THE DARK SIDE OF BELLE*

Tadeusz Lesiak

The Henryk Niewodniczański Institute of Nuclear Physics
Polish Academy of Science
Radzikowskiego 152, 31-342 Kraków, Poland

(Received September 11, 2007)

We report results of two studies performed by the Belle collaboration in search for a light dark matter candidate. A search for the invisible decay of the $\Upsilon(1S)$ via the $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ transition yields no signal and an upper limit for the branching fraction at the 90% confidence level is determined to be $\mathcal{B}(\Upsilon(1S) \to \text{invisible}) < 2.5 \times 10^{-3}$. No significant signal is also observed for the rare decays $B \to h^{(*)}\nu\overline{\nu}$, where $h^{(*)}$ stands for a light meson and we set upper limits on the branching fractions at 90% confidence level. The limits on $B^0 \to K^{*0}\nu\overline{\nu}$ and $B^+ \to K^+\nu\overline{\nu}$ decays are more stringent than the previous constraints, while the first searches for $B^0 \to K^0\nu\overline{\nu},\ \pi^0\nu\overline{\nu},\ \rho^0\nu\overline{\nu},\ \phi\nu\overline{\nu}$ and $B^+ \to K^{*+}\nu\overline{\nu},\ \rho^+\nu\overline{\nu}$ are reported.

PACS numbers: 13.25.Gv, 95.30.Cq, 13.25.Hw, 14.40.Nd

1. Introduction

The enigma of dark matter is being extensively investigated in many broad fields of research. Among terrestial tools to dig out the dark matter candidate one usually keeps in mind the experiments aimed at the interaction of the so-called weakly interacting massive particles (WIMP) inside the fiducial volume of the detector or direct searches *e.g.* for the lightest supersymmetric particle in the accelerators working or being planned at the energy frontier [1]. This article describes some of the searches for dark matter which come from “flavour physics” and are carried on at the so-called B-factories *i.e.* electron-positron accelerators working at the center-of-mass energy corresponding to masses of the Υ resonances. The two studies presented below are based on data collected in the Belle detector working at the KEKB e^+e^- collider, one of the two B-factories which are currently operational. Both the KEKB and Belle will be briefly described below (Sec. 2). The next two sections will be devoted to the search for dark matter in invisible decays of the $\Upsilon(1S)$ and the decays $B \to h^{(*)}\nu\overline{\nu}$, respectively.

* Presented at the XLVII Cracow School of Theoretical Physics, Zakopane, Poland, June 14–22, 2007.

2. The KEKB accelerator and the Belle detector

The KEKB [2] e^+e^- accelerator is located in Tsukuba (Japan). The electron and positron beams are asymmetric in energy: 3.4 on 7.8 GeV on $\Upsilon(3S)$ and 3.5 on 8 GeV on $\Upsilon(4S)$, respectively. This collider is currently a record holder as far as the luminosity is concerned (the peak value: $1.72 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$). The integrated luminosity of the KEKB exceeds $710\,\mathrm{pb^{-1}}$.

The Belle detector is a large-solid-angle magnetic spectrometer located at the KEKB collider, and consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Čerenkov 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 super-conducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail elsewhere [3].

3. Search for invisible decays of the $\Upsilon(1S)$

The decay in which the final state particles interact so weakly that they are not observable in a detector is defined as "invisible". According to the standard model (SM) the only particles which can contribute do the invisible final states are neutrinos. Thus, the observation of the invisible decay rate with a larger branching fraction than the standard model prediction would be an implication of physics beyond the SM. One possibility is a decay into dark matter particles, χ.

In the SM, quarkonium decay to the two-neutrino final state is predicted to have a branching fraction $\mathcal{B}(\Upsilon(1S) \to \nu\bar{\nu}) = (9.9 \pm 0.5) \times 10^{-6}$ [4]. A much larger invisible branching fraction $\mathcal{B}(\Upsilon(1S) \to \chi\chi) \simeq 6 \times 10^{-3}$ is predicted [5] for dark matter particles that are lighter than the b quark. Here, the pair annihilation cross section of dark matter particles to a SM quark pair $\sigma(\chi\chi \to q\bar{q})$ is estimated based on cosmological arguments, and the time-reversed reaction is assumed to have the same cross section, *i.e.* $\sigma(q\bar{q} \to \chi\chi) = \sigma(\chi\chi \to q\bar{q})$. The previous upper limits for the invisible $\Upsilon(1S)$ branching fraction were reported by ARGUS (23×10^{-3} with 90% confidence level) [6] and CLEO (50×10^{-3} with 95% confidence level) [7], which are about one order of magnitude above the prediction [5].

