PROCEEDINGS OF SCIENCE

Charmonium(-like) states

G. Cibinetto[*†]
INFN Ferrara
E-mail: cibinett@fe.infn.it

In this letter we review the recent results about charmonium-like states. Particular focus is given to the studies of the $X(3872)$ and $X(3915)$ in $\gamma\gamma$ fusion. New results on the charged charmonia states $Z(4430)^+$, $Z_1(4050)^+$ and $Z_2(4250)^+$ are presented as well as the status of $J^{PC} = 1^{--}$ states discovered in e^+e^- annihilation after initial state radiation.

The XIth International Conference on Heavy Quarks and Leptons,
June 11-15, 2012
Prague, Czech Republic

*Speaker.
†BABAR collaboration.

PoS(HQL 2012)005

1. Introduction

The charmonium spectroscopy has been revived by the discovery of many new states above the open charm threshold. While some of these states appear to be consistent with conventional $c\bar{c}$, others do not behave like standard mesons, and could be made of a larger number of constituents. While this possibility has been considered since the beginning of the standard model [1], the actual identification of such states would represent a major revolution in our understanding of elementary particles. The most likely possible states beyond the conventional mesons are:

- molecules: loosely bound states of a pair of mesons ($[Q\bar{q}][q'\overline{Q}]$). This system would be stable if the binding energy were to set the mass of the states below the sum of the two mesons masses. While this could be the case for $Q = b$, this does not apply when $Q = c$. In this case the dominant binding mechanism should be pion exchange. Being weakly bound, the mesons tend to decay as if they were free [2].
- tetraquarks: a bound state of four quarks usually represented as $[Qq][\overline{q'Q}]$. A full nonet of states is predicted for each spin-parity therefore a large number of states is expected [3] [4].
- hybrids: a bound state of a quark-antiquark pair and a number of constituent gluons. The lowest-lying state from lattice calculation is expected to have mass about 4.1 GeV/c^2 and quantum numbers $J^{PC} = 0^{+-}$. Since a quarkonium state cannot have these quantum numbers, this would be a unique signature for hybrids [5].

In addition there is the possibility that some observed enhancements are just due to threshold effects: a given amplitude might be magnified when new hadronic final states become energetically available.

While there are some good experimental candidates for exotics states, the overall picture is still not completely clear and needs confirmations as well as discrimination between different explanations. In the next sections we will discuss the latest experimental results with the aim to set some constraint on the possible interpretation of such new states.

2. $\gamma\gamma$ interaction

Two-photon fusion is a useful production mode for studying such states. The e^+ and e^- are scattered at small angles and are therefore undetected implying that the photons are quasi-real. This allows production of final state with the quantum numbers $J^{PC} = 0^{\pm+}, 2^{\pm+}, 4^{\pm+}, ..., 3^{++}, 5^{++}, ...$. A further consequence is that the transverse momentum (p_T) of the hadronic system is expected to be low. In addition, these events are characterized by low particle multiplicity and low energy.

2.1 $\gamma\gamma \to J/\psi\omega$

The charmonium-like state $X(3915)$ was first observed [6] by Belle in two-photon fusion events decaying into $J/\psi\omega$. In addition, it was seen decaying into $J/\psi\omega$ in B decay analysis, along with the $X(3872)$ [7]. The nature of the X(3872) is still unclear. It is commonly accepted [8] that its quantum numbers can be 1^{++} or 2^{-+}; observing the $X(3872)$ in $\gamma\gamma$ production would favor the latter assignment.

BABAR studied the process $\gamma\gamma \to J/\psi\omega$ to search for the $X(3915)$ and the $X(3872)$ resonances using a data sample of 519 fb^{-1}. Figure 1 shows the reconstructed $J/\psi\omega$ invariant mass distribution after all the selection criteria have been applied. A large peak at near 3915 MeV/c^2 is observed with a significance of 7.6σ. The measured resonance parameters are $m_{X(3915)} = (3919.4 \pm 2.2 \pm 1.6)$ MeV/c^2, $\Gamma_{X(3915)} = (13 \pm 6 \pm 3)$ MeV. The measured value of the two-photon width times the branching fraction, $\Gamma_{\gamma\gamma}[X(3915)] \times \mathscr{B}(X(3915) \to J/\psi\omega)$ is $(52 \pm 10 \pm 3)$ eV and $(10.5 \pm 1.9 \pm 0.6)$ eV for two spin hypotheses J = 0 and J = 2, respectively, where the first error is statistical and the second is systematic. In addition, an upper limit (UL) at 90% confidence level (CL) is obtained for the X(3872), $\Gamma_{\gamma\gamma}[X(3872)] \times \mathscr{B}(X(3872) \to J/\psi\omega) < 1.7$ eV, assuming J=2. All the results are in good agreement with the Belle analysis [6].

