SLAC-PUB-12317
January 2007

Looking for Exotica at the B Factories

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Invited talk at the 17th DAE-BRNS High Energy Physics Symposium,
IIT, Kharagpur, India, December 11–15, 2006.

SLAC-PUB-12317
January 22, 2007

Abstract

Current experiments at the B factories, designed to perform precision measurements of matter-antimatter asymmetry in the B meson system, have a much broader physics reach especially in the sector of quarkonium spectroscopy. Here we present a minireview on the new charmonium-like states observed at the B factories including the $X(3872)$ and $Y(4260)$.

1 Introduction

More than 30 years after the November Revolution, quarkonium spectroscopy seems to be on a great resurgence trail thanks to the discovery of many new states at the B factories and elsewhere. It all began with the discovery of the enigmatic $D_{sJ}(2317)$ resonance by the *BABAR* Collaboration in April 2003[1]. Soon after CLEO, Belle, CDF and DØ at Fermilab, and BES joined the marathon raising the number almost to the double digits. This collection of new states has in some cases confirmed quark model and lattice QCD calculations while a few others poses serious challenge to our current understanding of the strong interaction. In this report I present an experimental survey of new charmonium-like states discovered and studied at the B factories; the *BABAR* experiment[2] at the PEP-II asymmetric energy e^+e^- storage

Work supported in part by the US Department of Energy contract DE-AC02-76SF00515

rings located at the Stanford Linear Accelerator Center (SLAC) in the US, and the Belle experiment[3] at the KEKB energy-asymmetric e^+e^- collider in Tsukuba, Japan.

This minireview starts with some brief remarks on unique features of the experiments those in conjunction with the high precision data delivered by the B factories have made this quarkonium sojourn a reality! The bulk of this report is concentrated on the six new states, namely $X(3872)$, $X(3940)$, $Y(3940)$, $Y(4260)$, $Y(4320)$, and $Z(3930)$ followed by possible theoretical model(s) to explain them. In the last section I summarize my conclusions about these states.

2 Experiments at the Beauty Factories

Both B-factory experiments, *BABAR* and Belle are designed to carry out precision CP violation measurements on the beauty meson sector, so it is natural they have so much in common. In particular, they have:

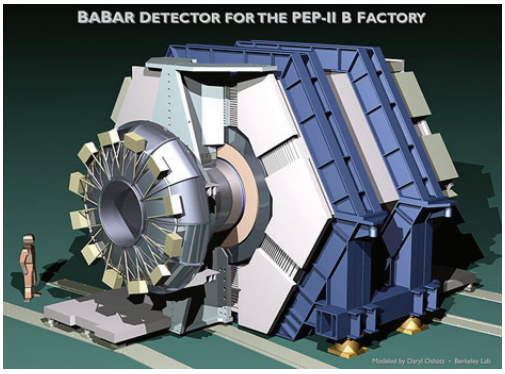
- A precision tracking system composed of a silicon vertex detector, whose main role is to locate the secondary decay vertices close to the origin, and a central drift chamber that measures momenta and angles of charged particles.

- Excellent charged-particle identification (PID) capability accomplished by combining information on the specific ionization (dE/dx) in the two tracking devices with that of a dedicated PID system. For the latter, *BABAR* uses an innovative design in the Detector of Internally Reflected Cerenkov radiation. Belle makes use of an array of time-of-flight counters whose performance is augmented by an Aerogel Cerenkov Counter system at higher momenta.

- An electromagnetic calorimeter, comprising CsI(Tl) crystals, which is used to measure the energies and angular positions of photons and electrons.

- Iron flux return of the magnet instrumented with resistive plate chambers to identify muons and neutral hadrons over a broad kinematic range.

Figure 1 shows the layout of the *BABAR* and Belle detectors. Although it is the overall performance that drives the thing, the most important detector



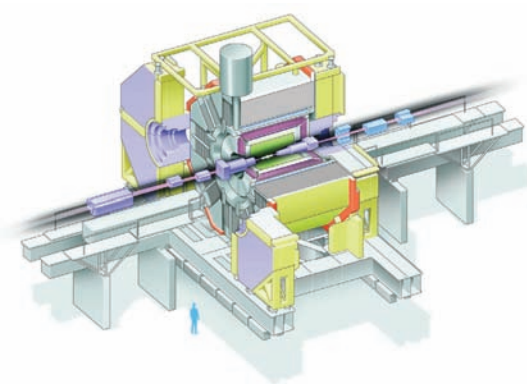


Figure 1: Layout of the *BABAR* and Belle detectors.

components for spectroscopic studies are the PID system and the calorimetry. To add on to this brilliant detector performance, the B factories are accumulating high quality data by leaps and bounds. The results reported here are based on data collected by *BABAR* and Belle although relevant results from other experiments will be cross-referenced as appropriate.

