Charmonium spectroscopy at BABAR

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Charmonium Spectroscopy at BaBar

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1 Introduction

We discuss the study of charmonium resonances performed at the BaBar experiment. The BaBar experiment [1], which ran between October 1999 and September 2007, is located on the PEP-II asymmetric ring, at the SLAC National Accelerator Laboratory. It recorded 531 fb^{-1} of data with e^+e^- collisions, including 433 fb^{-1} at the Υ(4S) energy. This corresponds to a total amount of 475×10^6 $B\overline{B}$ pairs produced, and 633×10^6 $c\overline{c}$ pairs.

A charmonium resonance is a bound state of a charm and an anti-charm quark ($c\overline{c}$). Figure 1 shows the actual state of knowledge on the charmonium spectrum. Basically all states below the open-charm threshold are observed and explained. However, as it can be seen from the figure, many new states have been discovered since 2003. These new states do not seem to correspond to the expected charmonium masses, and could be well the first indication of exotic states, *i.e.* states that are not made of the aggregation of two quarks. These exotic states are predicted by theory, but none have been definitively confirmed. Several models have been discussed. These exotic states could be hybrid states: these consist of $c\bar{c}g$ states with excited gluonic degrees of freedom. The lowest-mass hybrid is predicted at a mass of about 4.2 GeV/c^2. They are expected to decay predominantly in $D\overline{D}^*$ final states. Another possibility for exotics would be tetraquark states which are bound states of four quarks: they are predicted to have a small width above the open-charm threshold. A large number of such states is predicted. Exotic states could also be constituted of loosely bound states of a pair of mesons (molecular states). They are also predicted to have a small width above the threshold, while only a small number of states is expected.

A clear exotic signature will be non-charmonium J^{PC}, unnaturally small width or non-null charge. In the following, we will investigate a few of these new states with the $X(3872)$, the $Y(4260)$, $Y(4350)$, and the $Z(4430)$.

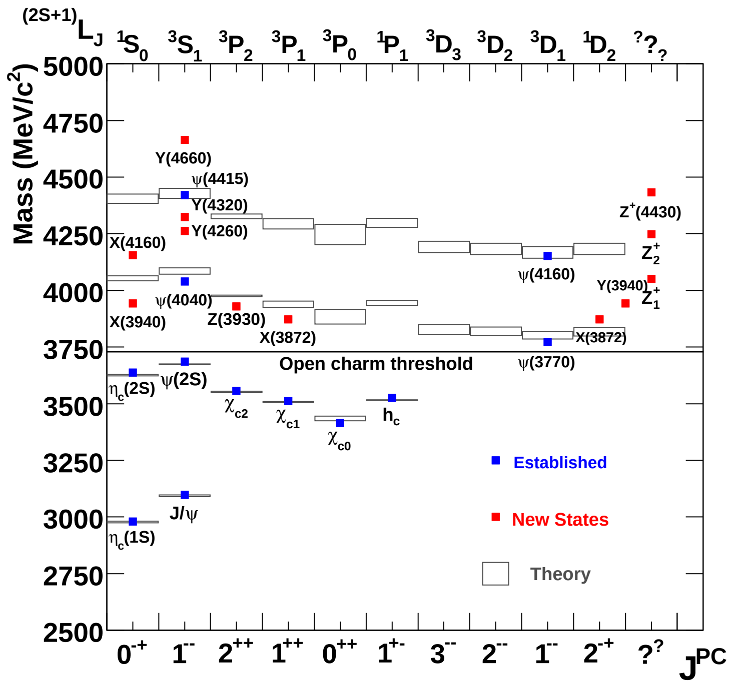

Figure 1: Spectrum of the known charmonium states. Blue squares represent the charmonium states that are established and well measured, red squares show charmonium(-like) states which were discovered recently at the B-factories. The empty rectangles indicate the prediction by the potential models [2]. The horizontal line shows the open-charm threshold.

2 $X(3872)$

The $X(3872)$ meson was discovered by Belle [3] in $B^{\pm} \to X(3872)K^{\pm}$ with $X(3872) \to J/\psi\pi^+\pi^-$ in 2003, and quickly confirmed by the BaBar, CDF and D0 experiments [3]. Its mass is known very precisely, 3871.4 ± 0.6 MeV$/c^2$, and its width is less than 2.3 MeV at 90% confidence level. This state is very close to the $D^{*0}\overline{D}^0$ threshold which is at (3871.8 ± 0.4) MeV$/c^2$. This resonance was also observed in the final state $J/\psi\gamma$ [4], which implies that its C quantum number is equal to $+1$. The study of the $\pi^+\pi^-$ invariant mass distribution by Belle and an angular analysis by CDF shows that $J^{PC} = 1^{++}$ is favored (although 2^{++} is still possible) [4]. It has also to be noted that a search for a charged partner was performed by BaBar, but no signal was found [4].

