to the two vector threshold. Second, it is striking that there are at least two structures observed in the same $J/\psi\phi$ spectrum from the same exclusive $B$ decays. The two structures do not need to arise from the same mechanism, but if they are, this could be a pointer to a new kind of spectroscopy. It will also be
interesting to search for vector-vector structures composed entirely of c and b quarks near threshold because they may offer simpler systems to model theoretically.

5. Summary

The discovery of the $X(3872)$ in 2003 initiated a new chapter in the study of exotic states. The evidence found in the $J/\psi \phi$ mass spectrum from exclusive $B$ decays and two-photon process provide several exotic charmonium candidates: they all have a mass well beyond the open-charm pair threshold, a relatively narrow width, positive C-parity, and do not fit into the conventional charmonium picture. All of these reported structures need further studies. Various possible interpretations such as molecule, tetra-quark, charmed hybrid, nuclei-like structures have been proposed but none of them is established. The $pp$ run at the LHC is now over until 2015, but CMS has roughly four times more data on tape to be analyzed and LHCb is expected to have about ten times the data to be analyzed. ATLAS, on the other hand, has not yet been heard from but they can also contribute to the current studies. The properties of these structures, such as mass, width, decay channels and quantum numbers, can be studied with increased statistics. At the LHC one can also search in other heavy quarkonium decay channels for vector-vector analogs of the $J/\psi \phi$ structures. With joint experimental and theoretical effort, hopefully we will obtain a clear grand picture and eventually understand the nature of these queer structures—which may indeed lead us to a new kind of spectroscopy.

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References

1. J. Beringer et al. (Particle Data Group), Phys. Rev. D 86, 010001 (2012).
2. F. Abe et al, CDF Collaboration, Phys. Rev. Lett. 81, 2432 (1998).
3. F. Abe et al, CDF Collaboration, Phys. Rev. D 58, 112004 (1998).
4. A. Abulencia et al., CDF Collaboration, Phys. Rev. Lett. 96 082002 (2006).
5. T. Aaltonen et al., CDF Collaboration, Phys. Rev. Lett. 100 182002 (2008).
6. V.M. Abazov et al., D0 Collaboration, Phys. Rev. Lett. 101 012001 (2008).
7. R. L. Jaffe, Phys. Rev. D 15 267 (1977).
review of $J/\psi\phi$ 19

