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X Y Z particles at BABAR*

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Abstract This paper intends to shortly summarize the recent results on Spectroscopy, published from the BABAR Collaboration. The BABAR experiment is a B-factory, at SLAC, where asymmetric energy beams of electron-positron are accelerated and collide at the energy in the center of mass of $\Upsilon(4S)$. In 9 years of data taking, BABAR had collected 433 fb^{-1} equivalent luminosity on-peak-data at the $\Upsilon(4S)$ energy, 30 fb^{-1} data at the $\Upsilon(3S)$ energy, 15 fb^{-1} data at the $\Upsilon(2S)$ energy, and a scan around $\Upsilon(4S)$ was done, collecting 25 pb^{-1} every 5 MeV. Thanks to the high luminosity achieved, it is possible to perform high precision measurements, and spectroscopy studies. An update on the measurement of the state X(3872) will be given, as final result published by using the whole dataset available. Then, a new preliminary Y(4260) measurement is reported, and the study of the invariant mass $J/\psi\pi^+\pi^-$ in ISR events is shown, where no evidence of the state Y(4050) is highlighted. As conclusion, the results on the angular distribution analysis performed on the state Z(4430) are reported.

Key words spectroscopy, charmonium, BABAR

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1 Introduction

The XYZ puzzle in Charmonium Physics is one of the most interesting and charming topic of Spectroscopy, in particular from the discovery of that resonant state called X(3872). In fact, several new observed states do not fit theretical expectations, as you can see in the Fig. 1. As consequence, many interpretations like HQT, Chiral Simmetry, quark model, bag model, molecular or tetraquark interpretations, etc.etc.[1], were proposed from theorists, in order to make order and try to understand if all these resonant states are pieces of the same puzzles, or they are the hint of something new.

Proofs to support this or that theory are searched, looking for decay channels that can confirm what these (some times) controversial resonant states are. Spectroscopy studies in BABAR are performed in:

1) production in continuum, using data collected at the energy in the center of mass of $\Upsilon(4S)$;

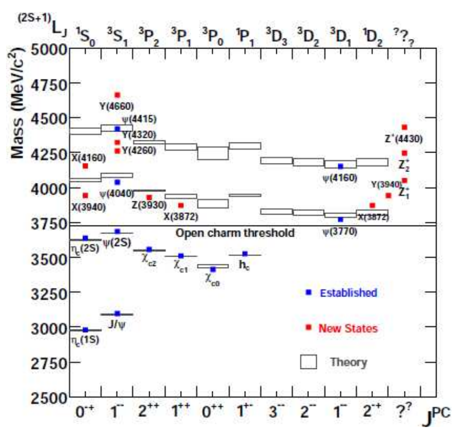

Fig. 1. Spectrum of the known charmonium states. Blue squares represent the charmonium states that are established and well measured, red squares show (like-)charmonium states which were discovered recently at the B-factories. The empty rectangles indicate the prediction by the potential models [1].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

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2) B decays analysis (b-color-suppressed decays and open-charm physics);

3) $\Upsilon(nS) \to \Upsilon(mS)$ transitions;

Aiming the challenge of the XYZ interpretation, here below some experimental results of the studies performed from the BABAR experiment, are presented.

2 X(3872)

The first non-expected state observed at Belle [2], then confirmed from CDF [3], D0 [4] and BABAR [5], is X(3872), by analyzing the invariant mass $J/\psi\pi^+\pi^-$ in B decays. In BABAR this analysis was repeated on the full dataset, showing a mass shift Δm_X between the mass measurements of the charged and the neutral B channel ($B^\pm \to XK^\pm$ and $B^0 \to XK^0_S$, respectively, with $X \to J/\psi\pi^+\pi^-$), equal to $(2.7 \pm 1.6 \pm 0.4)$ MeV/c^2. The BR measurements confirm the results obtained in the previous analysis performed in BABAR, as detailed explained in Ref. [6]. Also the ratio between the BR of the charged and the neutral B decay channel was measured, equal to $(0.41 \pm 0.24 \pm 0.05)$. The mass shift and the ratio as mentioned are important measurements, in order to give some theoretical explanation of what the state X(3872) is. Some plots related to the X(3872) analysis are shown in Fig. 2 and Fig. 3, where a very narrow but evident peak is shown for the charged B channel (with 8.6σ significance), while only 2.3σ significance was measured in the neutral channel.