The BaBar experiment has recently performed an update of the study of the decays of $B^+ \to X(3872)K^+$ and $B^0 \to X(3872)K^0$ with $X(3872) \to J/\psi\pi^+\pi^-$ [5], using 413 fb^{-1} of data. The invariant masses of the $J/\psi\pi^+\pi^-$ combination are shown in Fig. 2 for the two channels. A clear signal is observed in the charged channel, with a significance of 8.6σ. The neutral channel indicates the presence of the signal with a significance of 2.3σ. From these fits, they obtain the branching fractions $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (8.4 \pm 1.5 \pm 0.7) \times 10^{-6}$ and $\mathcal{B}(B^0 \to X(3872)K^0) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (3.5 \pm 1.9 \pm 0.4) \times 10^{-6}$, where the first error is statistical and the second error is systematic. The ratio of the neutral over charged channel is measured to be $0.41 \pm 0.24 \pm 0.05$. The natural width of the $X(3872)$ is constrained to be below 3.3 MeV at the 90% confidence level.

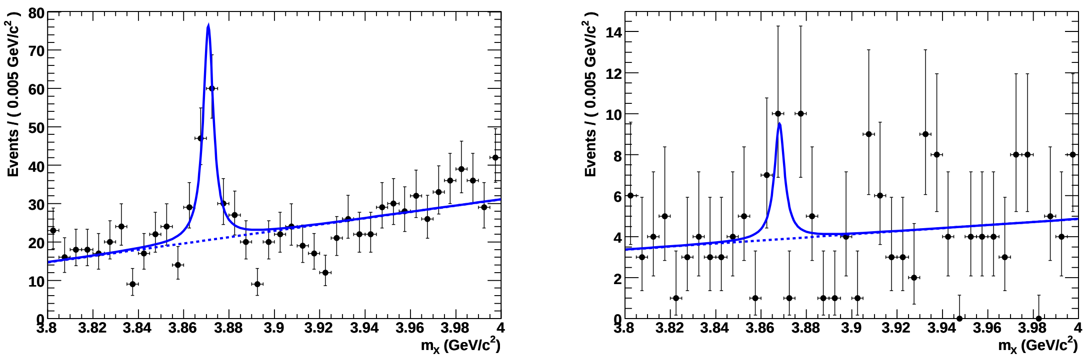

Figure 2: Invariant mass distributions for the $J/\psi\pi^+\pi^-$ final state for $B^+ \to X(3872)K^+$ (left) and $B^0 \to X(3872)K^0$ (right). The dots are the data, the dashed line represents the combinatorial background fit and the solid line the total fit.

The BaBar Collaboration also studied the final states $X(3872) \to J/\psi\gamma$ and $X(3872) \to \psi(2S)\gamma$ in the decays $B^+ \to X(3872)K^{(*)+}$ and $B^0 \to X(3872)K^{(*)0}$ [6]. Using 424 fb^{-1}, they obtain the invariant mass distributions shown in Fig. 3 in the $B^+ \to X(3872)K^+$ final states. They find a 3.6σ evidence for the $X(3872) \to J/\psi\gamma$ final states and find the first evidence of the decay mode $X(3872) \to \psi(2S)\gamma$ with a 3.5σ significance. No signal is found in the final states with a neutral or excited K meson. These observations imply a C-parity quantum number equal to +1. They measure the products of the branching fractions $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to \psi(2S)\gamma) = (9.5 \pm 2.7 \pm 0.6) \times 10^{-6}$ and $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to J/\psi\gamma) = (2.8 \pm 0.8 \pm 0.1) \times 10^{-6}$. The ratio of these two branching fractions is found to be 3.4 ± 1.4.