3 Ensemble of Exotica

3.1 $X(3872)$ - the poster boy

The $X(3872)$ was first observed in the decay $B^- \to X(3872)K^-, X \to J/\psi\,\pi^+\pi^-$[4] by the Belle Collaboration[5] and subsequently confirmed by the *BABAR*[6], CDF[7] and DØ[8] Collaborations. The mass of this state is $m = 3871.2 \pm 0.5\,\mathrm{MeV}$ and the width is $\Gamma < 2.3\,\mathrm{MeV}$ at 90 % confidence level (CL) which is consistent with the detector resolution. Study of the $\pi^+\pi^-$ invariant mass distribution in the decay $X(3872) \to J/\psi\,\pi^+\pi^-$ suggests that it may proceed through an intermediate ρ^0 resonance. If so, one can expect to find its charged isospin partner $X(3872)^-$. *BABAR* has searched for this state in the decays $B^- \to J/\psi\,\pi^-\pi^0 K^0_S$ and $B^0 \to J/\psi\,\pi^-\pi^0 K^+$. However, no evidence for a charged $X(3872)$ has been found[9] and we set the following upper limits at 90 % CL: $\mathcal{B}(B^- \to X(3872)^- K^0_S, X^- \to J/\psi\,\pi^-\pi^0) < 11 \times 10^{-6}$ and $\mathcal{B}(B^0 \to X(3872)^- K^+, X^- \to J/\psi\,\pi^-\pi^0) < 5.4 \times 10^{-6}$. A search for $X(3872)$ in the initial state radiation (ISR) process $e^+e^- \to X(3872)\gamma_{ISR}$ via the decay to $J/\psi\,\pi^+\pi^-$ has yielded a null result[10]. This strongly disfavors a $J^{PC} = 1^{--}$ assignment to X. On the other hand, strong evidence

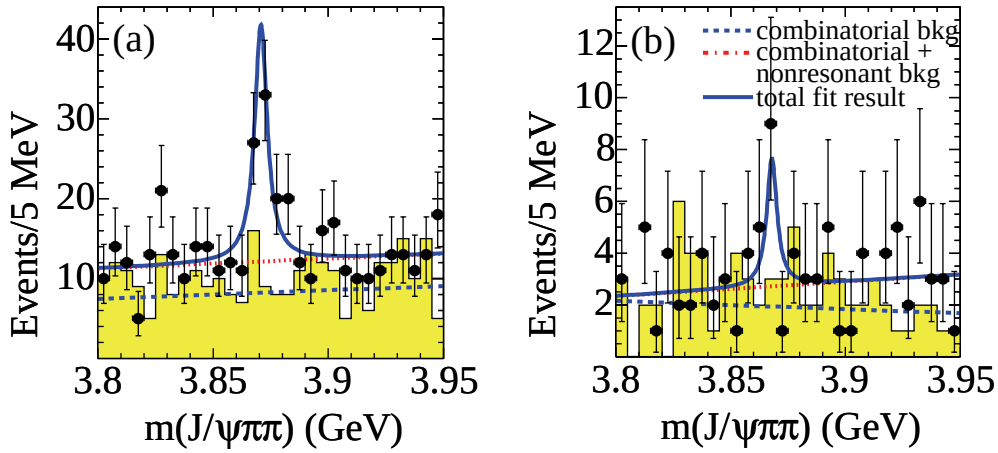


Figure 2: The $J/\psi\pi^+\pi^-$ invariant mass distribution in the signal region for (a) $B^- \to X(3872)K^-$ and (b) $B^0 \to X(3872)K^0_S$ decays from *BABAR*.