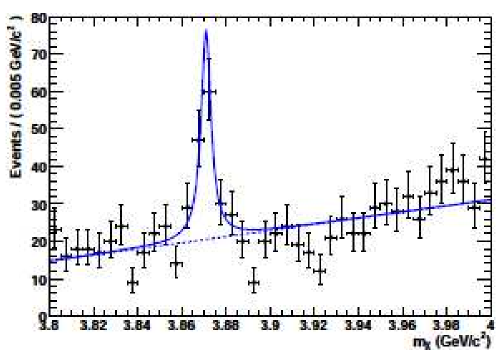

Fig. 2. $J/\psi\pi^+\pi^-$ invariant mass distributions for final state $B^\pm \to X(3872)K^\pm$.

As the $\pi^+\pi^-$ invariant mass is compatible with the ρ mass, in the analysis of $B \to X(3872)K$, with $X(3872) \to J/\psi\pi^+\pi^-$, this narrow state is expected to have ispospin $I = 1$. But the search for charged X partners did not succeed until now ([7, 8]); then, we can conclude that X(3872) is an isospin violating state, with $I = 0$ favored.

An interesting result related to the X(3872) analysis is reported in Refs. [9, 10], where the analysis of the invariant mass $J/\psi\gamma$ and $\psi(2S)\gamma$, compatible with X(3872) mass and width, leds to the conclusion that the C-parity of the X(3872) state is positive: $J^C = 1^+$. The mass of $X \to J/\psi\gamma$ and $X \to \psi(2S)\gamma$ were measured with 3.6σ and 3.5σ significance, respectively. A clear peak is shown, as reported in Fig. 4 and Fig. 5, but only for the charged B channel: no evidence of signal was found by analyzing the neutral B channel or excited K meson.

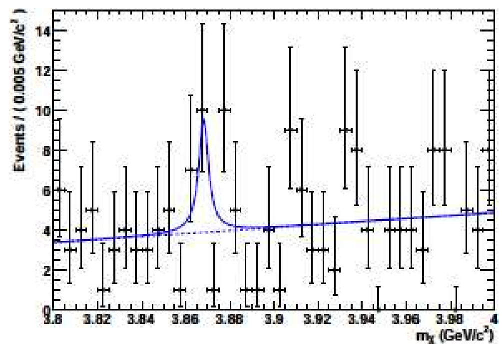

Fig. 3. $J/\psi\pi^+\pi^-$ invariant mass distributions final state $B^0 \to X(3872)K^0_S$.

Surprising results related to the X(3872) analysis still come from the paper quoted in Ref. [11], where the analysis of the invariant mass $D^{0(*)}\bar{D}^{0(*)}$ in B decays is reported, as shown in Fig. 6. This analysis reports a mass shift Δm_X, from the mass world average of $X \to J/\psi\pi^+\pi^-$, equal to 4.5σ significance. Although at the beginning BABAR and Belle were in agreement on this result, recently there was an update from Belle concerning this analysis [12], showing that they disagree on the BABAR BR measurements of $B \to XK$, with $X \to D^0\bar{D}^0$, and the mass measurements of the X(3872) state, too, because they have confirmed now a good agreement between the mass measurement of X(3872) by analyzing both, $J/\psi\pi^+\pi^-$ and $D^0\bar{D}^0$ invariant mass. However, several authors have proposed explanations for the mass shift as mentioned. A possible explanation for the BABAR mass shift measurement is that 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 X(3872) is a state with the quantum number $J^P = 2^-$, for instance. Anyway, X(3872) is a state just below the threshold, and 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.

The explanation of the state X(3872) is still now rather difficult, as there is no satisfactory $c\bar{c}$ assignment for this resonance.

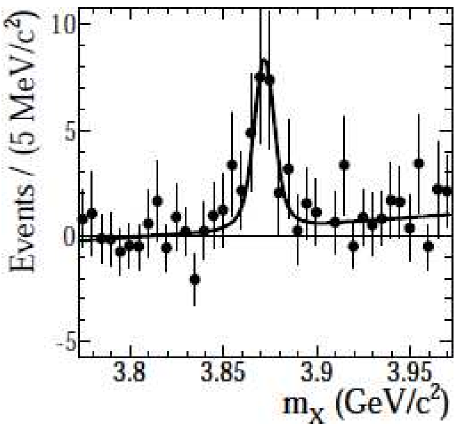

Fig. 4. Number of extracted signal events versus the invariant mass for $B^{\pm} \to X(3872)K^{\pm}$ followed by $X(3872) \to J/\psi\gamma$. The dots are the data, the solid line represents the fit to the data.