In 2006, the Belle experiment did a study of the channel $B \to \overline{D}^0 D^0 \pi^0 K$ and observed a clear excess in the $\overline{D}^0 D^0 \pi^0$ invariant mass [7]. The singularity of this result comes from the measurement of the mass: $3875.4 \pm 0.7^{+1.2}_{-2.0}$ MeV/c^2, which is in disagreement with the mass measured in the $X(3872) \to J/\psi\pi^+\pi^-$ channel. This discrepancy was confirmed by the BaBar experiment [7], looking at the $B \to \overline{D}^0 D^{*0} K$ channels (where both decays of D^{*0}, $D^0\pi^0$ and $D^0\gamma$, are taken into account, and

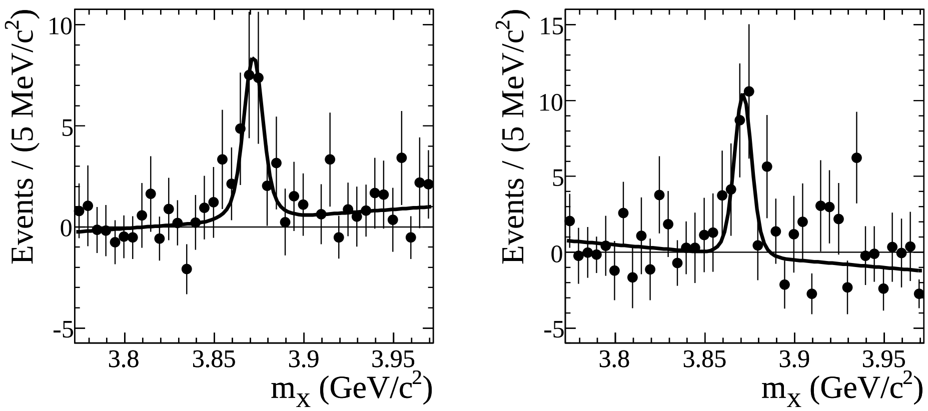

Figure 3: Number of extracted signal events versus the invariant mass for $B^+ \to X(3872)K^+$ followed by $X(3872) \to J/\psi\gamma$ (left) and by $X(3872) \to \psi(2S)\gamma$ (right). The dots are the data, the solid line represents the fit to the data.

where the B and K mesons are either charged or neutral). Figure 4 shows the $\overline{D}^0 D^{*0}$ invariant mass using 347 fb^{-1} of data. An excess with a 4.9σ significance is observed in the $\overline{D}^0 D^{*0}$ invariant mass, with a mass of $3875.1^{+0.7}_{-0.5} \pm 0.5$ MeV/c^2. This mass measurement is 4.5σ away from the $X(3872)$ mass in the $J/\psi\pi^+\pi^-$ channel. A measurement of the width of this state was also performed and the value found is $\Gamma = 3.0^{+1.9}_{-1.4} \pm 0.9$ MeV. The angular study was inconclusive. Recently, the Belle experiment presented an update [7] of this analysis in this channel with 605 fb^{-1} and they find a mass of $3872.6^{+0.5}_{-0.4} \pm 0.4$ MeV/c^2, which is in better agreement with the measurement performed for the $J/\psi\pi^+\pi^-$ final states. This result is however in disagreement with the BaBar result in $\overline{D}^0 D^{*0}$. Several authors have proposed an explanation for this discrepancy between the $J/\psi\pi^+\pi^-$ and $\overline{D}^0 D^{*0}$ final states. For example, in Ref. [8], they argue that there is no proximity of a threshold in $X(3872) \to J/\psi\pi^+\pi^-$, and in consequence the mass and width measurement correspond to the real particle. On the contrary, for the $X(3782) \to \overline{D}^0 D^{*0}$, the threshold $\overline{D}^0 D^{*0}$ is very close to the resonance. In particular, if the $X(3872)$ is just below the threshold, the lineshape could create an artificial peak above the threshold, which is the one measured experimentally, and which parameters would not correspond to the real particle properties. Another possible explanation for this mass shift is given in Ref. [9]: if the $X(3872)$ width is of the order of 2-3 MeV, then the peak position is sensitive to the angular momentum due to the proximity of the threshold. A mass shift of about 3 MeV/c^2 is expected if the $X(3872)$ has quantum numbers $J^P = 2^-$.