of the radiative decay $X(3872) \to J/\psi\,\gamma$ by both *BABAR*[11] and Belle[12] experiments implies $C = +1$. This when added together with angular analysis results from Belle[13] and CDF[14], a J^{PC} value of 1^{++} for the $X(3872)$ seems most likely. The only known charmonium candidate that can come close to this pattern of measurements is χ'_{c1}, but it has an expected mass of 3950 MeV. Clearly an alternative approach beyond the traditional charmonium model is needed to explain this state. The small width of the $X(3872)$ and its proximity to the $D^0\overline{D}^{*0}$ threshold, 3871.8 ± 0.5 MeV, have led to the current two most-popular proposals; *i.e.* it could be a weakly bound $D\overline{D}^*$ molecule-like state[15] or a diquark-antidiquark state[16]. To investigate these models, both *BABAR* and Belle have updated their earlier studies with higher statistics, and by looking into other decay modes.

Using a dataset comprising about 232 million $B\overline{B}$ pairs, *BABAR* has studied the decays $B^- \to J/\psi\,\pi^+\pi^-K^-$ and $B^0 \to J/\psi\,\pi^+\pi^-K^0_S$. Figure 2 shows the $J/\psi\,\pi^+\pi^-$ invariant mass distributions for these two B decay modes[17] which are fitted to a nonrelativistic Breit-Wigner shape for the signal, and to a linear function for the nonresonant and combinatorial backgrounds. For the charged B mode, we obtain 61.2 ± 15.3 while for the B^0 mode only 8.3 ± 4.5 signal events. These yields are then translated to the respective branching fractions by taking efficiency corrections into account: $\mathcal{B}^- \equiv \mathcal{B}(B^- \to X(3872)K^-, X \to J/\psi\,\pi^+\pi^-) = (10.1 \pm 2.5 \pm 1.0) \times 10^{-6}$

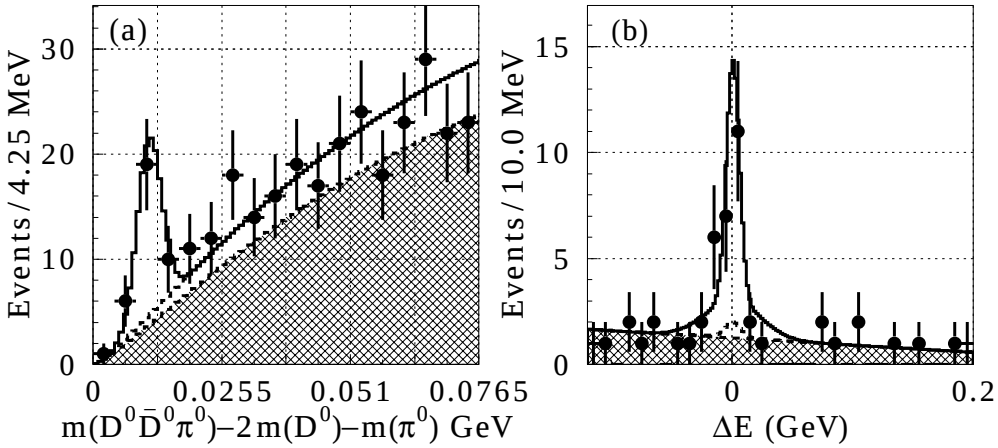


Figure 3: The projections of (a) Q-value and (b) ΔE distribution in the signal region from Belle. Dots are the data points, the hatched histogram corresponds to the combinatorial background; the dashed histogram denotes the total background while the solid line is the combined fit result.

and $\mathcal{B}^0 \equiv \mathcal{B}(B^0 \to X(3872)K^0_S, X \to J/\psi\,\pi^+\pi^-) = (5.1 \pm 2.8 \pm 0.7) \times 10^{-6}$, where uncertainties are statistical and systematic, respectively. From these we derive a ratio of the branching fractions, $\mathcal{R} = \mathcal{B}^0/\mathcal{B}^- = 0.50 \pm 0.30 \pm 0.05$. We also measure the mass difference of the $X(3872)$ state from the charged and neutral B decay modes, Δm, to be $2.7 \pm 1.3 \pm 0.2\,\mathrm{MeV}$. The diquark-antidiquark model predicts $\mathcal{R} = 1$ and Δm to be $7 \pm 2\,\mathrm{MeV}$. The expected ratio of branching fractions is consistent with our measurement, $0.13 < \mathcal{R} < 1.10$ at 90 % CL, and the observed Δm is consistent with zero, and with the model prediction within two standard deviations (σ). This result seems to slightly disfavor the molecule model that predicts $\mathcal{R}$ to be at most 10 %.

