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RECENT MEASUREMENTS OF $|V_{ub}|$ AND γ IN BABAR

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Abstract

We present recent results of the measurements, employed by the BaBar Collaboration, of the Cabibbo-Kobayashi-Maskawa (CKM) matrix element V_{ub} in absolute value $|V_{ub}|$, and phase γ.

1 Introduction

With the discovery of CP violation in the B^0 mesons, and the precise measurement [1] of the angle β of the Unitarity Triangle (UT), the experimental effort focus on the measurements of other parameters to overconstraint the CKM matrix. The information on the side R_b opposite to the angle β is crucial. In the Wolfenstain parameterization, $|R_b| = \lambda^{-1}(1-\lambda^2/2)|V_{ub}/V_{cb}|$, and the R_b phase is the angle γ. The parameters $|V_{ub}/V_{cb}|$ and γ play a special role in the CKM matrix, because they can be extracted from pure tree level decays, so their values are to high accuracy independent of any new physics contributions. The parameter $|V_{cb}|$ is known, from a global fit to the heavy quark parameters [2], with an uncertainties of about 2%, so at present the uncertainty on $|V_{ub}|$, close to 7%, is the limiting factor to the constraint, so we will focus the rest of the paper only to $|V_{ub}|$. A comprehensive review of $|V_{ub}|$ and γ measurements is beyond the scope of this paper. We will present only the most recent measurements.

2 Inclusive Measurement of $|V_{ub}|$

The semileptonic are characterized by an electroweak current that probes the B dynamics allowing to determine the CKM matrix element in a clear environment. Their simplicity is only apparent, because we are interested in precision measurements, the complexity specific of QCD dynamics have to be addressed and taken in consideration.

The full rate for $B \to X_u \ell\nu$ decays is related to the free quark rate by Operator Product Expansion (OPE) techniques [3]. If the full decay rate were experimentally accessible, the resulting theoretical uncertainties on $|V_{ub}|$ would be of the order of 5% [4]. In practice the measurable rate is strongly reduced since the background from $B \to X_c \ell\nu$ decays (that dominates the signal by

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a factor 50) must be suppressed by requiring stringent kinematic cuts. The reduced accessible rate breakdown the OPE and this increase considerably the theoretical uncertainty. The cuts relies on the u quark mass being much lighter than the c quark, as a consequence the distribution of some variables, like p_ℓ, the lepton momentum, extends to higher values for the signal. Whereas the distribution of the hadronic mass m_X of the hadronic jet produced by the fragmentation of the quark u, extends toward lower values. It is possible to select regions of the phase space where the signal over background is reasonable, but usually the acceptances tend to be small (from 6% requiring p_ℓ above the kinematic endpoint of the leptons from $B \to X_c \ell \nu$, to 70% requiring m_X lower than the mass of the D meson). In the reduced phase space, the leading term of the non-perturbative correction to the expected rate, becomes of the order Λ_{QCD}/m_b instead of Λ^2_{QCD}/m^2_b, and is described by the distribution function (call *shape function*) of the momentum of the b quark inside the B meson. The shape function cannot be computed perturbatively and must determined experimentally. It is function of m_b and the other heavy quark parameters that describe the internal structure of the B meson, which can be determined by other processes like $B \to X_c \ell \nu$ and $b \to s\gamma$ decays. The measurement of the partial branching ratio $\Delta\mathcal{B}(B \to X_u \ell \nu)$ can be translated into $|V_{ub}|$ by $|V_{ub}| = \sqrt{\Delta\mathcal{B}/(\tau_B \cdot \Gamma_{th})}$, where τ_B is the B meson lifetime, and Γ_{th} is the reduced decay rate defined as $\Gamma_{th} = \Delta\Gamma_{th}/|V_{ub}|^2$, where $\Delta\Gamma_{th}$ is the partial width into the phase space defined by the kinematic cuts, predicted by the theory [5].