The interpretation of the $X(3872)$ state is rather difficult [10] since there is no

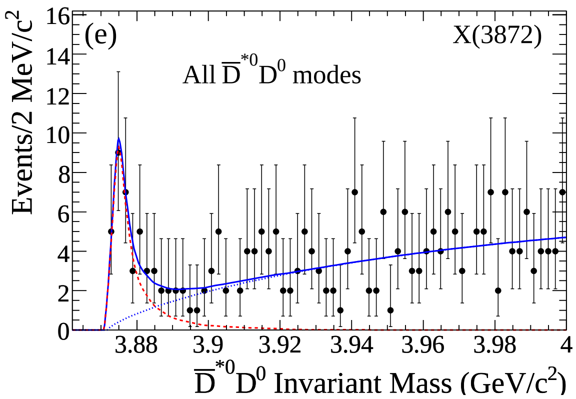

Figure 4: Invariant mass distribution of $\overline{D}^0 D^{*0}$ in the decay channel $B \to \overline{D}^0 D^{*0} K$. Points are data events, the solid line represents the fit to the data, the dashed line shows the contribution of the $X(3872)$ signal, and the dotted line shows the background contribution.

satisfactory $c\bar{c}$ assignment for this resonance. The coincidence between this resonance mass and the $\overline{D}^0 D^{*0}$ mass led some authors to propose that the $X(3872)$ is a bound state of the $\overline{D}^0$ and D^{*0} mesons with small binding energy (molecular state). One of the predictions of this model is that $B^0 \to X(3872)K^0$ is suppressed by approximately a factor 10 compared to $B^+ \to X(3872)K^+$. Experimentally, this ratio is measured by BaBar to $0.41 \pm 0.24 \pm 0.05$ in the $X(3872) \to J/\psi\pi^+\pi^-$ channel. This model favors $\overline{D}^0 D^{*0}$ decays over $J/\psi\pi^+\pi^-$, itself favored over $J/\psi\gamma$, consistent with the observations. However, the model predicts $X(3872) \to \psi(2S)\gamma$ to be suppressed, which is in contradiction with the observation. It has also been proposed that the X(3872) resonance is a tetraquark state. In this case, the model predicts two neutral states and two charged states, with a difference of mass between the two neutral states (produced respectively in B^0 and B^+ decays) of (7 ± 2) MeV/c^2. The experimental results in BaBar show a mass difference of $(2.7 \pm 1.6 \pm 0.4)$ MeV/c^2 in the $X(3872) \to J/\psi\pi^+\pi^-$ channel. Furthermore, no evidence for charged partners have been found so far. Another explanation for this state is that the $X(3872)$ could be a mixing of a $\overline{D}^0 D^{*0}$ state and a $c\bar{c}$ state. Further experimental results should help to better understand this resonance.

3 $Y(4260)$ and $Y(4350)$

The $Y(4260)$ state constitutes also quite a mystery. This state, with $J^{PC} = 1^{--}$, was discovered by BaBar in 2005 in $e^+e^- \to \gamma_{ISR}(J/\psi\pi^+\pi^-)$, with a photon radiated in the initial state [11] (ISR). BaBar recently updated [11] this measurement with an integrated luminosity of 454 fb^{-1}. The invariant mass of the $J/\psi\pi^+\pi^-$ combination can be seen in Fig. 5. From the fit to the invariant mass distribution, a mass of $M = (4252 \pm 6^{+2}_{-3})$ MeV/c^2 and a width of $\Gamma = (105 \pm 18^{+4}_{-6})$ MeV are obtained. This state was also seen by the Belle experiment with $M = (4247 \pm 12^{+17}_{-32})$ MeV/c^2 and $\Gamma = (108 \pm 19 \pm 10)$ MeV while CLEO measures $M = (4284^{+17}_{-16} \pm 4)$ MeV/c^2 [11]. Belle also reported an enhancement at a mass of about 4050 MeV/c^2 in this channel, which is not confirmed by the BaBar study.

BaBar performed recently a study [12] of the exclusive production of $D\overline{D}$, $D^*\overline{D}$, $D^*\overline{D}^*$ in initial-state-radiation events with an integrated luminosity of 384 fb^{-1}. Effectively, the $Y(4260)$ is expected to decay dominantly in these final states if it is a charmonium resonance. A plot combining the three decay modes is shown in Fig. 5. We observe from this plot that no $Y(4260)$ is seen in these channels.