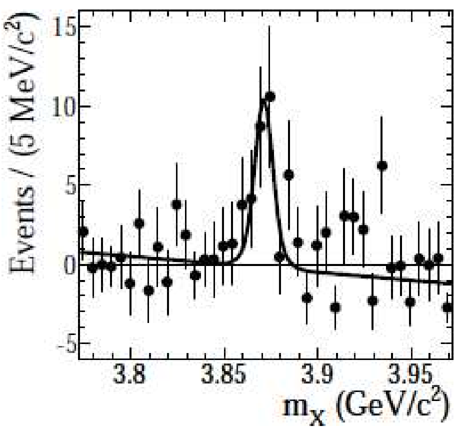

Fig. 5. Number of extracted signal events versus the invariant mass for $B^{\pm} \to X(3872)K^{\pm}$ followed by $X(3872) \to \psi(2S)\gamma$. The dots are the data, the solid line represents the fit to the data.

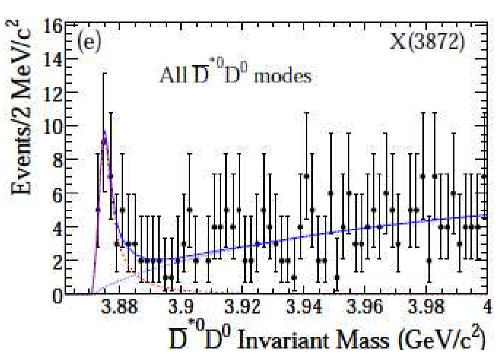

Fig. 6. Invariant mass distribution of $D^0\bar{D}^0$ in the decay channel $B \to D^0\bar{D}^0K$. Points are data events, the solid line represents the fit to the data, the dashed line shows the contribution of the X(3872) signal, and the dotted line shows the background contribution.

3 Y(4260)

First announced from BABAR [14, 15], then confirmed from CLEO-c (scan) [16], CLEO-III (in ISR events) [17] and Belle [18], the Y(4260) state is another unexpected piece of the puzzle in the $J^{PC}=1^{--}$ family. In fact, it was first observed in ISR events. The analysis $e^+e^- \to \gamma_{ISR}J/\psi\pi^+\pi^-$, was repeated, in BABAR, on the full dataset, and no evidence for the new announced state Y(4050) was found, while the old Y(4260) results were confirmed and improved: $m_Y = 4252\pm6^{+2}_{-3}$ MeV$/c^2$, $\Gamma_Y = 105\pm18^{+4}_{-6}$ MeV$/c^2$ [19].

No evidence of $Y(4260) \to D\bar{D}$, $Y(4260) \to p\bar{p}$ and $Y(4260) \to \phi\bar{\phi}$ was found [20–22], and recently a limit on the BR of $Y(4260) \to D\bar{D}$ was fixed [23] (see Fig. 7 and Fig. 8).

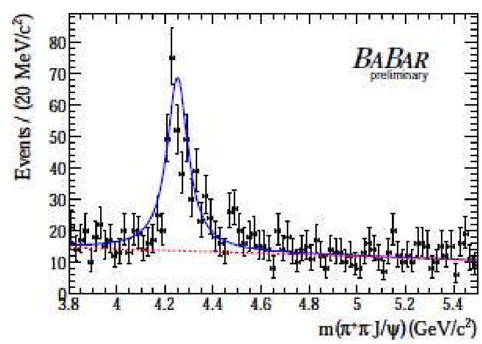

Fig. 7. Invariant mass distribution of $J/\psi\pi^+\pi^-$ in the decay channel $e^+e^- \to \gamma_{ISR}J/\psi\pi^+\pi^-$.