2.1 Measurement near the Endpoint of the Lepton Energy Spectrum

The endpoint region of the lepton-energy spectrum allows to access the $B \to X_u \ell \nu$ events measuring the rate of leptons beyond the kinematic endpoint for $B \to X_c \ell \nu$. The region of the phase space above this limit is $\approx 6\%$, so the acceptance of the cut on p_e is affected by large uncertainties due to the shape function. Moreover this region is sensitive to the weak annihilation contributions, which are not well known. In the last few years the backgrounds knowledge have improved, so it has been possible to relax the cut on p_e down to 2.0 GeV/c, increasing the acceptance to 26%, and reducing the total theoretical uncertainties [6]. In Fig.1, the distribution of the lepton momentum is shown. Using 88 million of $\Upsilon(4S)$ decays, the measured partial branching fraction is $\Delta\mathcal{B}(p_e > 2.0\ GeV) = (5.31 \pm 0.32_{stat} \pm 0.49_{syst}) \times 10^{-4}$. This partial branching ratio translates in $|V_{ub}| = (4.25 \pm 0.30_{exp} \pm 0.31_{theo}) \times 10^{-3}$.

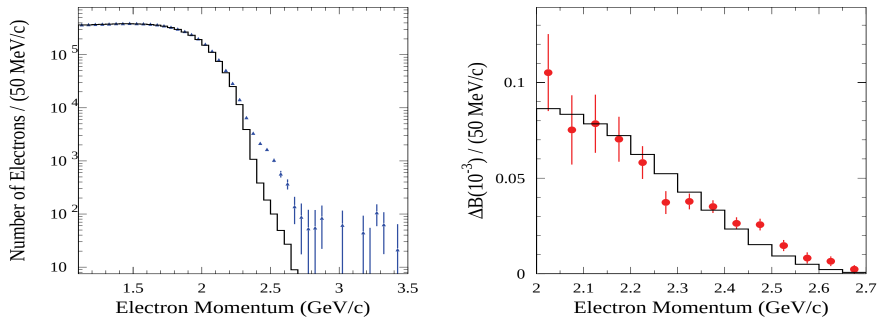

Figure 1: *(Left) on-resonance data after subtraction of the fitted non-$B\bar{B}$ background estimated using off-peak data collected at the center of mass energy 40 MeV below the $\Upsilon(4S)$ resonance. The histogram shows the simulated $B\bar{B}$ background, which is essentially described by the sum of the different charm components: $B \to D\ell\nu$, $B \to D^*\ell\nu$ $B \to D^{**}\ell\nu$. (Right) Differential branching ratio for $B \to X_u\ell\nu$ decays, as a function of the electron momentum, after the background subtraction and correcting for bremsstrahlung and final state radiation. The Monte Carlo signal simulation is superimposed to the data.*

2.2 Shape function free measurement using hadronic B tags

Recently BaBar published results using two new techniques to extract $|V_{ub}$ with a reduced dependence on the modeling of the shape function [8]. In the Ref. [7] is presented a technique (called LLR) that utilizes weight functions to relate $B \to X_u\ell\nu$ partial rate, with the photon energy spectrum in $B \to X_s\gamma$. The LLR method, applied to the hadronic mass m_X, combines the m_X spectra integrated below ζ, with the high energy part of the measured differential $B \to X_s\gamma$ photon energy spectrum, through the weight functions. The BaBar analysis the recoil of fully reconstructed B mesons on a sample of 88 million of $B\bar{B}$ events. Fig.2 shows the spectrum of the hadronic invariant mass m_X, before and after background subtraction. The partial rate $\Delta(B \to X_u\ell\nu)$ is determined by counting events requiring $m_X < \zeta$, and $|V_{ub}|$ is extracted by using the photon energy spectrum measured by BaBar [9]. The experimental errors increase at higher ζ, instead the theoretical uncertainty increase as the ζ is decreased (the LLR calculations are accurate up to corrections of order $(\Lambda m_B/(\zeta m_b))^2$). The optimal cut is $m_X < 1.67 GeV$, which gives a measurement with a 12% of total error, which is dominated by the statistical uncertainty on the $B \to X_u\ell\nu$ rate and on $B \to X_s\gamma$. The result is $|V_{ub}| = (4.43 \pm 0.45 \pm 0.29) \times 10^{-3}$. An alternative method to reduce the model dependence is to measure the $B \to X_u\ell\nu$ rate over the entire m_X

spectrum. In this case no extrapolation is needed to obtain the full rate, and the OPE expansion [4] can be used, but the statistical errors increases due to the large background subtraction needed to extract the signal. The result is $|V_{ub}| = (4.34 \pm 0.476 \pm 0.10) \times 10^{-3}$.

The $|V_{ub}|$ values obtained with these techniques are compatible with the measurements performed with other methods and with the latest average from the HFAG [10].