The Belle collaboration has recently reported the search for the invisible decay of the $\Upsilon(1S)$. The data sample used consists of $2.9\,\mathrm{fb^{-1}}$ collected on the $\Upsilon(3S)$ resonance (11×10^6 $\Upsilon(3S)$). This working point provides a clean sample of $\Upsilon(1S)$ decays.

The decays $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ are studied where only the cascade $\pi^+\pi^-$ pair is detected. If an $\Upsilon(1S)$ decay into an invisible final state does occur, it would appear as a peak at the $\Upsilon(1S)$ mass ($9.46\,\mathrm{GeV}/c^2$) in the distribution of recoil mass against the $\pi^+\pi^-$ system ($M^{\rm recoil}_{\pi^+\pi^-}$) without any detected decay products from the $\Upsilon(1S)$. The decays $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ followed by $\Upsilon(1S) \to \mu^+\mu^-$ are examined as control samples.

The invisible decay candidates are selected by requiring the presence of two oppositely charged tracks in the event, *i.e.* $\pi^+\pi^-$ tracks. The total visible energy in the ECL is required to be less than 3 GeV to reject $\Upsilon(1S)$ decays into final states consisting of neutral particles. To minimise any possible trigger bias, it is required that $\varphi_{\pi\pi} > 30^\circ$, $p_t > 0.17\,{\rm GeV}/c$ for the tracks, and $p_t > 0.30\,{\rm GeV}/c$ for at least one of the tracks. The overall detection efficiency, which is the product of the event reconstruction efficiency (9.1%) and the trigger efficiency (89.8%), is 8.2%.

To reconstruct events for the control sample, four charged tracks in an event, μ^+, μ^-, π^+, and π^-, are required. The signal yield in the control sample (4902$\pm$71 events) is extracted from an unbinned maximum likelihood fit in $\Delta M = M_{\mu^+\mu^-\pi^+\pi^-} - M_{\mu^+\mu^-}$ distribution. Using a detection efficiency of 39.7% for the control sample, which is determined from Monte Carlo (MC) calculations, it is estimated that $498 \times 10^3 \Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ decays are present in the data set. It is checked that the overall properties of the $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ decay are in agreement with MC calculations.

For those cases where all of the $\Upsilon(1S)$ decay products go outside of the detector acceptance, the $M^{\rm recoil}_{\pi^+\pi^-}$ distribution still peaks at the $\Upsilon(1S)$ mass and becomes a background to the invisible decay signal (Fig. 1). The largest sources of this "peaking background" are from decays to oppositely charged pairs such as $\Upsilon(1S) \to \mu^+\mu^-$ or e^+e^-, where the two tracks tend to be back-to-back, so that when one track escapes into the forward acceptance hole, the other track tends to escape into the backward acceptance hole. The total number of peaking background events is $133.2^{+19.7}_{-14.6}$, where both statistical and systematic errors are included.

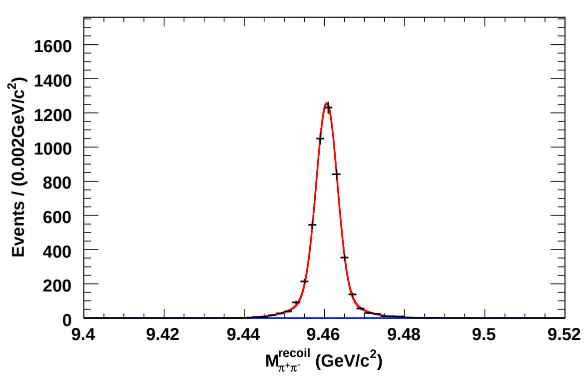

Fig. 1. $M^{\rm recoil}_{\pi^+\pi^-}$ distribution for the control sample $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \mu^+\mu^-$ decay candidates. The solid curve shows the fit results.