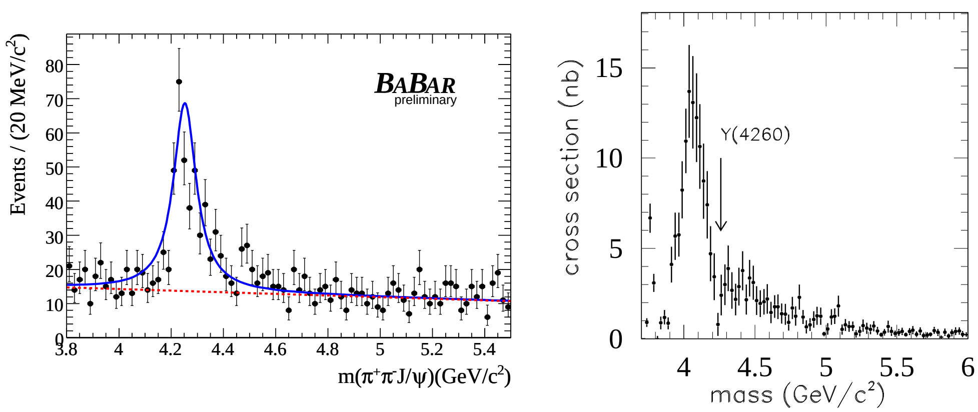

Figure 5: Left plot: $J/\psi\pi^+\pi^-$ invariant mass spectrum. Points with error bars represent the data, the solid curve shows the result of the fit, while the dashed curve represents the background component. Left plot: sum of the $e^+e^- \to D\overline{D}$, $e^+e^- \to D^*\overline{D}$, and $e^+e^- \to D^*\overline{D}^*$ cross-sections. The arrow indicates the position of the $Y(4260)$.

A 3σ enhancement was also reported by BaBar in $B \to Y(4260)K^-$, followed by $Y(4260) \to J/\psi\pi^+\pi^-$ [11], although this result needs confirmation by other experiments. Searches for this resonance were performed in other channels ($e^+e^- \to \gamma_{ISR}(\Phi\pi^+\pi^-)$, $e^+e^- \to \gamma_{ISR}(p\overline{p})$, $e^+e^- \to \gamma_{ISR}(J/\psi\gamma\gamma)$), but no positive results were reported [11].

It was natural to search for the decay of $Y(4260)$ going to $\psi(2S)\pi^+\pi^-$ in ISR production [13]. A clear signal is observed in this channel (see Fig. 6) with 298 fb^{-1}, however with a mass measurement incompatible with the previous BaBar result. The mass found in this channel is (4234 ± 24) MeV/c^2 with a width of (172 ± 33) MeV. This result was later confirmed by Belle with a mass of $(4361 \pm 9 \pm 9)$ MeV/c^2 and a width of $(74 \pm 15 \pm 10)$ MeV [13].

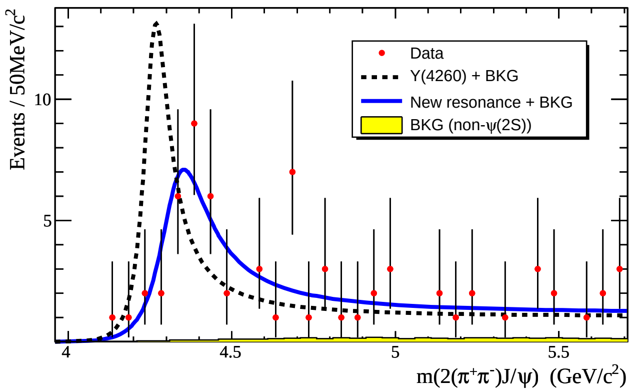

Figure 6: $\psi(2S)\pi^+\pi^-$ invariant mass spectrum.

The interpretation of these two new states is far from obvious [14]. There is no $c\bar{c}$ assignment for 1^{--} states of these masses. Possibilities that have been mentioned are tetraquark state $[cs][\overline{cs}]$, hybrid meson (where we expect a suppression of $D^{(*)}\overline{D}^{(*)}$ final states) or $\omega\chi_{c1}$ molecule.

4 $Z(4430)$

Belle has reported [15] in 2008 a new charged charmonium-like state in the decay $B \to Z^- K$ followed by $Z^- \to \psi(2S)\pi^-$, with a significance of 6.5σ. This result is intriguing since this is the first report of a charged resonance carrying hidden charm, and its minimal quark content should be $(c\bar{c}u\bar{d})$. The reported mass and width are respectively $(4433 \pm 4 \pm 2)$ MeV/c^2 and (45^{+18+30}_{-13-13}) MeV. Using the same data sample (605 fb^{-1}), Belle has confirmed this result using a Dalitz plot analysis [15]. They updated the value of the mass and the width to (4443^{+15+17}_{-12-13}) MeV/c^2 and (109^{+86+57}_{-43-52}) MeV.