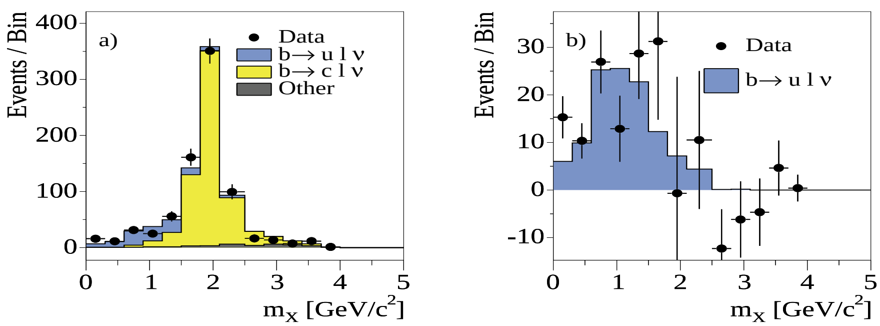

Figure 2: *The m_X for the $B \to X\ell\nu$ candidates. (Left) data and the fit components,(right) data and signal MC after subtraction of $B \to X_c\ell\nu$ and other backgrounds.*

3 Measurement of γ

The CP-violating phase γ can be measured with the charged B-decays $B^- \to \tilde{D}^{(*)0}K^{(*)-}$, where $\tilde{D}^0$ indicates either a D^0 or a $\overline{D}^0$ meson. The basic method is based on the fact that a B^- meson can decay into a color-allowed $D^{(*)0}K^{(*)-}$ final state via $b \to c\bar{u}s$ transition, instead the color-suppressed $\overline{D}^{*0}K^{*-}$ decay proceeds via a $b \to u\bar{c}s$ transitions. The amplitude of the $b \to c\bar{u}s$ ($\mathcal{A}(b \to c)$) is proportional to λ^3 and the amplitude of the $b \to u\bar{c}s$ ($\mathcal{A}(b \to u)$) transition is proportional to $\lambda^3\sqrt{\eta^2 + \rho^2}e^{i(\delta_B - \gamma)}$, where δ_B is the relative strong phase of those two transitions. If the $\tilde{D}^0$ decay in a final state common to D and $\overline{D}$, the total measured amplitude for $B^- \to \tilde{D}^{(*)0}K^{(*)-}$ decays is the sum of the amplitude $\mathcal{A}(b \to u)$ and $\mathcal{A}(b \to c)$ that interfere. This interference can lead to different B^+ and B^- decay rates, so to a measurable direct CP-violation.

The $\mathcal{A}(b \to u)$ amplitude is reduced with respect to $\mathcal{A}(b \to c)$ because a color suppressed diagram is involved. The parameter $r_B = |\mathcal{A}(b \to u)/|\mathcal{A}(b \to c)$, that determine the size of the direct CP violation, is a very critical parameter for these analysis: the smaller r_B, the smaller is the experimental sensitivity to γ. Its value is predicted to be in the range $0.1 - 0.3$ and it has to be fitted together with the weak phase γ and the strong phases δ_B (r_B and δ_B depends on the B final state).

Three methods are been usually used, depending essentially on the D^0 decay modes considered:

1. ADS [11] method considers the double CKM-suppressed D^0 final state, like $D^0 \to K^+\pi^-$. Here the favored $b \to c$ decay, followed by the suppressed D decay, interferes with the suppressed $b \to u$ decays, followed by the favored D final state. The relative similarity of the combined decays amplitudes enhances the possible interference. There are complications due to the unknown relative strong phase in the $D^0 - \overline{D}^0 \to [K^+\pi^-]$ system. Actually this method alone does not put strong constrain on the angle γ but allows to put limit on r_B.

2. GGSZ [12] study the decay $D^0 \to K^0_s\pi^-\pi^+$. This method is the one with the highest sensitivity to γ because of the best overall combination of branching ratio magnitude, $D - \overline{D}$ interference and background level. The D^0 final state can be accessed through many intermediate states with $CP+$ and $CP-$, therefore a Dalitz analysis is required to separate the various contributions. The physical observables are usually espressed in the Cartesian Coordinates, $x_\mp, y_\mp = Re, Im[r_B e^{i(\delta_B \pm \gamma)}]$, which are natural choice to describe the amplitude decays. The BaBar final result, is $\gamma = [67 \pm 28_{stat} \pm 13_{syst} \pm 11_{Dalitz\ model}]^o$, where the result is dominated by the statistical uncertainties.