The signal extraction is performed by an unbinned extended maximum likelihood fit to the $M^{\rm recoil}_{\pi^+\pi^-}$ distribution. The signal shape is modelled with a double Gaussian that is calibrated using the control sample shown in Fig. 1. In the fit, the amount of peaking background is fixed at the estimated value and the same shape as the signal is used. The shape of the combinatorial background is modelled with a first order polynomial whose slope is floated. Fig. 2 shows the $M^{\rm recoil}_{\pi^+\pi^-}$ distribution. The extracted signal yield, 38 ± 39 events, is consistent with zero observed events. The upper limit for the branching fraction is determined to be $\mathcal{B}(\Upsilon(1S) \to \text{invisible}) < 2.5 \times 10^{-3}$ at the 90% confidence level. This result disfavours the prediction in Ref. [5] for the $\Upsilon(1S)$ decay to a pair of dark matter particles that are lighter than the b quark.

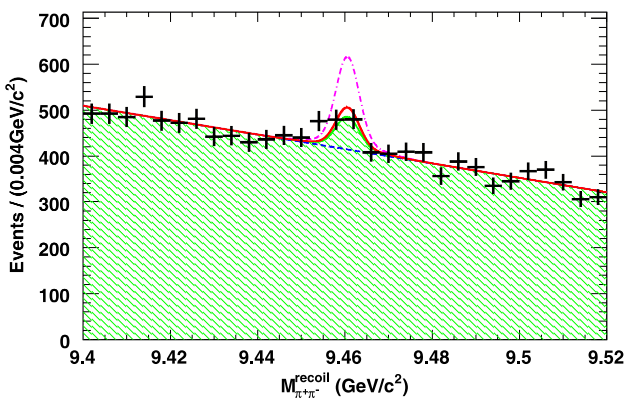

Fig. 2. Recoil mass distribution against two pions, $M^{\rm recoil}_{\pi^+\pi^-}$. The solid curve shows the result of the fit to signal plus background distributions, shaded area shows the total background contribution, dashed line shows the combinatorial background contribution, and the dot-dashed line shows the expected signal for $\mathcal{B}(\Upsilon(1S) \to \chi\chi)$ $= 6 \times 10^{-3}$.

4. Search for $B \to h^{(*)}\nu\overline{\nu}$ decays

The decays $B \to K^{(*)}\nu\overline{\nu}$ proceed through the flavour-changing neutral-current process $b \to s\nu\overline{\nu}$ and comprise a sensitivte probe of physics outside the standard model (SM). The dominant SM diagrams are shown in Fig. 3. Similarly, the decays $B \to (\pi,\rho)\nu\overline{\nu}$ proceed through $b \to d\nu\overline{\nu}$ processes. The SM branching fractions are estimated to be 1.3×10^{-5} and 4×10^{-6} for $B \to K^*\nu\overline{\nu}$ $B \to K\nu\overline{\nu}$ decays [8], respectively and are expected to be much lower for other modes. New physics such as SUSY particles or a possible fourth generation could potentially contribute to the penguin loop or box diagram and enhance the branching fractions [8]. According to Bird *et al.* [9] the decays $B \to h^{(*)}\nu\overline{\nu}$ offer the possibility of discovering light dark matter

(LDM) in $b \to s(d)$ transitions with large missing momentum (the pair of LDM particles might substitute $\nu\overline{\nu}$ in Fig. 3).

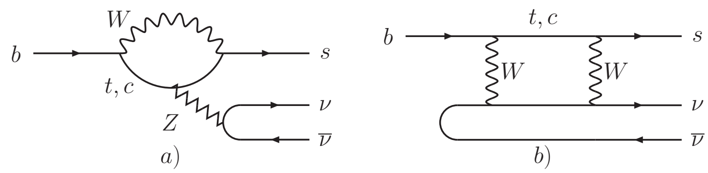

Fig. 3. The quark-level diagrams for $B \to K^*\nu\overline{\nu}$ decays.

