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REVIEW OF CKM RESULTS FROM BABAR

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Abstract. We present the latest results, as of August 2005, on CKM matrix elements from the BaBar experiment. Results projected on the $\bar{\rho}-\bar{\eta}$ plane from the CKM fitter group [1] are presented to show how the measurements compare with the Standard Model fits.

1 Introduction

The unitary CKM matrix [2] describes the coupling of the quark flavors and is given by:

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}.$$

The unitarity of this matrix can be expressed in six equations of the type $V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb}$ (the equation most useful in b-physics). Each of these six equations can be represented in geometric form as a triangle in the complex plane.

It is usual to parameterize this matrix in terms of four real parameters: A, λ, ρ, η as proposed by Wolfenstein [3].

$$V_{\rm CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3\,(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3\,[1-(\rho+i\eta)] & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4).$$

In this parameterization the elements $V_{ub} = A\lambda^3(\rho - i\eta) = |V_{ub}|e^{-i\gamma}$ and $V_{td} = A\lambda^3(1-(\rho+i\eta)) = |V_{td}|e^{-i\beta}$ are complex and we can represent the unitarity triangle in the $\rho-\eta$ plane, or normalizing the base of this triangle to 1, in the $\bar{\rho}-\bar{\eta}$ plane as shown in Figure 1 where ($\bar{\rho} = (1-\lambda^2/2)\rho$ and $\bar{\eta} = (1-\lambda^2/2)\eta$. In the Wolfenstein approximation $V_{tb} = 1$ and $V_{ts} = -V_{cb}$. The angles of the triangle, $\beta = -\arg(V_{td}); \gamma = \arg(V^*_{ub}); \alpha = \pi - \gamma - \beta$, are determined by CP asymmetries. The sides and angles of this triangle parameterize the CKM matrix and in this report we present determinations of the sides and angles from the BaBar experiment. A separate report on measurements of the side labelled R_b will be given by V. Azzolini at this conference.

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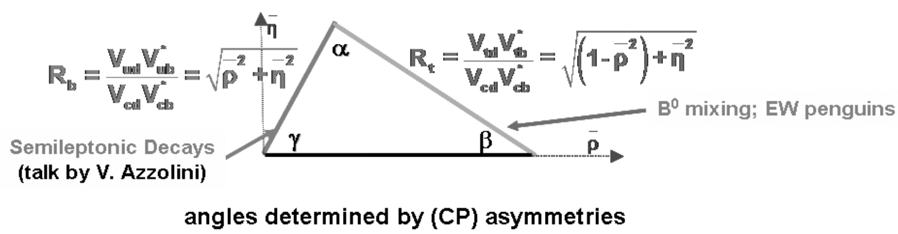

Figure 1: The CKM triangle

2 Experimental details

The data described in this report were taken with the BaBar detector at the SLAC PEP-II Asymmetric B-factory by the BaBar collaboration. The collaboration consists of over 600 physicists from 81 institutions in 11 countries. The detector is characterized by precision tracking, high-resolution calorimetry and excellent particle-type identification and has been described in detail elsewhere [4]. The PEP-II Asymmetric B-factory collides e^- of ~ 9 GeV with e^+ of ~ 3.1 GeV so that the center of mass energy corresponds to the mass of $\Upsilon(4S)$ resonance. At the $\Upsilon(4S)$, $\sigma_{b\bar{b}}/\sigma_{\mathrm{hadrons}} \approx 1/4$. The $B\bar{B}$ events of interest can be distinguished from the hadronic background due to the difference of the topological and kinematic characteristics of the events. Analysis specific experimental details can be found in the publications cited and the references therein. The bulk of the results present here are based on a sample of over 200 million $B\bar{B}$ pairs.