8. M. Gell-Mann, Phys. Lett. B 8, 214 (1964).
9. G.S. Bali, et al., Phys. Lett. B 309, 378 (1993).
10. C. J. Morningstar and M. Peardon, Phys. Rev. D 60, 034509 (1999).
11. C. Morningstar and M. Peardon, Phys. Rev. D 60, 034509 (1999).
12. W.J. Lee and D. Weingarten, Phys. Rev. D 61, 014015 (2000).
13. F.E. Close and A. Kirk, Eur. Phys. J. C 21, 531 (2001).
14. C. Amsler and N.A. Tornqvist, Phys. Reports 389, 61 (2004).
15. C. Morningstar and M. Peardon, Phys. Rev. D 60, 034509 (1999).
16. W.J. Lee and D. Weingarten, Phys. Rev. D 61, 014015 (2000).
17. F. Eichten et. al., Phys. Rev. D 17, 3090 (1978).
18. S. Pakvasa, and M. Suzuki, Phys. Lett. B 579, 67-73 (2004).
19. T. Aaltonen et al., CDF Collaboration, Phys. Rev. Lett. 103, 152001 (2009).
20. A. Abulencia et al., CDF Collaboration, Phys. Rev. Lett. 96, 102002 (2006).
21. A. Abulencia et al., CDF Collaboration, Phys. Rev. Lett. 98, 132002 (2007).
22. P. del Amo Sanchez et al., BaBar Collaboration, Phys. Rev. 82, 011101R (2010).
23. E. Eichten et. al., Phys. Rev. D 57, 5653-5657 (1998).
24. S. Eidelman et al., Phys. Rev. D 60, 034509 (1999).
56. A.B. Arbuzov et al., J. High Energy Phys. 9812, 009 (1998).
57. S. Binnew, J.H. Kuhn, and K. Melnikov, Phys. Lett. B 459, 279 (1999).
58. M. Benayoun et al., Mod. Phys. Lett. A 14, 2605 (1999).
59. N.V. Drenska, R. Faccini, and A.D. Polosa, Phys. Rev. D 79 077502 (2009).
60. C. N. Yang, Phys. Rev. 77, 242 (1950).
61. A. Anastassov et al., CLEO Collaboration, Phys. Rev. Lett. 84, 1393(2000).
62. A. Aubert et al., BaBar Collaboration, Phys. Rev. Lett. 91, 071801 (2003).
63. D. Acosta et al., CDF Collaboration, Phys. Rev. D 71, 032001 (2005).
64. A. Abulencia et al. CDF Collaboration, Phys. Rev. Lett. 97, 242003 (2006).
65. A. Abashian et al., Belle Collaboration, Nucl. Instrum. Methods Phys. Res., Sect. A 479, 117 (2002).
66. A. A. Alves Jr et al., LHCb Collaboration, JINST 3, S08005 (2008).
67. J. Brodzicka, http://belle.kek.jp/belle/talks/LP09/Brodzicka.pdf, Lepton-Photon 2009, Hamburg.
68. K, Miyabayashi, “Other charmonium and cc-like results at Belle”, Quarkonium Working Group Workshop, 2010 Fermilab.
69. R. Aaij et al., LHCb Collaboration, Phys. Rev. D 85, 091103(R) (2012).
70. W. Qian, “XYZ at hadron colliders”, Workshop for New Results on Charmonium Production and Decays, March 6-8, 2013, Orsay France.
71. S. Brodsky, I. A. Schimit, and G. F. Teramond, Phys. Rev. Lett. 64 1011 (1990); D. A. Wasson, Phys. Rev. Lett. 67 2237 (1991).
72. S. Dubynsky and M.B. Voloshin, Phys. Lett. B 666, 344 (2008); I.V. Danilkin, V.D. Orlovsky, and Yu.A. Simonov, Phys. Rev. D 85 034012 (2012).
73. X. Liu, Phys. Lett. B 680, 137 (2009) [arXiv:0904.0136 [hep-ph]].
74. K. Abe et al., Belle Collaboration, Phys. Rev. Lett. 94 182002 (2005).
75. B. Aubert et al., Babar Collaboration, Phys. Rev. Lett. 101 082001 (2008).
76. X. Liu and S. -L. Zhu, Phys. Rev. D 80, 017502 (2009) [Erratum-ibid. D 85, 019902 (2012)] [arXiv:0903.2529 [hep-ph]].
77. N. Mahajan, Phys. Lett. B 679, 228 (2009) [arXiv:0903.3107 [hep-ph]].
78. T. Branz, T. Gutsche and V. E. Lyubovitskij, Phys. Rev. D 80, 054019 (2009) [arXiv:0903.5424 [hep-ph]].
79. J. -R. Zhang and M. -Q. Huang, Phys. Rev. D 80, 056004 (2009) [arXiv:0906.0090 [hep-ph]].
80. R. M. Albuquerque, M. E. Bracco and M. Nielsen, Phys. Lett. B 678, 186 (2009) [arXiv:0903.5540 [hep-ph]].
81. G. -J. Ding, Eur. Phys. J. C 64, 297 (2009) [arXiv:0904.1782 [hep-ph]].
82. F. Stancu, J. Phys. G 37, 075017 (2010) [arXiv:0906.2485 [hep-ph]].
83. P. R. Page, Phys. Lett. B 402 183-188 (1997).
84. E. van Beveren and G. Rupp, [arXiv:0906.2278 [hep-ph]].
85. L. -L. Shen, X. -L. Chen, Z. -G. Luo, P. -Z. Huang, S. -L. Zhu, P. -F. Yu and X. Liu, Eur. Phys. J. C 70, 183 (2010) [arXiv:1005.0994 [hep-ph]].
86. X. Liu, Z. -G. Luo and S. -L. Zhu, Phys. Lett. B 699, 341 (2011) [Erratum-ibid. B 707, 577 (2012)] [arXiv:1011.1045 [hep-ph]].
87. J. He and X. Liu, Eur. Phys. J. C 72 1986 (2012); S. Finazzo, M. Nielsen, and X. Liu, Phys. Lett. B 701 101-106 (2011);
88. Z. Wang, Int. J. Mod. Phys. A 26 4929-4943 (2011).
89. L. Liu et al. [Hadron Spectrum Collaboration], JHEP 1207, 126 (2012) [arXiv:1204.5425 [hep-ph]].
90. X. Liu, Z. -G. Luo, Z. -F. Sun and , Phys. Rev. Lett. 104, 122001 (2010) [arXiv:0911.3694 [hep-ph]].
91. J. R. Zhang and M. Q. Huang, Commun. Theor. Phys. 54 1075-1090 (2010).
92. Z. -G. Wang, Phys. Lett. B 690, 403 (2010) [arXiv:0912.4626 [hep-ph]].
93. A. Etkin et al., Phys. Rev. Lett. 49 1620 (1982).
94. J. E. Augustin et al., DM2 Collaboration, Nucl. Phys. Proc. Suppl. 21 136-141 (1991).
95. Z. Bai et al., MARK-III Collaboration, Phys. Rev. Lett. 65 1309-1312 (1990).
96. M. Ablikim et al., BES Collaboration, Phys. Lett. B 662 330-335 (2008).
97. M. Ablikim et al., BES Collaboration, Phys. Rev. Lett. 96 162002 (2006).
98. C. Liu et al., Belle Collaboration, Phys. Rev. D 79 071102(R) (2009).
99. M. Ablikim et al., BES Collaboration, Phys. Rev. D 73 112007 (2006).
100. D. Bisello et al., DM2 Collaboration, Phys. Rev. D 39 701 (1989).
101. Z. Bai et al., BES Collaboration, Phys. Lett. B 472 207-214 (2000).
102. M. Ablikim et al., BES Collaboration, Phys. Rev. D 77 012001 (2008).