The Belle collaboration has recently reported the first search for the decays $B \to h^{(*)}\nu\overline{\nu}$ [10] ($h^{(*)}$ stands for K^+, K^0_S, K^{*0}, K^{*+}, π^+, π^0, ρ^0, ρ^+, and ϕ) using a $492\,\mathrm{fb}^{-1}$ data sample recorded at the $\Upsilon(4S)$ resonance, corresponding to 535×10^6 B-meson pairs. The above huge data sample allows for application of the so-called "offline B-meson beam" method, which is a powerful tool in particular for B meson decays involving neutrinos in the final state. In this approach, one of the B mesons in the $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ event is fully reconstructed as the tag-side B candidate (B_{tag}). The remaining particles are assumed to be products of the signal-side B meson (B_{sig}). The B_{tag} candidates are reconstructed in one of the following modes: $B^0 \to D^{(*)-}\pi^+$, $D^{(*)-}\rho^+$, $D^{(*)-}a_1^+$, $D^{(*)-}D_s^{(*)+}$, $B^+ \to \overline{D}^{(*)0}\pi^+$, $\overline{D}^{(*)0}\rho^+$, $\overline{D}^{(*)0}a_1^+$, and $\overline{D}^{(*)0}D_s^{(*)+}$. The D^- mesons are reconstructed as $D^- \to K^0_S\pi^-$, $K^0_S\pi^-\pi^0$, $K^0_S\pi^-\pi^+\pi^-$, $K^+\pi^-\pi^-$, and $K^+\pi^-\pi^-\pi^0$. The following decay channels are included for $\overline{D}^0$ mesons: $\overline{D}^0 \to K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, $K^0_S\pi^0$, $K^0_S\pi^-\pi^+$, $K^0_S\pi^-\pi^+\pi^0$ and K^-K^+. The D^{*-} ($\overline{D}^{*0}$) mesons are reconstructed as $\overline{D}^0\pi^-$ ($\overline{D}^0\pi^0$ and $\overline{D}^0\gamma$). Furthermore, $D_s^{*+} \to D_s^+\gamma$, $D_s^+ \to K^0_S K^+$ and $K^+K^-\pi^+$ decays are reconstructed. B_{tag} candidates are selected using the beam-energy constrained mass $M_{\mathrm{bc}} \equiv (E^2_{\mathrm{beam}} - p_B^2)^{1/2}$ and the energy difference $\Delta E \equiv E_B - E_{\mathrm{beam}}$, where E_B and p_B are the reconstructed energy and momentum of the B_{tag} candidate in the $\Upsilon(4S)$ CM frame, and E_{beam} is the beam energy in this frame.

The decays $B_{\mathrm{sig}} \to K^+\nu\overline{\nu}$, $\pi^+\nu\overline{\nu}$, $K^0_S\nu\overline{\nu}$, and $\pi^0\nu\overline{\nu}$ are reconstructed from single K^+, π^+, K^0_S, and π^0 candidates, respectively. The $B^0 \to K^{*0}\nu\overline{\nu}$ candidate is reconstructed from a charged pion and an oppositely charged kaon, while for $B^+ \to K^{*+}\nu\overline{\nu}$ decays a K^0_S candidate and a charged pion, or a charged kaon and a π^0 candidate are used to form a candidate. Furthermore, $B^0 \to \rho^0\nu\overline{\nu}$ decays are reconstructed using pairs of charged pions with opposite charge. For $B^+ \to \rho^+\nu\overline{\nu}$, a charged pion and a π^0 candidate are used. A ϕ meson is formed from a K^+K^- pair.

B_{sig} candidates are selected using the variable $E_{\mathrm{ECL}} \equiv E_{\mathrm{tot}} - E_{\mathrm{rec}}$, where E_{tot} and E_{rec} are the total visible energy measured by the ECL detector and the measured energy of reconstructed objects including the B_{tag} and the signal side $h^{(*)}$ candidate, respectively. The decays $B \to D^{*}\ell\nu$ are examined as control samples; the observed $E_{\rm ECL}$ distributions are found to be in good agreement with Monte Carlo simulations [11]. The signal region is defined by $E_{\rm ECL} < 0.3\,{\rm GeV}$ while the sideband region is given by $0.45\,{\rm GeV} < E_{\rm ECL} < 1.5\,{\rm GeV}$.