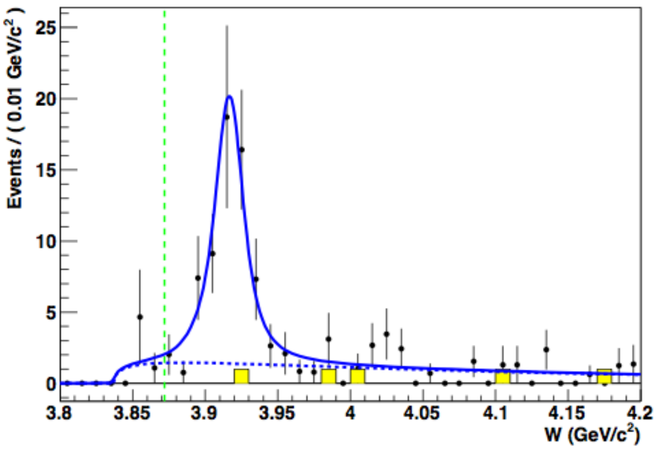

Figure 1: The efficiency-corrected invariant mass distribution for the $J/\psi\omega$ final state. The solid line represents the total fit function. The dashed line is the background contribution. The solid histogram is the non $J/\psi\omega$ background estimated from sidebands. The vertical dashed line is placed at the $X(3872)$ mass.

2.2 $\gamma\gamma \to \eta_c\pi^+\pi^-$

Studies of charmonium-like states in recent years have been performed using the $J/\psi\pi^+\pi^-$ final state [9], but no search using the $\eta_c\pi^+\pi^-$ final state has been conducted. Such a search may shed light on the internal dynamic of these states. This analysis has been studied for the first time and is performed to search for resonances decaying into $\eta_c\pi^+\pi^-$, using a data sample of 474 fb^{-1}. The η_c was reconstructed via its decay to $K^0_S K^+\pi^-$, with $K^0_S \to \pi^+\pi^-$. The signal yield for each X resonance is extracted from a two-dimensional fit to m($K^0_S K^+\pi^-$) and m($K^0_S K^+\pi^-\pi^+\pi^-$). Figure 2 presents the two dimensional fits around each of the resonances. No significant signal is observed in any of the fits. Table 1 summarizes all the fit results. Upper limits are obtained on the branching fractions $\mathscr{B}(\eta_c(2S) \to \eta_c\pi^+\pi^-) < 7.4\%$ and $\mathscr{B}(\chi_{c2}(1P) \to \eta_c\pi^+\pi^-) < 2.2\%$ at 90% CL.

Table 1: Results of the $\gamma\gamma \to \eta_c \pi^+ \pi^-$ fits. For each resonance X, we show the peak mass and width used in the fit and the 90% CL upper limit on the product of the two-photon partial width $\Gamma_{\gamma\gamma}$ and the $X \to \eta_c \pi\pi$ branching fraction. For the $X(3872)$ and the $X(3915)$ we assume J = 2.

Resonances	M_X (MeV/c^2)	Γ_X (MeV)	UL $\Gamma_{\gamma\gamma}$ (eV)
$\chi_{c2}(1P)$	3556.20 ± 0.99	1.97 ± 0.11	15.7
$\eta_c(2S)$	3638.5 ± 1.7	13.4 ± 5.6	133
$X(3872)$	3871.57 ± 0.25	3.0 ± 2.1	11.1
$X(3915)$	3915.0 ± 3.6	17.0 ± 10.4	16
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	19