3 Determination of R_T [5, 6]

Radiative penguin dominated decays can be used to extract the ratio of CKM matrix elements $|V_{td}/V_{ts}|$. While not yet competitive with the constraint on this side of the unitarity triangle from the ratio $\Delta m_d/\Delta m_s$, recent BaBar results are reported here.
BaBar has an upper limit on the branching ratios for the decays $B \to \rho(770)\gamma$ and $B^0 \to \omega(782)\gamma$ [5]. The SU(3) weighted branching ratio

$$BR(B \to (\rho/\omega)\gamma) = \frac{1}{2}\{BR(B^+ \to \rho^+\gamma) + \frac{\tau_{B^+}}{\tau_{B^0}}[BR(B^0 \to \rho^0\gamma) + BR(B^0 \to \omega\gamma)]\}$$

is then combined with the previously reported BaBar measurement of $BR(B \to K^*\gamma)$ [5] to calculate a limit of $BR(B \to (\rho/\omega)\gamma)/BR(B \to K^*\gamma) < 0.029$ at 90% C.L. This limit constrains the ratio of CKM elements $|V_{td}/V_{ts}|$ by means of the equation [7, 8]:

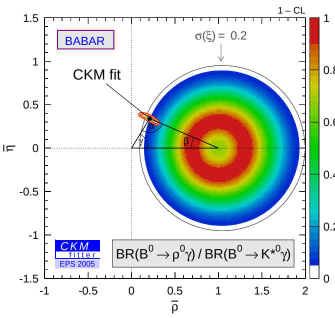

Figure 2: CKM fitter group constraint in the $\bar{\rho} - \bar{\eta}$ for R_t based on the ratio of the penguin branching ratios as described in the text.

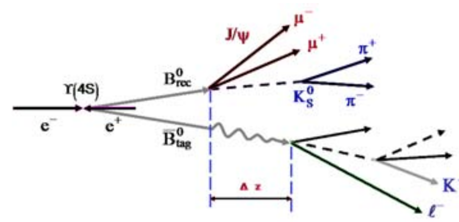

Figure 3: Time dependencies are measured by using the fact that the at the $\Upsilon(4S)$ the $B\bar{B}$ is produced coherently. By tagging the flavor of one B-meson (using the lepton charge, kaon charge, or a neural network) one determines the flavor of the other B-meson, B_{rec}, at the same time (set to t=0).

$$\frac{BR(B \to (\rho/\omega)\gamma)}{B \to K^*\gamma} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \left(\frac{1 - m_\rho^2/M_B^2}{1 - m_{K^*}^2/M_B^2}\right)^3 \zeta^2[1 + \Delta R],$$

Both ζ, which describes the flavor-SU(3) breaking between ρ/ω and K^*, and ΔR, which accounts for annihilation diagrams, must be taken from theory. [7–9] The resulting limit on R_T in the $\bar{\rho} - \bar{\eta}$ plane is shown in figure 2

4 Determination of $\beta = \arg(V_{td}^*)$ [10–16]

We now turn to the determination of the angles of the unitarity triangle. Since the angles correspond to complex phases in the elements of the CKM-matrix, each of these measurements require interfering amplitudes. Because their mass- and weak-eigenstates differ, B^0 and $\bar{B}^0$ mesons can mix via the second order process (i.e. box diagrams). The loops in these diagrams are dominated by t-quark exchanges so that amplitude is sensitive to V_{td} and thus to the angle β. The mixing creates a linear combination of the two states $pB^0 + q\bar{B}^0$, where $(q/p) \approx e^{2i\beta}$. Since absolute phases cannot be measured for a single amplitude, we must search for processes in which there is a competing amplitude which will allow sensitivity to this phase via the interference term. For example, the B and $\bar{B}$ may decay to a common final state, f, so that B may reach that state either by direct decay or by first becoming a $\bar{B}$ and then decaying. In such a situation we can have interference between the direct decay and the decay via the mixing. We introduce the parameter