3. GLW [13]: the $\tilde{D}^0$ is reconstructed in various CP-eigenstate. In principle this methods is very clean to determine γ with an 8-fold ambiguity, but the small CP-asymmetry, and the small branching ratios to produce the secondary D^0 CP-eigenstate, make this method difficult with present dataset available. But this measurements can be combined with the measurements from the Dalitz to improve the knowledge of the of the angle γ and the parameter r_B. The recent result [14] obtained by BaBar with this method is reported in the following.

All these methods are theoretically very clean because the main contributions to the amplitude comes from tree-level diagrams.

3.1 Direct CP violation in charged B decays

The result of the GLW analysis are usually expressed in terms of the 4 observables: the partial rate charge asymmetry $A_{CP\pm}$ and the charge averaged

Table 1: *Measured ratios $R_{CP\pm}$ and $A_{CP\pm}$ for CP+ and CP- D^0 decays mode. The first error is statistical and the second is systematic.*

D^0 mode	R_{CP}	A_{CP}
CP+	$0.90 \pm 0.11 \pm 0.04$	$0.35 \pm 0.13 \pm 0.04$
CP-	$0.86 \pm 0.10 \pm 0.05$	$-0.06 \pm 0.13 \pm 0.04$

partial rate $R_{CP\pm}$, which are defined in [14] Only three are independent because $R_{CP+}A_{CP+} = -R_{CP-}A_{CP-}$, but we have exactly three unknown, γ, r_B and δ_B, so the measurement is in principle enough to extract γ.

We reconstruct the $B^- \to D^0 h^-$ decays, where the track h^- is a kaon or a pion. The D^0 are reconstructed in the CP-even eigenstates $\pi^-\pi^+$ and K^-K^+ and in the CP-odd eigenstates $K_s^0\pi^0$, $K_s^0\omega$ and $K_s^0\phi$, and in the non-CP flavor eigenstate $K^-\pi^+$. Fig.3 shows the distribution of ΔE for $K\pi$, CP-even and CP-odd modes, after enhancing the $h = K$ purity requiring that the prompt track is compatible with the kaon hypothesis. The measured partial rate R and the asymmetry, obtained with a sample of 232 million of $\Upsilon(4S)$ decays in $B\overline{B}$, are reported in Tab.1.

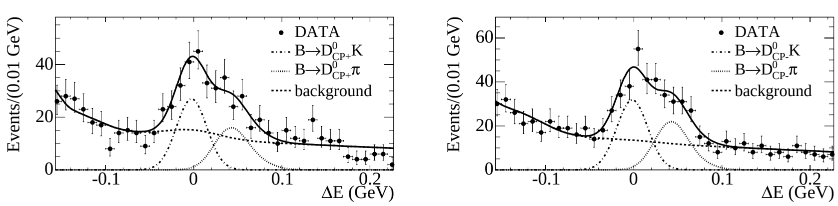

Figure 3: *Distribution of ΔE for events enhanced in $B^- \to D^0 K^-$ signal. Left: $B^- \to D^0_{CP+}K^-$; right: $B^- \to D^0_{CP-}K^-$. The ΔE is computed in the kaon hypotesis, for the $B^- \to D^0\pi^-$ background the ΔE distribution is shifted toward higher value.*

We also express the result in terms of the Cartesian observable $x_\pm$ using the relation $x_\pm = [R_{CP+}(1 \mp A_{CP+}) - R_{CP-}(1 \mp A_{CP-})]/4$. The resulting values are $x_+ = -0.082 \pm 0.053 \pm 0.018$ and $x_- = +0.102 \pm 0.062 \pm 0.022$, which are consistent with the ones obtained through a Dalitz analysis, and the precision is comparable.

A combination of the result of the direct γ measurements described above, including the result of the BELLE collaboration, has been obtained by the UTfit Collaboration [15] using a Bayesian approach, $\gamma = 65 \pm 20^o$, that is consistent with the overall indirect prediction obtained for the standard model CKM triangle fit using all the other usual inputs: $\gamma = 61.1 \pm 4.5^o$, where the total error is dominated by the statistics uncertainty.