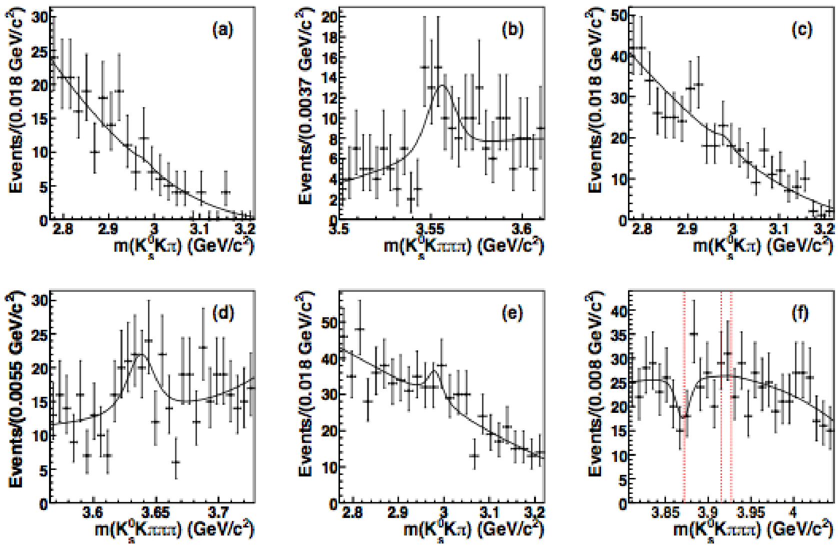

Figure 2: Distributions of (a,c,e) m($K^0_S K^+ \pi^-$) and (b,d,f) m($K^0_S K^+ \pi^- \pi^+ \pi^-$) with the fit function overlaid for the fit regions of the (a,b) $\chi_{c2}(1P)$, (c,d) $\eta_c(2S)$, and (e,f) $X(3872)$, $X(3915)$ and $\chi_{c2}(2P)$. The vertical dashed lines in (f) indicate the peak mass positions of the $X(3872)$, $X(3915)$, and $\chi_{c2}(2P)$.

3. Charged charmonia

The Belle Collaboration reported the observation of a resonance-like structure, $Z(4430)^+ \to \psi(2S)\pi^+$ in the analysis of $B \to \psi(2S)K\pi$ [10]. This claim has generated a great deal of interest [11] since such states must have a minimum quark content $c\bar{c}\bar{d}u$, and thus would represent an unequivocal manifestation of four-quark meson states. The *BABAR* collaboration did not see the $Z(4430)^+$ in an analysis of the decay $B \to \psi(2S)K\pi$ [12]; *BABAR* also studied [12] the $B \to J/\psi K\pi$ where there is no evidence for resonances neither in the $J/\psi\pi$ nor in the $J/\psi k$ systems. All resonance activity seems confined to the $k\pi$ system. Recently Belle performed an amplitude analysis of the $J/\psi K\pi$ [13] system finding no significant evidence of the $Z(4430)^+$ in agreement with the *BABAR* result. The Belle Collaboration has also reported the observation of two resonance-like structures in the study of $\bar{B}^0 \to \chi_{c1} K^- \pi^+$ [14]. These are labeled as $Z_1(4050)^+$

and $Z_2(4250)^+$, both decaying to $\chi_{c1}\pi^+$. *BABAR* studied the same final states [15] to search for the $Z_1(4050)^+$ and $Z_2(4250)^+$ decay into $\chi_{c1}\pi^+$ in $\bar{B}^0 \to \chi_{c1}K^-\pi^+$ and $B^+ \to K^0_S\chi_{c1}\pi^+$ where $\chi_{c1} \to J/\psi\gamma$, using a data sample of 429 fb^{-1}. The $\chi_{c1}\pi^+$ mass distribution, background-subtracted and efficiency-corrected, was modeled using the $k\pi$ mass distribution and the corresponding normalized $k\pi$ Legendre polynomial moments. Figure 3 shows the results of the fits done on the $\chi_{c1}\pi^+$ mass spectrum: no significant resonant structure is present in the $\chi_{c1}\pi$ system; in every case the yield significance does not exceed 2σ. The ULs on the 90% CL on the branching fractions are: $\mathscr{B}(\bar{B}^0 \to Z_1(4050)^+K^-) \times \mathscr{B}(Z_1(4050)^+ \to \chi_{c1}\pi^+) < 1.8x10^{-5}$; $\mathscr{B}(\bar{B}^0 \to Z_2(4250)^+K^-) \times \mathscr{B}(Z_2(4250)^+ \to \chi_{c1}\pi^+) < 4.0x10^{-5}$ and $\mathscr{B}(\bar{B}^0 \to Z^+K^-) \times \mathscr{B}(Z^+ \to \chi_{c1}\pi^+) < 4.7x10^{-5}$.