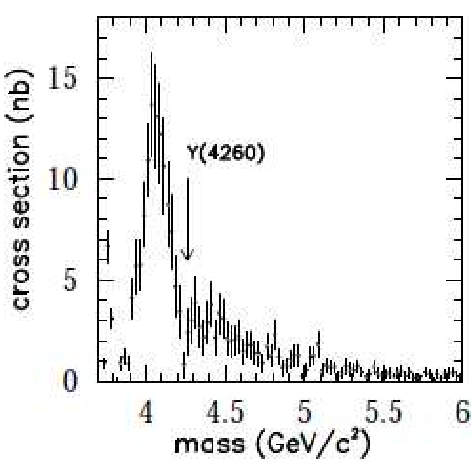

Fig. 8. Sum of $e^+e^- \to D\bar{D}$, $e^+e^- \to D\bar{D}^*$, $e^+e^- \to D^*\bar{D}^*$ cross section. The arrow in this plot shows the position where Y(4260) is supposed to be.

4 Y(4350)

A natural extension of the analysis $e^+e^- \to \gamma_{ISR}$ $J/\psi\pi^+\pi^-$, is the analysis: $e^+e^- \to \gamma_{ISR}\psi(2S)\pi^+\pi^-$, where a new state was observed by BABAR instead of Y(4260) [24]. This new state is characterized from a mass value $m_Y = 4324 \pm 24$ MeV/c^2 and width: $\Gamma_Y = 172 \pm 33$ MeV/c^2. New exiting results on this analysis are expected in BABAR, using the full dataset now available.

5 Y(3940)

The state Y(3940), first announced from Belle [13], was confirmed from BABAR [25] in the analysis $B^\pm \to YK^\pm$, with $Y \to J/\psi\omega$, $\omega \to \pi^+\pi^-\pi^0$. Some plots related to this analysis are reported in Fig. 9. The mass and the width of the Y state

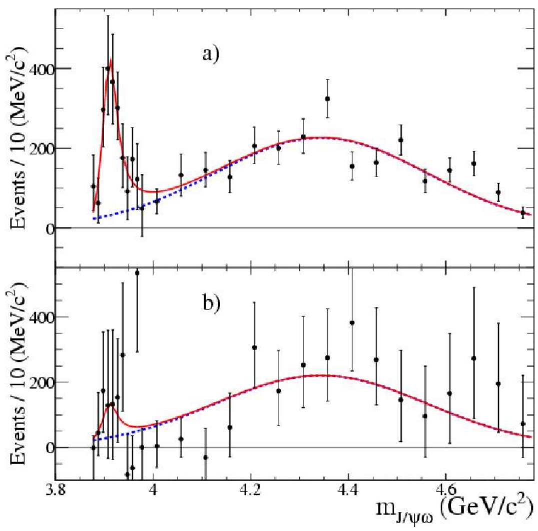

Fig. 9. The top-figure shows the invariant mass $J/\psi\omega$ in the channel $B^\pm \to J/\psi\omega K^\pm$; the bottom-figure shows the invariant mass $J/\psi\omega$ in the channel $B^0 \to J/\psi\omega K^0_S$.

observed by BABAR are not in good agreement with what observed by Belle, in a similar analysis performed by analyzing B decays, that quotes higher mass value and larger width for the compatible Y(3940) state, decaying to $J/\psi\omega$. However, it is interesting to notice that in a new analysis performed by Belle ($e^+e^- \to \gamma\gamma \to Y$ events, no B decays) a new state absolutely compatible with the Y(3940) mass and Y(3940) width observed from BABAR was found. However, the mass and width quoted from BABAR are: $m_Y = 3914.6^{+3.8}_{-3.4}$ MeV/c^2 and $\Gamma_Y = 34^{+12}_{-8} \pm 5$ MeV/c^2.

6 Z(4430)

In the analysis $B \to ZK$, with $Z \to \psi(2S)\pi^-$, Belle claimed to observe a new resonant state, with 6.5σ significance, with mass value equal to $(4443^{+15}{}_{-12}{}^{+17}{}_{-13})$ MeV/c^2 and width equal to $(109^{+86}{}_{-43}{}^{+57}{}_{-52})$ MeV/c^2 [26, 27]. This is a very important issue, because if it is going to be confirmed from other experiments, it would be a genuine $c\bar{c}d\bar{d}$ tetra-quark state.

BABAR analyzed the decay: $B^{\pm,0} \to J/\psi\pi^-K^{\pm,0}$ and $B^{\pm,0} \to \psi(2S)\pi^-K^{\pm,0}$, in order to have a more complete and clear point of view on this new state.