BaBar performed a search [16] for the $Z(4430)$ resonance (using 413 fb^{-1}) in the channels $B \to \psi\pi^- K$ where the ψ stands either for J/ψ or $\psi(2S)$ and where B and K are either charged or neutral. In this analysis, the $K\pi^-$ system is carefully treated to take into account the structures in mass and angular distributions (by means of Legendre polynomials). The reflections of the $K\pi^-$ structure are then projected in the $\psi\pi^-$ mass distribution, and used to determine if additional contributions are needed above this $K\pi^-$ projection. It is shown that a good description is obtained with such a method and that no additional structure is needed to describe the data. Figure 7 shows the $\psi\pi^-$ invariant masses for the different channels after efficiency correction. A S-wave Breit-Wigner is used to describe the $Z(4430)$ signal. Figures 7 (a) and (d) are for the entire data samples, Fig. 7 (b) and (e) are for the K^* regions, and Fig. 7 (c) and (f) are for the $K^*(892)$ and $K^*(1430)$ veto region combined (corresponding to the Belle selection). No enhancement is seen in the $J/\psi\pi^-$ channel. In the $\psi(2S)\pi^-$ channels (d) and (e), enhancements are present with a significance lower than 3σ and masses different from the one from Belle. Using the same selection as Belle (f), BaBar find a compatible mass, but with a significance of only 1.9σ. We can conclude that no $Z(4430)$ signal is observed in the current BaBar data sample.

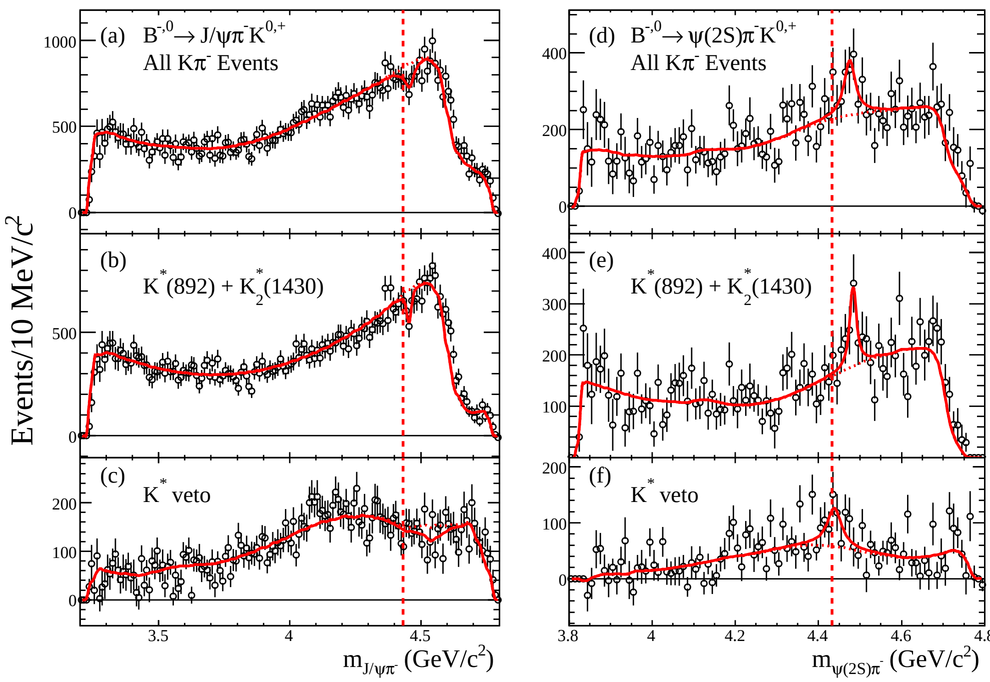

Figure 7: Results of the fits to the corrected mass distributions. The solid line is the total fit while the dashed line is the background contribution. The vertical lines indicate the position of the hypothetical $Z(4430)$.

5 Conclusions

Although no new resonances were discovered in many years, BaBar has given an impressive list of new results since 1999. Many of these new resonances could not be explained by usual quark content. The nature of the $X(3872)$, the $Y(4260)$, the

$Y(4350)$, and the $Z(4430)$ is still unclear. These states are not charmonium states, and are probably the first occurrences of non-standard quark content.

Theoretically, these states are still actively in debate, and new ideas will probably emerge in the near future.

Analyzes are still in progress with the current data set in BaBar: more decay modes for the resonances presented here are being investigated. We also expect contributions from LHCb and Super-B/Belle II experiments which will collect data at high luminosity.

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