The reconstructed $E_{\rm ECL}$ distributions are shown in Fig. 4. The $E_{\rm ECL}$ distributions of background are estimated with MC simulations; in particular, a large $b \to c$ MC sample corresponding to ten times the data luminosity is introduced with a preselection on the generator information. The background $E_{\rm ECL}$ distributions are normalized by the number of events in the sideband region. None of the signal modes has a significant signal and the respective upper limits on the branching fractions are evaluated (Table I).

The limits obtained for $B^0 \to K^{*0}\nu\overline{\nu}$ and $B^+ \to K^+\nu\overline{\nu}$ decays are more stringent than the previous constraints from DELPHI [12] and BaBar [13] by factors of 3 and 3.7, respectively. The first searches for $B^0 \to K^0\nu\overline{\nu}$, $\pi^0\nu\overline{\nu}$,

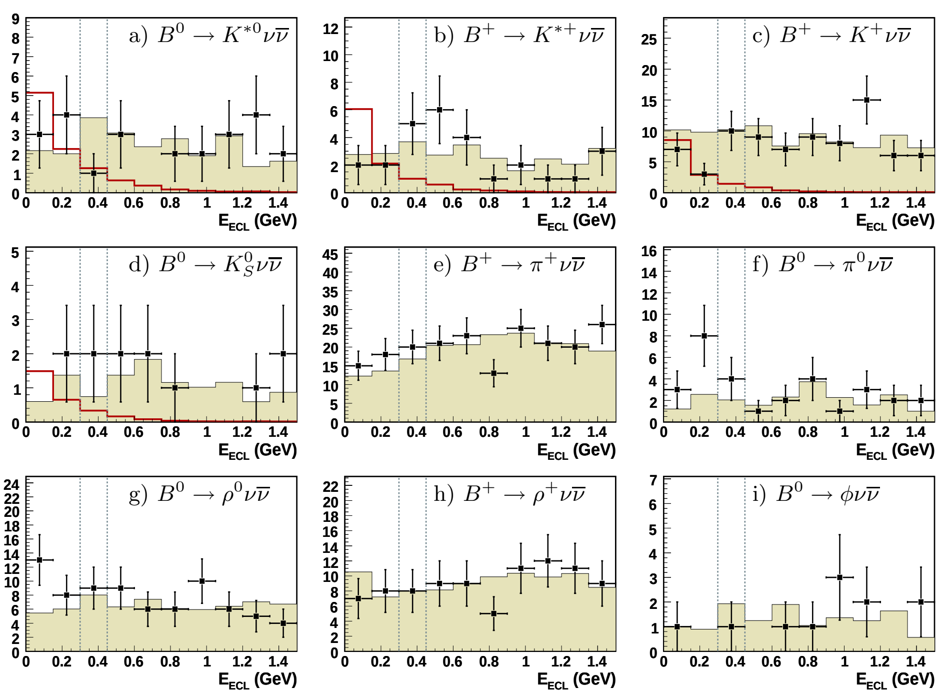

Fig. 4. The $E_{\rm ECL}$ distributions for $B \to h^{(*)}\nu\overline{\nu}$ decays. The shaded histograms show the background distributions from MC simulations and are normalized to sideband data. The open histograms show the SM expected signal distributions for $B \to K^{(*)}\nu\overline{\nu}$ decays multiplied by a factor of 20 for the comparison. The vertical dashed lines show the upper bound (left) of the signal box and the lower bound (right) of the sideband region.

$\rho^0\nu\overline{\nu}$, $\phi\nu\overline{\nu}$, and $B^+ \to K^{*+}\nu\overline{\nu}$, $\rho^+\nu\overline{\nu}$ are carried out, and upper limits on the branching fraction of order 10^{-4} are obtained. The limit on $B^+ \to \pi^+\nu\overline{\nu}$ is less restrictive than BaBar's result [13] due to a larger number of observed events in the signal box. The results on $B \to K^{(*)}\nu\overline{\nu}$ reported here are one order of magnitude above the predictions of Ref. [8] and hence still allow room for substantial non-SM contributions.

TABLE I

A summary of the number of observed events in the signal box ($N_{\rm obs}$) and sideband regions ($N_{\rm side}$), expected background yields (N_b) in the signal box, reconstruction efficiencies including both $B_{\rm tag}$ and $B_{\rm sig}$ (ε), and the upper limits (U.L.) on the branching fractions at 90% CL.