$$\lambda_f = (\frac{q}{p})\frac{\bar{A}_f}{A_f},$$

where the first term comes from the mixing and the second from the decay. The time-dependent CP asymmetry is then given by

$$A_{CP}(t) = \frac{N(\overline{B^0}(t) \to f_{CP}) - N(B^0(t) \to f_{CP})}{N(\overline{B^0}(t) \to f_{CP}) + N(B^0(t) \to f_{CP})} = S_f rmsin(\Delta mt) - C_f \cos(\Delta mt),$$

where $S_f = 2\mathrm{Im}(\lambda_f))/(1+|\lambda_f|^2)$ and $C_f = (1-|\lambda_f|^2)/(1+|\lambda_f|^2)$ can then be measured. Note that for a single weak phase $|\lambda| = 1$ and $S_f = Im(\lambda_f); C_f = 0$. For the general case a factor η_f represents the CP value of the state f, and we can compare the values of $-\eta_f S$ and C_f obtained in different final states.

These time dependent measurements are made possible by the boost of cm frame at the PEP-II Asymmetric b-factory. The principle of the time dependent measurements is shown in Figure 3. The interference between the $B^0\bar{B}^0$ mixing and the tree diagram for the transitions $b \to c\bar{c}s$ can be studied in the B decays modes $J/\psi K_S, J/\psi K_L, \psi(2s)K_S, \chi_{c1}K_S, \eta_c K_S, J/\psi K^{*0}(K_S\pi^0)$. Here the amplitudes $A_f \sim V_{cb}V_{cs}$ so that $\lambda \sim e^{-2i\beta}$. The time dependent asymmetry is then given by $A_{CP} \approx \sin(2\beta)\sin(\Delta mt)$. A BABAR analysis of these charmonium modes yields $\sin(2\beta) = 0.722 \pm 0.040(\mathrm{stat.}) \pm 0.034(\mathrm{syst.})$ [10]. The results for the individual modes are shown in the upper part of Figure 4.

BABAR also has studied β in the transitions $b \to c\bar{c}d$ by looking for charmed mesons in the final states: $D^{(*)+}D^{(*)-}$, where the notation $D^{(*)}$ indicates either a D or a D^* meson. Unlike the charmonium case where there is only a single tree-level amplitude, in this case there is a competing penguin process. In the Standard Model the penguin contribution is predicted to be small, in this limit $|C| \to 0$. The data are consistent with this limit. The results for the parameter S in a given final state f, with the CP of the final state accounted for, η_f, are shown in Figure 4. The band indicates the value from the charmonium modes only.

A study has also been made of of decays via s-penguin diagrams such as $B \to \phi K, \phi\pi, \eta' K$. In the last case, interference with doubly CKM-suppressed $b \to u$ amplitudes which introduce the angle γ can influence the extraction of $\sin(2\beta)$. Recall that for $\lambda \approx 0, -\eta S = \sin(2\beta)$ and $C = 0$ for each mode. The results for ηS and C are given in Figure 6. While C is consistent with 0, the naive average for S is $\sim 2.7\sigma$ below the value obtained from the charmonium measurements. Additional data should clarify the cause of this discrepancy.

The four-fold ambiguity in extracting β from $\sin(2\beta)$ can be reduced to a two-fold ambiguity by utilizing the interference of the CP-even and CP-odd amplitudes in the decays of the B^0 to a vector-vector final state such as $J/\psi K^{*0}$

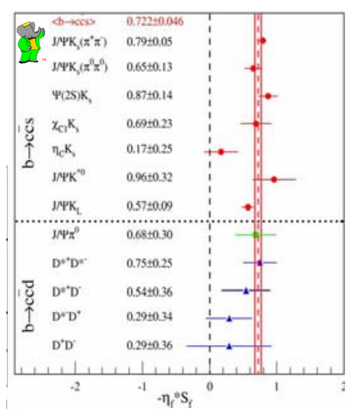

Figure 4: Summary of the determinations of $S \approx \sin(2\beta)$ for the charmonium and open charmed modes.