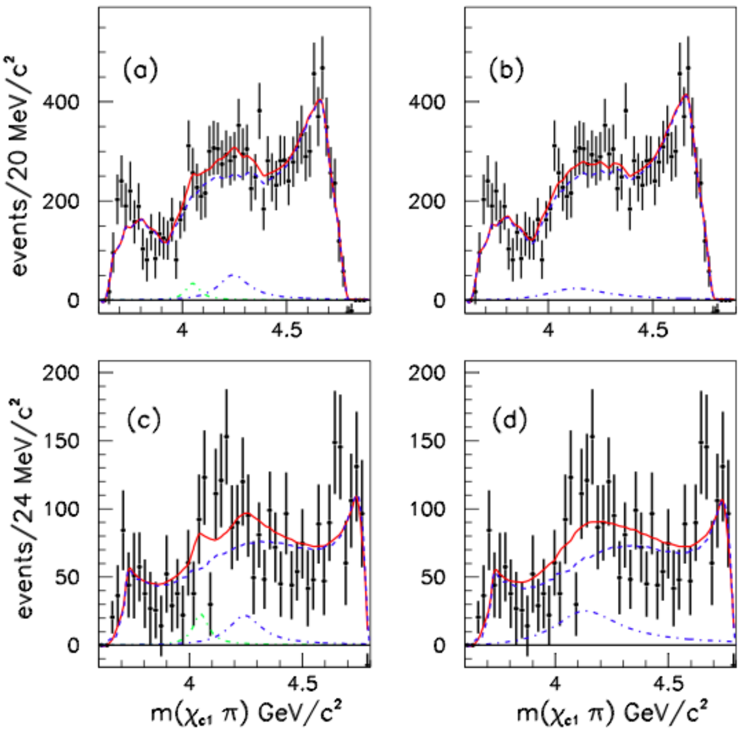

Figure 3: (a),(b) Background-subtracted and efficiency-corrected $\chi_{c1}\pi$ mass distribution for $B \to \chi_{c1}k\pi$. (a) Fit with $Z_1(4050)^+$ and $Z_2(4250)^+$ resonances. (b) Fit with only the $Z(4150)^+$ resonance. (c),(d) Efficiency-corrected and background-subtracted $\chi_{c1}\pi$ mass distribution in the $K\pi$ mass region where Belle found the maximum resonance activity, $1.0 < m^2(K\pi) < 1.75GeV^2/c^4$. (c) Fit with $Z_1(4050)^+$ and $Z_2(4250)^+$ resonances. (d) Fit with only the $Z(4150)^+$ resonance. The dot-dashed curves indicate the fitted resonant contributions.

4. Charmonium-like states after initial state radiation at the B-factories

4.1 The $J/\psi\pi^+\pi^-$ invariant mass spectrum

The Y (4260) was discovered [16] in the initial-state-radiation (ISR) process $e^+e^- \to \gamma_{ISR}Y(4260)$, $Y(4260) \to J/\psi\pi^+\pi^-$. Since it is produced directly in e^+e^- annihilation, it has $J^{PC} = 1^{--}$. The observation of the decay mode $J/\psi\pi^0\pi^0$ [17] established that it has zero isospin. However it is not observed to decay to $D^*\bar{D}^*$ [18], nor to $D_s^*\bar{D}_s^*$ [19], so that its properties do not lend themselves to a simple charmonium interpretation, and its nature is still unclear. A subsequent Belle analysis [20] of the same final state suggested also the existence of an additional resonance around 4.1 GeV/c^2 that they dubbed the Y(4008). BABAR performed a new analysis to study the reaction $J/\psi\pi^+\pi^-$ in ISR using a data sample of 454 fb^{-1} [21]. Figure 4 shows the $J/\psi\pi^+\pi^-$ mass spectrum from 3.74 GeV/c^2 to 5.5 GeV/c^2: a clear signal of the Y(4260) is observed for which the values obtained are $m_{Y(4260)} = 4244 \pm 5 \pm 4$ MeV/c^2, $\Gamma_{Y(4260)} = 114^{+16}_{-15} \pm 7$ MeV and $\Gamma_{ee} \times \mathscr{B}(J/\psi\pi^+\pi^-) = 9.2 \pm 0.8 \pm 0.7$ eV. No evidence for the state at $\sim$4 GeV/c^2 reported by Belle [20] is seen. A study of the $\pi^+\pi^-$ system from the Y(4260) decay to $J/\psi\pi^+\pi^-$ is done. The di-pion system is in a predominantly S-wave state. The mass distribution exhibits an $f_0(980)$ signal, for which a simple model indicates a branching ratio with respect to $J/\psi\pi^+\pi^-$ of 0.17 ± 0.13 (stat).