Mode	$N_{\rm obs}$	$N_{\rm side}$	N_b	$\varepsilon(\times 10^{-5})$	U.L.
$K^{*0}\nu\overline{\nu}$	7	16	4.2 ± 1.4	5.1 ± 0.3	$< 3.4 \times 10^{-4}$
$K^{*+}\nu\overline{\nu}$	4	18	5.6 ± 1.8	5.8 ± 0.7	$< 1.4 \times 10^{-4}$
$\to K_S^0\pi^+$	1	7	2.3 ± 1.2	2.8 ± 0.3	—
$\to K^+\pi^0$	3	11	3.3 ± 1.4	3.0 ± 0.4	—
$K^+\nu\overline{\nu}$	10	60	20.0 ± 4.0	26.7 ± 2.9	$< 1.4 \times 10^{-5}$
$K^0\nu\overline{\nu}$	2	8	2.0 ± 0.9	5.0 ± 0.3	$< 1.6 \times 10^{-4}$
$\pi^+\nu\overline{\nu}$	33	149	25.9 ± 3.9	24.2 ± 2.6	$< 1.7 \times 10^{-4}$
$\pi^0\nu\overline{\nu}$	11	15	3.8 ± 1.3	12.8 ± 0.8	$< 2.2 \times 10^{-4}$
$\rho^0\nu\overline{\nu}$	21	46	11.5 ± 2.3	8.4 ± 0.5	$< 4.4 \times 10^{-4}$
$\rho^+\nu\overline{\nu}$	15	66	17.8 ± 3.2	8.5 ± 1.1	$< 1.5 \times 10^{-4}$
$\phi\nu\overline{\nu}$	1	9	1.9 ± 0.9	9.6 ± 1.4	$< 5.8 \times 10^{-5}$

5. Summary

The Belle collaboration has performed the search for a light dark matter candidate using two approaches. First the invisible decays of the $\Upsilon(1S)$ were studied via the $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ transition. No signal was found and an upper limit of 2.5×10^{-3} at the 90% confidence level for $\mathcal{B}(\Upsilon(1S) \to$ invisible) was obtained. This result disfavors the theoretical expectations for the $\Upsilon(1S)$ decay to a pair of dark matter particles that are lighter than the b quark. Second, no signal was observed in the search for $B \to h^{(*)}\nu\overline{\nu}$ decays. The upper limits evaluated for these decays are generally above the standard model predictions. A higher luminosity B-factory experiment is necessary to probe the SM predictions for $B \to h^{(*)}\nu\overline{\nu}$ branching fractions.

REFERENCES

[1] L. Roszkowski, *Acta Phys. Pol. B* **38**, 3925 (2007), these proceedings.

[2] S. Kurokawa, E. Kikutani, *Nucl. Instrum. Methods* **A499**, 1 (2003) and references therein.

[3] A. Abashian *et al.* [Belle Collaboration], *Nucl. Instrum. Methods* **A479**, 117 (2002).

[4] L.N. Chang, O. Lebedev, J.N. Ng, *Phys. Lett.* **B441**, 419 (1998).

[5] B. McElrath, *Phys. Rev.* **D72**, 103508 (2005); we quote the corrected branching fraction value, 6×10^{-3}, from the private communication with the author.

[6] H. Albrecht *et al.* [ARGUS Collaboration], *Phys. Lett.* **B179**, 403 (1986).

[7] D. Besson *et al.* [CLEO Collaboration], *Phys. Rev.* **D30**, 1433 (1984).

[8] G. Buchalla, G. Hiller, G. Isidori, *Phys. Rev.* **D63**, 014015 (2000).

[9] C. Bird, P. Jackson, R. Kowalewski, M. Pospelov, *Phys. Rev. Lett.* **93**, 201803 (2004).

[10] K.F. Chen *et al.* [BELLE Collaboration], `arXiv:0707.0138 [hep-ex]`.

[11] K. Ikado *et al.*, *Phys. Rev. Lett.* **97**, 251802 (2006).

[12] W. Adam *et al.* [DELPHI Collaboration], *Z. Phys.* **C72**, 207 (1996).

[13] B. Aubert *et al.* [BaBar Collaboration], *Phys. Rev. Lett.* **94**, 101801 (2005).