Belle has reported the observation of a near-threshold enhancement in the $D^0\overline{D}^0\pi^0$ system from both neutral and charged decays of $B \to D^0\overline{D}^0\pi^0 K$[18]. To determine the exact peak position as well as the branching fraction, the two-dimensional distribution of ΔE *i.e.* the difference of energy of the B candidate and the beam energy *vs.* Q-value ($= m_{D^0\bar{D}^0\pi^0} - 2m_{D^0} - m_{\pi^0}$) is fitted. Projections onto Q-value for $|\Delta E| < 25\,\mathrm{MeV}$ and ΔE for $6\,\mathrm{MeV} < Q\text{-value} < 14\,\mathrm{MeV}$ are shown in Figure 3 along with the total fit result. The observed $D^0\overline{D}^0\pi^0$ mass is found out to be $3875.2 \pm 0.7^{+0.3}_{-1.6} \pm 0.8\,\mathrm{MeV}$, where the first error is statistical, the asymmetric one is due to uncertainty on the π^0 energy scale and the last one is due to the uncertainty associated

with the D^0 mass. Assuming the threshold peak is due to the production and subsequent decay of $X(3872)$ to $D^0\overline{D}^0\pi^0$ final state, this measurement is $2\,\sigma$ higher than the world-average value of $X(3872)$ mass reported earlier. Corresponding branching fractions for the neutral and charged modes are $\mathcal{B}(B^0 \to X(3872)K^0_S, X \to D^0\overline{D}^0\pi^0) = (1.66 \pm 0.70^{+0.32}_{-0.37}) \times 10^{-4}$ and $\mathcal{B}(B^- \to X(3872)K^-, X \to D^0\overline{D}^0\pi^0) = (1.02 \pm 0.31^{+0.21}_{-0.29}) \times 10^{-4}$. This can be translated to $\mathcal{R}$ (ratio of branching fractions) to be little over one which is in reasonable agreement with the diquark-antidiquark model. However, we need more data to discriminate convincingly between these two models.

3.2 $X(3940)$ in double charmonium

At the B factories exclusive B decays are not the only source of charmonium states. *BABAR* has also studied double charmonium production in the process $e^+e^- \to \gamma^* \to J/\psi\, c\overline{c}$ using $124\,\mathrm{fb}^{-1}$ of data[19]. Only $c\overline{c}$ states with even C-parity are expected in this reaction, although if there is a contribution from $e^+e^- \to \gamma^*\gamma^* \to J/\psi\, c\overline{c}$, odd C-parity states could also be produced. In this study, we first reconstruct a J/ψ candidate via the e^+e^- or $\mu^+\mu^-$ decay mode and then calculate the mass of the system recoiling against it. Three even C-parity charmonium states, η_c, χ_{c0}, and $\eta_c(2S)$ are observed, while there is no evidence for any odd C-parity state such as the J/ψ. The distribution is fitted to obtain the yield for each state, from which the production cross section is calculated. Due to the requirement of at least five charged tracks in the event for background suppression purposes, we report the product of the production cross section and the branching fraction to states with more than two tracks. The results are $17.6 \pm 2.8^{+1.5}_{-2.1}\,\mathrm{fb}$, $10.3 \pm 2.5^{+1.4}_{-1.8}\,\mathrm{fb}$ and $16.4 \pm 3.7^{+2.4}_{-3.0}\,\mathrm{fb}$ for η_c, χ_{c0} and $\eta_c(2S)$, respectively. The Belle measurement[20] in these three charmonium states agrees with *BABAR* and both are an order of magnitude higher than those predicted by nonrelativistic QCD[21]. However, recent works incorporating charm quark dynamics[22] seem to narrow down the discrepancy.