3.2 Different path toward γ

The angle γ can also be extracted using the neutral B^0 decays [16]. The time dependent CP asymmetry in the decay modes $B^0 \to D^{(*)\pm}\pi^{\mp}$, which allows to measure $sin(2\beta+\gamma)$, have been extensively studied by BaBar [17] and BELLE [18]. In these modes the CP-asymmetry arise due to a phase difference between two amplitudes of very different magnitudes, one, which involve the $B\bar{B}$ mixing, is suppressed by the product of two small CKM elements (V_{ub} and V_{cd}), the other is instead CKM favored (proportional to V_{cb}). The resulting interference between the two amplitudes, proportional to $r_B sin(2\beta+\gamma\pm\delta)$ is small, because the parameter r_B for the $B^0 \to D^{(*)\pm}\pi^{\mp}$ decay mode is close to 0.02. The parameter r_B have to be extracted from other measurements, for example through the measurement of the $B^0 \to D_s^{(*)\pm}\pi^{\mp}$ [19], using $SU(3)$ symmetry.

Recently have been proposed many others decays modes that could in principle overcome the difficulties summarized above. The rest of this section is devoted to illustrate the results of these studies. In Ref. [20] was proposed to use two-body final states $B^0 \to D^{(*)}h$ with other types of light mesons h. The basic idea is that decays amplitudes with light scalar or tensor mesons, such as a_0^+ or, a_2^+, emitted from weak currents, are suppressed due to the small coupling constants. This means that the CKM favoured process ($b \to c$) is expected to be suppressed, and can be comparable with the CKM-suppressed transitions, resulting in a large CP-asymmetry. In BaBar an extensive search of the $B^0 \to D_s^{(*)+}a_{0,2}^-$ has been performed using about 230 million $\Upsilon(4S)$ decays into $B\overline{B}$ pairs [21]. We do not observe any evidence of the decays $B^0 \to D_s^+a_0^-$, $B^0 \to D_s^+a_2^-$, $B^0 \to D_s^{*+}a^{-0}$ and $B^0 \to D_s^{*+}a_2^-$, and set 90% C.L. upper limits on their branching fractions respectively of 1.9×10^{-5}, 19×10^{-5}, 3.6×10^{-5} and 20×10^{-5}. The upper limit for $B^0 \to D_s^+a_0^-$ is lower than theoretical expectation, so a revision of the $B \to a_0X$ transition form factors have to be performed. The upper limits suggested, through the $SU(3)$ symmetry, that the branching ratios of $B^0 \to D^{(*)+}a_{0,2}^-$, is too small for CP-asymmetry measurements at the present B-factories.

The decay $\overline{B}^0 \to D^{(*)0}\overline{K}^0$ offer a new approach to determine $sin(2\beta+\gamma)$ [13, 11, 22]. The CP asymmetry appears as a result of the interference between two diagrams leading to the same final state $D^{(*)0}\overline{K}^0$. Both diagrams are color suppressed, this means that the parameter r_B is large, the expected value is close to 0.4, so the CP-asymmetry is expected to be large. On the other hand the self tagged decays process $\overline{B}^0 \to D^{(*)0}\overline{K}^{*0}$ with the $K^* \to K^-\pi^+$ can be used to gain insight into the CKM suppressed diagram in $\overline{B}^0 \rightarrow D^{(*)0}\overline{K}^0$. Using a sample of 226 million of $B\overline{B}$ decays, the CKM favored processes have been observed [23], and the following branching fraction have been measured $\mathcal{B}(B \rightarrow D^{*0}\overline{K}^0) = (3.6 \pm 1.2 \pm 0.3) \times 10^{-5}$, $\mathcal{B}(B \rightarrow D^0\overline{K}^0) = (5.3 \pm 0.7 \pm 0.3) \times 10^{-5}$. Instead the CKM suppressed mode $B \rightarrow \overline{D}^0\overline{K}^{*0}$ has not been observed, an upper limit at 90% of C.L. of 1.1×10^{-5} has been put on the $\mathcal{B}(B \rightarrow \overline{D}^0\overline{K}^{*0})$. This limit can be translated into the limit $r_B < 0.40$ at 90% C.L. The present signal yields combined with the limit on r_B suggest that this method cannot be used with the present B-Factories.