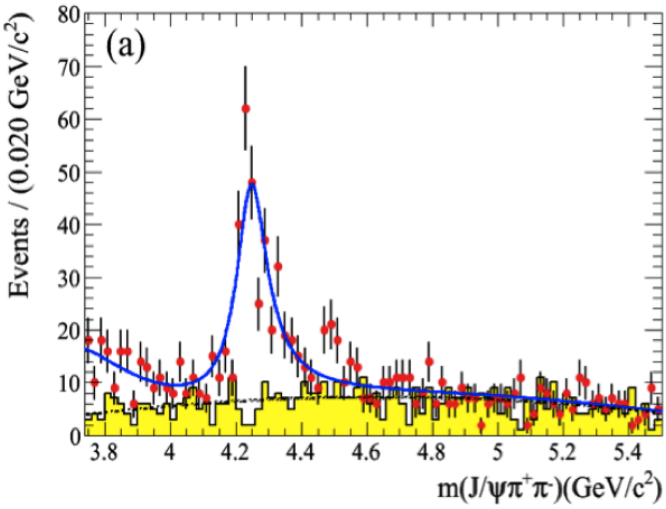

Figure 4: The $J/\psi\pi^+\pi^-$ mass spectrum from 3.74 GeV/c^2 to 5.5 GeV/c^2; the points represent the data and the shaded histogram is the background from the J/ψ sidebands; the solid curve represents the fit result

4.2 The $\psi(2S)\pi^+\pi^-$ invariant mass spectrum

In addition to the $Y(4260)$, two more $J^{PC} = 1^{--}$ states, the $Y(4360)$ and the $Y(4660)$, have been reported in ISR production, via $e^+e^- \to \gamma_{ISR}\psi(2S)\pi^+\pi^-$ [22][23]. The $Y(4660)$ has been observed only in the Belle experiment [23], and so it is important to confirm the existence of this state. BABAR used a data sample corresponding to an integrated luminosity of 520 fb^{-1} to perform an analysis which utilize the ISR mechanism to study the reaction $e^+e^- \to \psi(2S)\pi^+\pi^-$ in the center-of-mass energy range 3.95 - 5.95 GeV, where the $\psi(2S)$ decays to $J/\psi\pi^+\pi^-$ or to $\ell^+\ell^-$; for the latter, $\ell^+\ell^-$ represents either e^+e^- or $\mu^+\mu^-$. The $\psi(2S)\pi^+\pi^-$ invariant mass spectrum for $\psi(2S) \to J/\psi\pi^+\pi^-$ is reported in Figure 5. BABAR observed two resonant structures, that have been interpreted as the $Y(4360)$ and the $Y(4660)$, respectively. For the first resonance $m_{Y(4360)} = 4340 \pm 16(stat) \pm 9(syst)$ MeV/c^2 and $\Gamma_{Y(4360)} = 94 \pm 32(stat) \pm 13(syst)$ MeV, and for the second $m_{Y(4660)} = 4669 \pm 21(stat) \pm 3(syst)$ MeV/c^2 and $\Gamma_{Y(4660)} = 104 \pm 48(stat) \pm 10(syst)$ MeV, confirming the report in Ref. [23] of a structure near 4.65 GeV/c^2, and obtain consistent parameter values for this state.

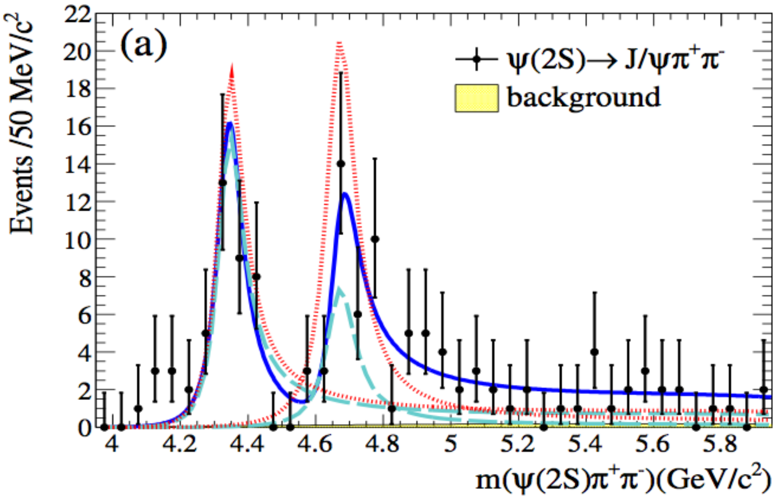

Figure 5: The $\psi(2S)\pi^+\pi^-$ invariant mass distribution from threshold to 5.95 GeV/c^2 for $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$; the points with error bars represent the data in the $\psi(2S)$ signal region, and the shaded histogram is the background estimated from the $\psi(2S)$ sideband regions. The solid curve shows the result of the fit.