An interesting addendum to these measurements is the observation of a new resonance by Belle[20] at a Breit-Wigner mass of $3943 \pm 6 \pm 6\,\mathrm{MeV}$ and width $15.4 \pm 10.1\,\mathrm{MeV}$ as shown in Figure 4. The new state $X(3940)$ is found to decay to $D\overline{D}^*$, but not to $D\overline{D}$ or $\omega J/\psi$. The dominance of the $D\overline{D}^*$ decay mode hints at the possibility that the $X(3940)$ is the $2^3P_1(c\overline{c})$ χ'_{c1} state. It is natural to try the $2P(c\overline{c})$ since 2^3P_J states are predicted to lie in the mass window of $[3920, 3980]\,\mathrm{MeV}$ with expected widths $20 - 130\,\mathrm{MeV}$. The problem with this interpretation is, however, there is no clear-cut evidence for

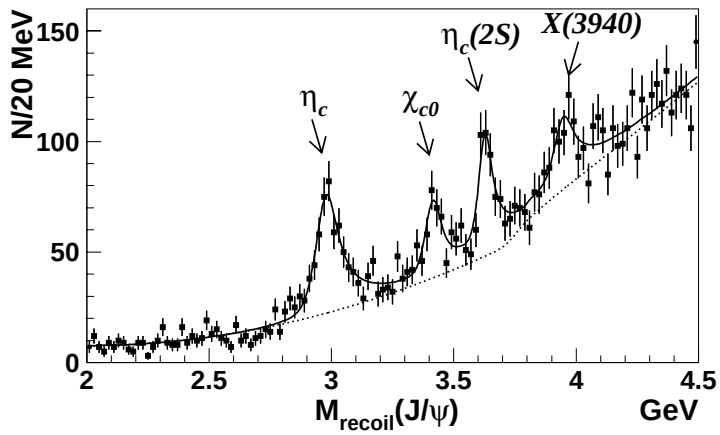


Figure 4: The X(3940) signal in the J/ψ recoil mass spectrum of the double charmonium production process from Belle. Black dots are data, the dashed curve is the background contribution while total fit result is denoted by the solid line.

the $2^3P_1(c\overline{c})$ χ_{c1} in the plot. Thus one is bound to suspect that the χ'_{c1} should not be a strong signal in this reaction. This has led to alternative speculations that $X(3940)$ could be the radially-excited η''_c. Unfortunately this also has its own problem as the expected η''_c mass is $4040 - 4060\,\mathrm{MeV}$, approximately $100\,\mathrm{MeV}$ higher than the measured value. An angular analysis of the decay products will cast some light on the quantum numbers of $X(3940)$ and hence help on unambiguously identifying the state.

3.3 The $Y(3940)$ - is it a twin?

Belle claims the discovery of a second resonance at $3940\,\mathrm{MeV}$[23], this time as a threshold enhancement in the $\omega J/\psi$ subsystem of the process $B \to K\omega J/\psi$, $\omega \to \pi^+\pi^-\pi^0$. The reported mass and width are $3943 \pm 11(\mathrm{stat}) \pm 13(\mathrm{syst})\,\mathrm{MeV}$ and $87 \pm 22(\mathrm{stat}) \pm 26(\mathrm{syst})\,\mathrm{MeV}$, respectively. The new state is referred as $Y(3940)$ and has not been seen in the decay mode $Y \to D\overline{D}$ or $D\overline{D}^*$. The mass and width being similar to those of $X(3940)$ suggests Y could be a radially excited P-wave charmonium. However, the $\omega J/\psi$ decay mode is peculiar in a sense that Belle measures $\mathcal{B}(B \to KY(3940))\mathcal{B}(Y \to \omega J/\psi) = (7.1 \pm 1.3 \pm 3.1) \times 10^{-5}$ while we expect $\mathcal{B}(B \to K\chi'_{cJ}) < \mathcal{B}(B \to K\chi_{cJ})\{= (4 \pm 1) \times 10^{-4}\}$. So if we have to identify $Y(3940)$ with χ'_{cJ}, it