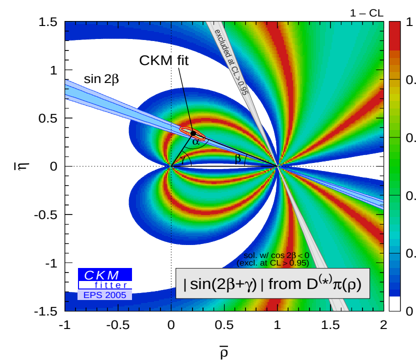

Figure 5: CKM fitter group constraint in the $\bar{\rho} - \bar{\eta}$ plane from $\sin(2\beta + \gamma)$ measurements. The $\sin(2\beta)$ constraint is also shown.

to determine $\cos(2\beta)$. The ambiguity due to the strong phases are removed by observing the S- and P-wave interference in the the $K\pi$ final state. BaBar finds $\cos(2\beta) > 0$ at 85% CL.

5 $\sin(2\beta + \gamma)$ analysis [20]

Constraints on the combination of CKM angles, $\sin(2\beta + \gamma)$ can be obtained from the interference of the tree-level CKM-favored $b \to c$ and $B\bar{B}$ mixing followed by the CKM suppressed $b \to u$ transitions by studying the time evolution of decays of the type $B \to D^{(*)} + \pi(\rho)$. The parameter λ characterizing the mixing is then given by $\lambda \approx re^{-2i\beta}e^{-i\gamma}$ where r is given by,

$$r = \left| \frac{A(B^0 \to D^{(*)+}h^-)}{A(\overline{B}^0 \to D^{(*)+}h^-)} \right|.$$

Since the $b \to u$ transitions are doubly CKM suppressed, r^2 is expected to be small ($\approx .02$), in which case $S \approx 2r\sin(2\beta + \gamma + \delta)$ and $C \approx 1$. BaBar has presented results based on a maximum likelihood fit to the time dependent decay distributions. The resulting constraints in the $\bar{\rho} - \bar{\eta}$ plane are shown in Figure 5.

6 Determination of $\alpha = \pi - \beta - \gamma$ [17–19]

The angle α is accessible via the combination of mixing and a $b \to u$ transition in decays such as $B^0 \to \pi\pi, \rho\rho$ and $\rho\pi$. In this case the amplitude $A_f \sim$

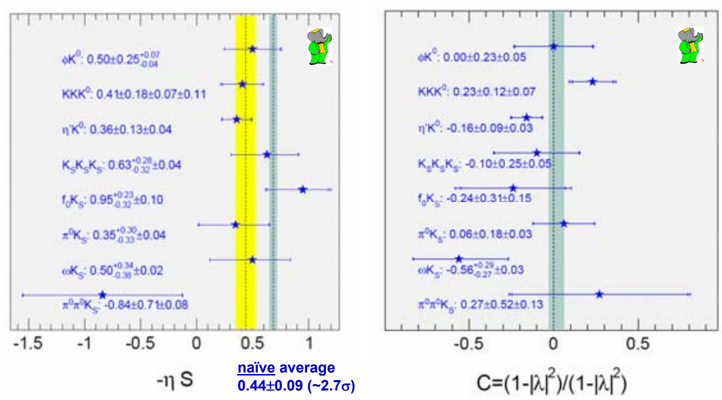

Figure 6: The values of η_s and C obtained from s-penguin decays. The dark bands indicate the results obtained from the charmonium measurements.