5. Summary

The study of spectroscopy of the heavy flavor mesonic states continues to provide useful information about the dynamics of the quarks and gluons interaction at hadronic scale. In this paper we reviewed the recent results on charmonium-like spectroscopy. Particular focus has been given to the study of the $X(3872)$ and $X(3915)$ in $\gamma\gamma$ production; after almost one decade from the discovery of the $X(3872)$, despite the abundance of measurements, there's still no solid consensus about its nature. Charged charmonia states would be an unequivocal signature of exotic states, but their discovery still needs to be confirmed by a second experiment. For the 1^{--} states discovered in e^+e^- annihilation after initial state radiation only one decay mode has been observed for each state despite the many searches making the puzzle even more intriguing.

6. Acknowledgment

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MES (Russia), MICIIN (Spain), STFC (United Kingdom). Individuals have received support from the Marie Curie EIF (Euro- pean Union) and the A. P. Sloan Foundation (USA).

References

[1] M. Gell-Mann, Phys. Lett. 8, 214 (1964).

[2] E. Braaten and M. Kusunkoi, Phys. Rev. D **69**, 074005 (2004); N. A. Tornqvist, Phys. Lett. B **590**, 209 (2004); E. S. Swanson, Phys. Lett B **598**, 197 (2004); M. B. Voloshin, Phys. Lett. B **579**, 316 (2004).

[3] L. Maiani *et al.*, Phys. Rev. D **71**, 014028 (2005);

[4] T. W. Chiu and T. H. Hsieh, Phys. Rev. D **73**, 111503 (2006).

[5] P. Lacock *et al.*, Phys. Lett. B **401**, 308 (1997); F. E. Close and P. R. Page, Phys. Lett. B **628**, 215 (2005).

[6] S. Uehara et al. (Belle Collaboration), Phys. Rev. Lett. 104, 092001 (2010).

[7] P. del Amo Sanchez et al. (*BABAR* Collaboration), Phys. Rev. D. 82, 011101(R) (2010).

[8] A. Abulencia et al. (CDF Collaboration), Phys. Rev. Lett. 99, 132002 (2007).

[9] B. Aubert et al. (*BABAR* Collaboration), Phys. Rev. Lett. 95, 142001 (2005);
C. Z. Yuan et al. (Belle Collaboration), Phys. Rev. Lett. 99, 182004 (2007);
D. Acosta et al. (CDF Col- laboration), Phys. Rev. Lett. 93, 072001 (2004);
V.M. Abazov et al. (D0 Collaboration), Phys. Rev. Lett. 93, 162002 (2004).

[10] S.K. Choi et al. (Belle Collaboration), Phys.Rev.Lett. 100, 142001 (2008). R. Mizuk et al. (Belle Collaboration), Phys. Rev. D80, 031104(R) (2009).

[11] N. Drenska et al., Riv. Nuovo Cim. 033, 633 (2010).

[12] B. Aubert et al. (*BABAR* Collaboration), Phys. Rev. D79, 112001 (2009).

[13] Presented by K.Chilikin at CHARM12, 14-17 May 2012, Honolulu, Hawai'i.

[14] R. Mizuk et al. (Belle Collaboration), Phys.Rev. D78, 072004 (2008).

[15] J. P. Lees et al. (*BABAR* Collaboration), Phys. Rev. D 85, 052003 (2012).

[16] B. Aubert et al., Phys. Rev. Lett. 95, 142001 (2005).

[17] T. E. Coan et al. Phys. Rev. Lett. 96, 162003 (2006).

[18] B. Aubert et al., Phys. Rev. D 79, 092001 (2009); G. Pakhlova et al., Phys. Rev. D 77, 011103 (2008).

[19] P. del Amo Sanchez et al., Phys. Rev. D 82, 052004 (2010); J. Libby et al., Nucl. Phys. B, Proc. Suppl. 181- 182, 127 (2008).

[20] C. Z. Yuan et al. (Belle Collaboration), Phys. Rev. Lett. 99, 182004 (2007).

[21] *BABAR*Collaboration, hep-ex/1204.2158v1

[22] B. Aubert et al., Phys. Rev. Lett. 98, 212001 (2007).

[23] X. L. Wang et al., Phys. Rev. Lett. 99, 142002 (2007).