The three body decays $B \rightarrow DK\pi$ decays have been proposed [24] as an alternative method for measuring γ. This method is self-tagged and not require time-dependent analysis. In these modes, the CKM suppressed $b \rightarrow u\bar{c}s$ transition includes color-allowed diagrams, thus larger rates and significant CP violation are expected. In addition a Dalitz analysis of the $DK\pi$ final state can resolve the strong phase and reduce the ambiguity to two-fold, compared to the GLW standard method. Using a sample of 226 million $B\overline{B}$ events, a measurement of the CKM favored $B^0 \rightarrow \overline{D}^0K^+\pi^-$ decay has been performed [25]: $\mathcal{B}(B^0 \rightarrow \overline{D}^0K^+\pi^-) = (88 \pm 15 \pm 9) \times 10^{-6}$. The search of the CKM suppressed $B^0 \rightarrow D^0K^+\pi^-$ decays have also been performed, but no signal was found. The upper limit on the branching ratio, at 90% of C.L. is $\mathcal{B}(B^0 \rightarrow D^0K^+\pi^-) < 19\times10^{-6}$. The event yields in this channel are lower than expected indicating that a larger data sample is required to constrain γ.

4 Conclusion

The study of the B decays to extraction the CKM parameter V_{ub} both in module and in weak phase, is pursued with great effort both by BaBar and BELLE Collaborations. The measurement of $|V_{ub}|$ is dominated by the theoretical uncertainty, but the recent theoretical development in this field, driven by the experimental measurements, has reduced the total uncertainty on the inclusive $|V_{ub}|$ to under 7.4%. Further reduction are expected in the next future. Instead the measurement of γ is limited by the statistical uncertainty, so it is crucial to have large sample of B mesons, and add togheter the informations coming out from many different decays modes.

References

1. B.Aubert *et al.*, Phys.Rev.Lett **94**, 161803 (2005); K.Abe *et al.*, Phys.Rev.Lett **87**, 091802 (2005);

2. O. Buchmuller and H. Flaecher, Phys. Rev. D **73**, 073008 (2006)

3. A.V.Manoher and M.B.Wise, Phys. Rev. D **49**, 1310 (1994), I.I.Bigi et al., Phys. Rev. Lett. **71**, 496 (1993)
4. N.Uraltsev, Int. J. Mod. Phys. A **14**, 4641 (1999)
5. F. de Fazio, M. Neubert, JHEP **06**, 017 (1999)
C.W.Bauer et al., Phys. Rev. D **064**, 113004 (2001)
B.O.Lange, M.Neubert,G.Paz, Phys. Rev. D **72**, 073006 (2005)
J.R.Andersen and E.Gardi, JHEP **0601**, 097 (2006)
6. B.Aubert *et al.*, Phys. Rev. D **73**, 012006 (2006)
7. A.K.Leibovich, I.Low and I.Z.Rothstein, Phys. Rev. D **61**, 053006 (2000)
8. B.Aubert *et al.*, hep-ex/0601046, *submitted to Phys.Rev.Lett.*
9. B.Aubert *et al.*, Phys. Rev. D **72**, 052004 (2005)
10. Heavy Flavor Averaging Group, hep-ex/0603003
11. D.Atwood, I.Dunietz and A.Soni, Phys. Rev. Lett.**78**, 3257 (1997)
12. A.Giri *et al.*, Phys. Rev.D **68**, 054018 (2003)
13. M.Gronau, D.London et.al Phys.Lett.B**253**, 483 (1991); M.Gronau, D.Wyler, Phys.Lett.B**265**, 172 (1991);
14. B.Aubert *et al.*, Phys. Rev. D **73**, 051105 (2006)
15. UTfit Collaboration, JHEP **0507**, 028, (2005); http://www.utfit.org/
16. I.Dunietz, Phys.Lett.B **427**, 179 (1998); R.Fleischer, Nucl.Phys.B671, 459 (2003)
17. B.Aubert *et al.*, hep-ex/0602049; B.Aubert *et al.*, Phys.Rev. D**71**, 112003 (2005);
18. F.J.Ronga *et al.*, hep-ex/0604013 (*submitted to Phys.Rv.D*);
19. B.Aubert *et al.*, Phys. Rev. Lett. **90**, 181803 (2003)
20. M.Diehl, G.Hiller, Phys.Lett.B **517**, 125 (2001)
21. B.Aubert *et al.*, hep-ex/0512031;
22. B.Keyser, D.London et.al Phys.Rev.D**61**, 116013 (2000)
23. B.Aubert *et al.*, hep-ex/0604016
24. R.Aleksan, T.C.Petersen, A.Soffer, Phys.Rev.D **67**, 054018 (2003); M.Gronau. Phys.Lett.B*557*, 198 (2003)
25. B.Aubert *et al.*, hep-ex/0509036