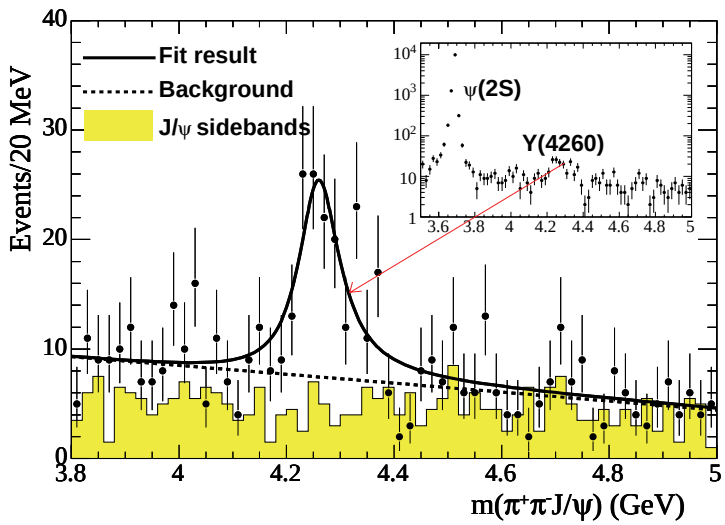


Figure 5: The $J/\psi\pi^+\pi^-$ invariant mass spectrum in the range 3.8−5.0 GeV and (inset) over a wider range that includes the $\psi(2S)$ state from *BABAR*.

would imply $\mathcal{B}(Y \to \omega J/\psi) > 12\,\%$, which is quite unusual for a canonical $c\bar{c}$ state above the open charm threshold.

Thus the $Y(3940)$ is something of an enigma, driving the claim of the Belle collaboration that it is a charmonium hybrid. The large width coupled with the unusual decay mode are consistent with the claim that a hybrid should have strongly suppressed $D\overline{D}$, $D\overline{D}^*$ or $D^*\overline{D}^*$ decay modes. However, a mass less than 4000 MeV is in conflict with the lattice QCD computations of low-lying hybrid spectrum. Thus more data are required before any concrete statement can be made on the exotic nature of $Y(3940)$.

3.4 Observation of the $Y(4260)$

ISR events produced in the $\Upsilon(4S)$ energy region at the B factories serve to probe interesting physics occurring at lower center-of-mass energies. Motivated by this, *BABAR* has investigated the process $e^+e^- \to J/\psi\,\pi^+\pi^-\gamma_{ISR}$ across the charmonium mass range, using a data sample of 233 fb^{-1} integrated luminosity[24]. These events are characterized by two pions, two leptons (electron or muon) making a J/ψ candidate and a small recoil mass squared against the $J/\psi\,\pi^+\pi^-$ system. Figure 5 shows the $J/\psi\,\pi^+\pi^-$ invariant mass spectrum for the selected candidates. A clear enhancement near

4.2 GeV is observed in addition to the expected $\psi(2S)$ peak. No other structure is evident in the spectrum, including the $X(3872)$. Using a maximum likelihood fit in which the signal is described by a single relativistic Breit-Wigner lineshape, we obtain a yield of 125 ± 23 events with a statistical significance of $8\,\sigma$ (the signal is referred to as the $Y(4260)$). Assuming the peak is due to a single resonance, the mass and width are determined to be $4259 \pm 8^{+2}_{-6}$ MeV and $88 \pm 23^{+6}_{-4}$ MeV, respectively. We also calculate a value of $\Gamma(Y(4260) \to e^+e^-) \cdot \mathcal{B}(Y \to J/\psi\,\pi^+\pi^-) = 5.5 \pm 1.0^{+0.8}_{-0.7}$ eV. Detection in the ISR process indicates $J^{PC} = 1^{--}$ for $Y(4260)$. We have weak evidence for $Y(4260)$ in the exclusive B decays[11]. In addition, it has been confirmed by the CLEO[25] and Belle[26] collaborations although at a slightly higher mass.

There are number of competing theoretical interpretations floating around the market to explain $Y(4260)$, such as charmonium hybrid[27], hadronic molecule[28] *etc.*. However, we would need a multitude of measurements with higher statistics to further pin down its properties, and hence the accompanying model.

3.5 Hot of the press - the $Y(4320)$?

In an effort to clarify the nature of the $Y(4260)$, *BABAR* has carried out a study of the process $e^+e^- \to \psi(2S)\,\pi^+\pi^-, \psi(2S) \to J/\psi\,\pi^+\pi^-$ using ISR events over a wide kinematic range from the threshold up to 8 GeV[29]. The data represent an integrated luminosity of $272\,\mathrm{fb}^{-1}$ recorded at $\sqrt{s} = 10.58$ GeV, near the $\Upsilon(4S)$ resonance, and $26\,\mathrm{fb}^{-1}$ recorded near 10.54 GeV. First a J/ψ candidate is reconstructed through the decay $J/\psi \to \ell^+\ell^-$ ($\ell = e$ or μ) which is combined with a pair of pion tracks to form $\psi(2S)$. Another pair of pions is then combined with the $\psi(2S)$ candidate and the resultant invariant mass distribution is studied. The detection of the accompanying ISR photon is not explicitly enforced as it is preferentially produced along the beampipe. Later, however, by studying the missing momentum direction we confirm the ISR characteristics of the event.