$V_{ub}V_{ud} \sim e^{-i\gamma}$ so that $\lambda \sim e^{-2i\gamma}e^{-2i\beta} \sim e^{-2i\alpha}$. In the absence of gluonic penguins, $S = \sin(2\alpha)$; $C = 0$ and $A_{CP}(t) \approx \sin(2\alpha)\sin(\Delta m t)$. The presence of the penguin contribution means that

$$\lambda = e^{2i\alpha}\frac{T + P\,e^{+i\gamma}e^{i\delta}}{T + P\,e^{-i\gamma}e^{i\delta}},$$

where T and P are the tree and penguin contributions to A_f and δ is a relative strong interaction phase. In this case $C \neq 0$ and $S = \sqrt{1-C^2}\sin(2\alpha_{eff}) \neq \sin(2\alpha)$. In order to extract α from α_{eff}, we need to unravel the effect of the strong phase. This can be done using an isospin analysis. The limits on α from these analyses are shown in Figure 7. An additional constraint on α comes from

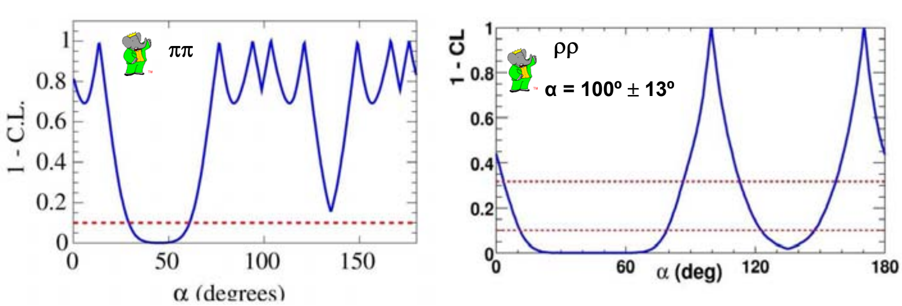

Figure 7: Confidence level as a function of alpha for the $\pi^+\pi^-$ and $\rho^+\rho^-$ analyses.

a time-dependent Dalitz plot analysis of $B^0 \rightarrow \pi^+\pi^-\pi^0$ decays. Interference at equal two-body invariant masses on the Dalitz plot gives information on the strong phases and yields an unambiguous fit of α and tree and penguin amplitudes. The combined results are shown in Figure 8.

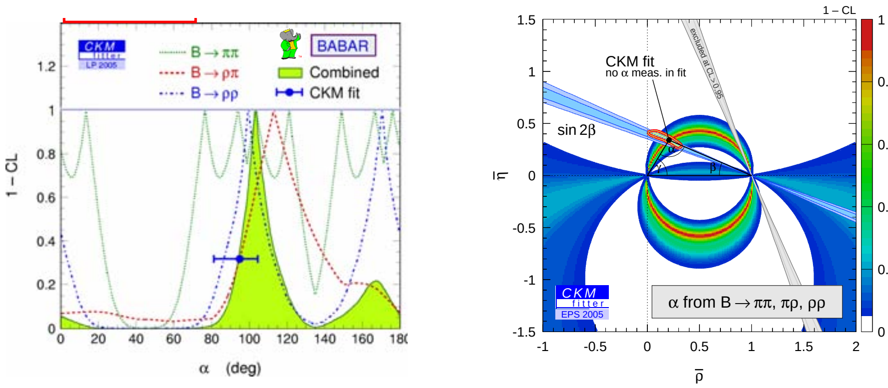

Figure 8: Combined results for α: (left) the CL plot for the BABAR data which yield $\alpha = 103^o + 11^o - 9^o$ (the horizontal bar is the result of the CKM fitter group); (right) the result in the $\bar{\rho} - \bar{\eta}$ plane.

7 Determination of $\gamma = \arg(V_{ub})$ [21–23]

The angle γ can be extracted using the interference that occurs when the D^0 and $\bar{D}^0$ decay to the same final state. The three methods exploiting these processes are: (1) D^0 goes to a CP eigenstate (GLW analysis [24]) ; (2) D^0 goes to a CKM suppressed $K\pi$ final state (ADS analysis [25]); and D^0 goes to a three-body final state and one uses the full three-body Dalitz plot (Dalitz analysis [26]). In these analyses one measures asymmetries, $A = (\Gamma(B^- \to D^{(*)0}K^-) - \Gamma(B^+ \to D^{(*)0}K^+))/(\Gamma(B^- \to D^{(*)0}K^-) - \Gamma(B^+ \to D^{(*)0}K^+))$ and the ratios of branching ratios.