In the most recent paper submitted from Belle, they claim to observe the new Z(4430) state by doing a full Dalitz-plot analysis. The analysis that BABAR performed to confirm the existence of this state is referred to the previous Belle paper, that anyway was confirmed from their second paper as in Ref. [27]. In the first analysis performed from Belle, the Dalitz plot was sliced in several areas of interest, putting a veto on K*(892) and K*(1430). The BABAR approach is quite different: BABAR, in this analysis, assumed that all the angular distribution information is described from the physics of the $K\pi$ system, reproduced thanks to the harmonic spherical functions. As general remark, when doing a Dalitz plot analysis,

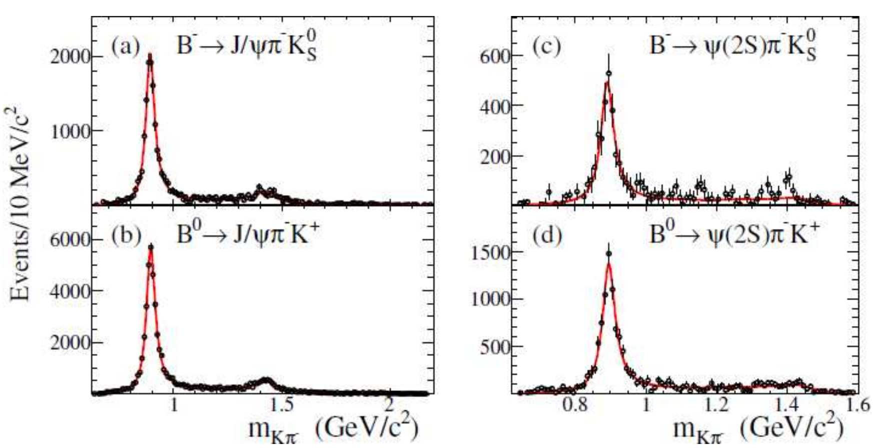

Fig. 10. The efficiency-corrected and sideband-subtracted $K\pi$ invariant mass distributions for (a) $B^- \to J/\psi\pi^-K^0_S$; (b) $B^0 \to J/\psi\pi^-K^+$; (c) $B^- \to \psi\pi^-K^0_S$; (d) $B^0 \to \psi\pi^-K^+$.

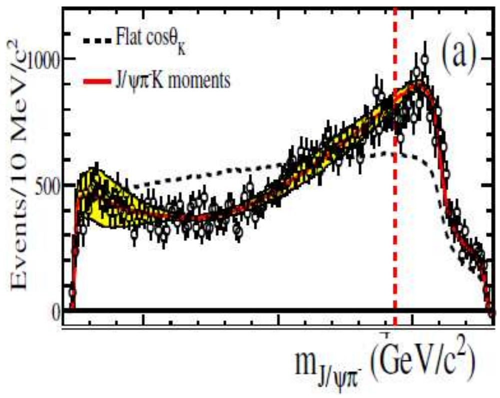

Fig. 11. $\psi\pi^-$ mass distributions for the combined decay mode $B^{\pm,0} \to J/\psi\pi^- K^{\pm,0}$. The points show the data after efficiency correction. The dashed curves show the $K\pi$ reflections. The shaded bands represent the effect of statistical uncertainty on the normalized momenta.

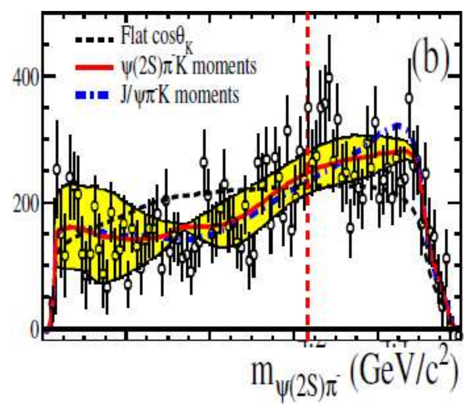

Fig. 12. $\psi\pi^-$ mass distributions for the combined decay mode $B^{\pm,0} \to \psi\pi^- K^{\pm,0}$. The points show the data after efficiency correction. The dashed curves show the $K\pi$ reflections. The shaded bands represent the effect of statistical uncertainty on the normalized momenta.