Figure 6 shows the invariant mass distribution of the $2(\pi^+\pi^-)J/\psi$ system up to 5.7 GeV in the final data sample. A structure around 4.32 GeV is observed in the mass spectrum. To better understand this structure, we fit the full mass region under several hypotheses assuming the peak is due to: (a) $Y(4260)$, (b) $\psi(4415)$ or (c) a new resonance whose mass and width kept as free parameters in the fit. The probabilities of fit χ^2 are determined to be 6.5×10^{-3}, 1.2×10^{-13} and 29 %, respectively. The new resonance hypothesis

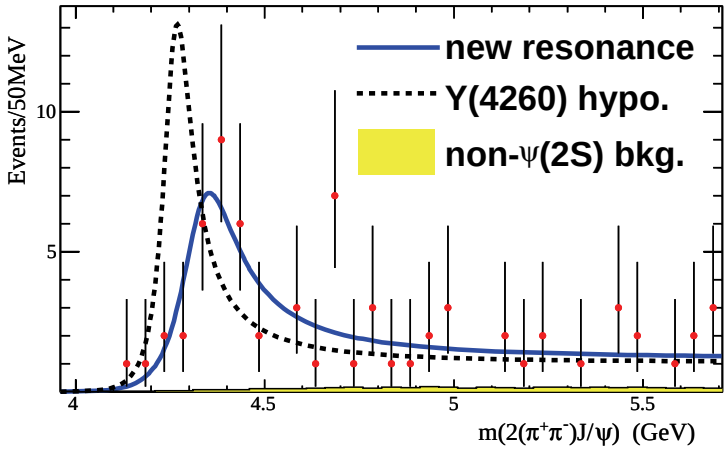


Figure 6: The $2(\pi^+\pi^-)J/\psi$ invariant mass spectrum up to 5.7 GeV for the final sample from *BABAR*. Red dots are data points while the shaded histogram and the curves are explained in the inset text.

that best describes the structure has a mass of 4324 ± 24 MeV and a width of 172 ± 33 MeV, where the errors are statistical only. Given the close proximity to $Y(4260)$ and statistical significance, more data would clarify the nature of this structure.

3.6 The $Z(3930)$ - the last alphabet?

This state is observed by the Belle collaboration in the two-photon mediated process, $e^+e^- \to \gamma^*\gamma^* \to D\overline{D}$[30] with a mass $3929 \pm 5 \pm 2$ MeV and a width $29 \pm 10 \pm 2$ MeV where the quoted uncertainties are statistical and systematic, respectively. The statistical significance of this claim is $5.5\,\sigma$. The $D\overline{D}$ helicity distribution is consistent with the $J = 2$ expectation. Similar to $X(3940)$ and $Y(3940)$ the Z seems an obvious candidate for χ'_{c2}. The predicted mass and width of χ'_{c2} are 3972 MeV and 80 MeV, respectively. However, if we set the χ'_{c2} mass to the measured value of 3929 MeV, its predicted width drops down to 47 MeV (reasonably close to the measurement) due to phase-space restriction. So at this stage we have no reason not to believe that the $Z(3930)$ is the previously unseen χ'_{c2} charmonium state.

4 Conclusions

The last few years have been very exciting for hadron spectroscopy studies at the B factories. Both *BABAR* and Belle are pioneering several sensitive searches for new charmonium states, some of the most recent ones are summarized in this report. As it seems Xs, Ys, and Zs are seriously challenging our current understanding of QCD in the nonperturbative domain. Least of the all, $X(3872)$ and $Y(4260)$ have made it clear that the simple quark model won't work for them and we need to look beyond the known horizon!

ACKNOWLEDGMENTS

It is a pleasure to thank the organizers of the DAE-BRNS High Energy Physics Symposium for their kind invitation to present a talk on such an exciting area of physics. Despite my earnest attempt I owe an apology to all whose work could not be reported here for lack of space. This work is supported in part by the Particle Physics and Astronomy Research Council of the UK, and the US Department of Energy under contract number DE-AC02-76SF00515.

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