To date the first two methods have given limited information about γ. The BaBar Dalitz plot analysis alone yields $\gamma = 67^o \pm 28^o(\text{stat.}) \pm 13^o(\text{expt.syst.}) \pm 11^o(\text{Dalitz method})$. The combined results for γ are shown in Figure 9 and yield a value of $\gamma = (51^{+23}_{-18})^o$.

8 Constraints in the $\bar{\rho} - \bar{\eta}$ plane

The net results are summarized in Figure 10. The progress in our understanding of CP-violation and the CKM-matrix in the Standard Model are illustrated in the right-hand part of the figure where we compare the state of knowledge prior to the operation of the b-factories with the current state of our knowledge.

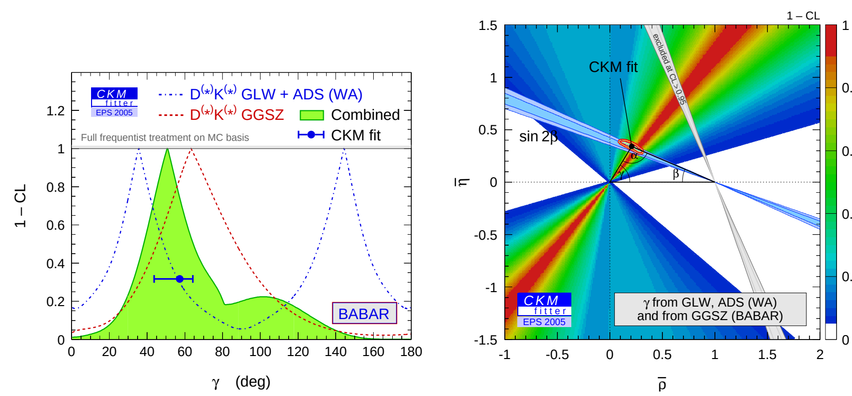

Figure 9: (left) CL for the values of γ from the world average for the GLW and ADS methods; the Dalitz method from BABAR and the combined result compared with the CKM fit ;(right) The constraint from γ in the $\bar{\rho} - \bar{\eta}$ plane.

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The over 600 hard working physicists in the BaBar collaboration have all been instrumental in collecting and analyzing the data whose results are presented. The CKM fitter group [1] has been instrumental in putting these results in the context of the Standard Model.

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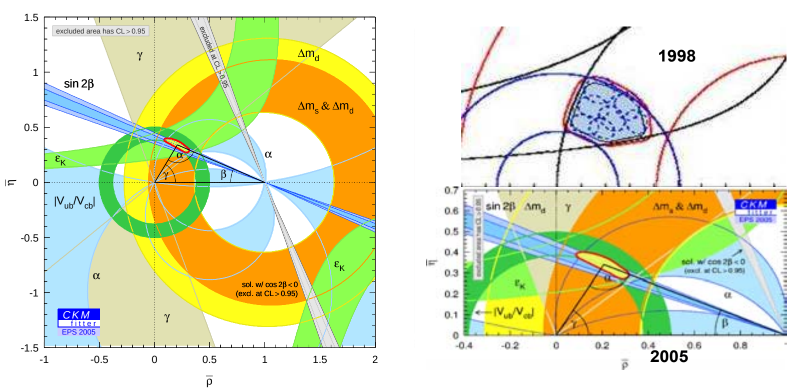

Figure 10: All measurements on the $\bar{\rho} - \bar{\eta}$ plane as of summer 2005. (left) The full plane; (right) the region of the CKM triangle with a comparison to the state of knowledge 1998.

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