the harmonic spherical functions momenta must be well reproduced from the fit (see Fig. 10). As in a full Dalits plot analysis the description of $J/\psi \to \mu^+\mu^-$ is rather complicated, and even worse is the algorithm to describe, in term of Dalitz plot, the decay $\psi(2S) \to \pi^+\pi^-$, because of many ambiguities, BABAR preferred, as first-level approach- to analyze the decay $B^{\pm,0} \to \psi\pi^- K^{\pm,0}$ by doing an angular distribution analysis, that, at this level, is equivalent to the Dalitz plot analysis, but more efficient and less complicated. A Montecarlo was built for these harmonic shperical momenta: it reproduces the main structures of the distribution as well. This is the reason why in the BABAR analysis the Legendre polynomials are used. As reported in Ref. [28], the fit well reproduces the distribution of the invariant mass. Then, the invariant mass distributions were corrected bin by bin with the proper efficiency, evaluated from the signal Montecarlo sample.

In Fig. 11 and Fig. 12 it is possible to notice that the $K\pi$ reflections reproduce the data: so, there is no need of any additional structure in the fit. In Fig. 13 and Fig. 14 the final fit to data is reported, showing that no significant Z(4430) signal is observed, using 433 fb^{-1} BABAR data.

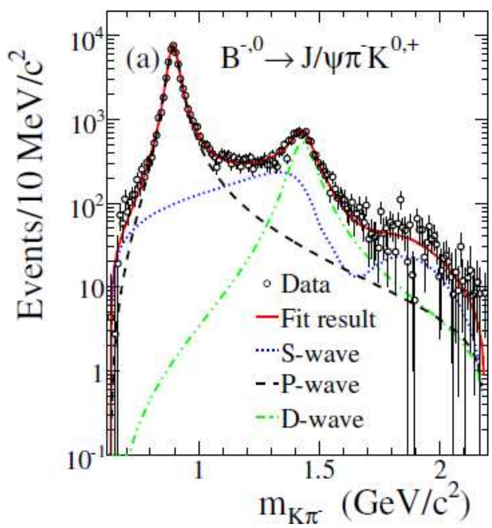

Fig. 13. The results of the fits to the $K\pi^-$ mass distributions for the combined $K\pi^-$ charge configuration, in $B^{\pm,0} \to J/\psi\pi^- K^{\pm,0}$. The data are shown as open dots, and the individual contributions are as indicated.

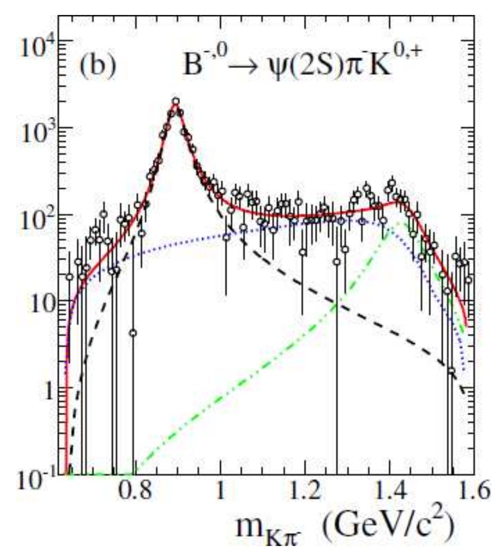

Fig. 14. The results of the fits to the $K\pi^-$ mass distributions for the combined $K\pi^-$ charge configuration, in $B^{\pm,0} \to \psi\pi^- K^{\pm,0}$. The data are shown as open dots, and the individual contributions are as indicated in Fig. 13.

7 Conclusion

Many analyses in BABAR are still ongoing, although this experiment is not taking data since two years. The recent results published definitively help to have more clear picture of the XYZ-charmonium puzzle.

Table 1. Summary table of the presented results.

resonance	J^{PC}	mass/(MeV/c^2)	width/(MeV/c^2)
X(3872)	1^{++} or 2^{-+}	3871.80±0.25	<2.3
Y(3940)	$?^{?+}$	3916±6	40±22
Y(4260)	1^{--}	4264±12	83±22
Y(4350)	1^{--}	4361±13	74±18

In Table 1 all the results presented in this paper are shown, as summary of mass value, width and quantum number assignment of all the confirmed resonant states as mentioned.

We are grateful for the extraordinary contributions of our PEP-II colleagues in achieving the excellent luminosity and machine conditions that have made this work possible. The success of this project also relies critically on the expertise and dedication of the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and the kind hospitality extended to them.

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