MEASUREMENT OF CKM ANGLES AT THE B-FACTORIES

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Abstract

The experiments BaBar and Belle have collected more than 1.2 billions $B\bar{B}$ pairs produced at the energy of the $\Upsilon(4S)$ resonance. With this data sample it has been possible to measure precisely the CP-violating phase of the Cabibbo-Kobayashi-Maskawa (CKM) matrix that describes the CP violation pattern in the Standard Model. In this paper we present a review of the measurements of the angles β, α and γ of the unitarity triangle which are related to the CKM matrix elements, with focus on recent results.

1 Introduction

CP violation is present in the Standard Model due to a non irreducible phase in the Cabibbo-Kobayashi-Maskawa matrix [1], V_{CKM}, that provides the couplings of the weak charged currents to the quarks. V_{CKM} is a unitary matrix and can be parameterized by three mixing angles and one (CP-violating) phase; its elements are fundamental parameters of the Standard Model and their values are not predicted by the theory. A common parametrization of V_{CKM} has been proposed by Wolfenstein [2] (fig. 1, top) in terms of the parameters λ, A, ρ and η. The unitary conditions can be graphically represented in a complex plane as triangles, of which the one corresponding to the relation $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ has roughly equal-length sides, of the order of λ^3. This triangle is called *unitarity triangle* and when the sides are divided by $V_{cd}V_{cb}^*$, the apices are $(0,0)$, $(1,0)$ and (ρ,η) (fig. 1, bottom). The angles, expressed in terms of the V_{CKM} elements are:

$$\alpha = arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right], \quad \beta = arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right], \quad \gamma = arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]. \tag{1}$$

$$V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

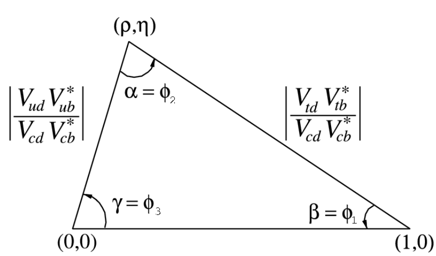


Figure 1: *Top: Wolfenstein parametrization of the CKM matrix. Bottom: the unitarity triangle showing the definition of the angles α, β and γ, also known as ϕ_1, ϕ_2, ϕ_3.*

The B factories primary physics goal is to measure and possibly to over constrain the sides and the angles of the unitarity triangle in order to test the

CKM mechanism and to search for inconsistencies that may show evidence of physics beyond the Standard Model.

2 Experimental techniques for time-dependent measurements

The measurement of the angles β and α discussed in this paper are performed through the study of time-dependent rates and CP asymmetries of neutral B mesons decays to a final state f (usually a CP eigenstate), that is accessible to both the B^0 and the $\bar{B}^0$. The time-dependent CP asymmetry is defined as

$$\begin{aligned}\mathcal{A}_{CP} &\equiv \frac{N(\bar{B}^0(\Delta t) \to f) - N(B^0(\Delta t) \to f)}{N(\bar{B}^0(\Delta t) \to f) + N(B^0(\Delta t) \to f)} \\ &= S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t),\end{aligned} \tag{2}$$

where $N(B^0(\Delta t) \to f)$ is the number of B^0 mesons decayed into the CP eigenstate at a time Δt after (or before) the decay of the $\bar{B}^0$ meson, Δm_d is the $B^0 - \bar{B}^0$ oscillation frequency, and the coefficients S_f and C_f are functions of the $B^0\bar{B}^0$ mixing parameters and of the decay amplitudes:

$$S_f = \frac{2\mathrm{Im}\lambda_f}{1+|\lambda_f|^2}, \quad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \qquad \text{with } \lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}\,. \tag{3}$$

The Standard Model predicts $q/p \simeq e^{-i2\beta}$ with good precision, A_f and $\bar{A}_f$ are the amplitudes of the $B^0 \to f$ and the $\bar{B}^0 \to f$ processes, respectively. If the decay is dominated by a single amplitude or by amplitudes with the same weak phase, then $|\lambda_f| = 1$, $C_f = 0$ and $S_f = \mathrm{Im}\lambda_f$.

The BaBar and Belle experiments take data at the colliders PEP-II and KEKB respectively, which are e^+e^- asymmetric-energy B factories operating at the center of mass (CM) energy of the $\Upsilon(4S)$ mass. Pairs of $B\bar{B}$ mesons are produced almost at rest in the decay of the $\Upsilon(4S)$ but thanks to the boost of the CM frame with respect to the laboratory frame the separation between the two decay vertices is increased to 250 μm on average. One of the B is reconstructed exclusively in the final state f while the other B in the event is reconstructed partially to determine its flavor (that determines the flavor of the other B, given the coherence of the initial state produced). The difference of the proper decay time Δt is measured from the spatial separation of the two decays vertices. The effective efficiency of the tagging algorithm is $\sim 30\%$ and the Δt resolution is $\sim$1.1 ps.

3 Measurement of β

The *golden* modes used to determine β are the $B^0 \to (c\bar{c})K^{(*)0}$ decays. These processes have amplitudes dominated by a single weak phase, thus in the Standard Model $S_f = -\eta_{CP}\sin 2\beta$ (η_{CP} is the final state CP eigenvalue) and $C_f = 0$ with a theoretical uncertainty estimated below the 1% level. From an experimental point of view these decay modes have relatively high branching ratios ($\sim 10^{-4}$) and low background. The BaBar result is based on 383 million $B\bar{B}$ pairs, where the modes $B^0 \to J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $\eta_c K^0_S$ (CP-odd), $B^0 \to J/\psi K^0_L$ (CP-even), and $B^0 \to J\psi K^{*0}(\pi^0 K^0_S)$ have been reconstructed. $J\psi K^{*0}$ is a vector-vector final state and requires an angular analysis to separate the CP-even and CP-odd part. The Belle result is based on the analysis of the modes $B^0 \to J/\psi K^0_S$ and $B^0 \to J/\psi K^0_L$ reconstructed in 535 million $B\bar{B}$ pairs.

Figure 2 shows the time-dependent decay rates and CP asymmetry for the two results. The amplitude of the sin-like asymmetry, corrected for the probability of wrongly assigning the flavor of the decaying B and for resolution effects measures sin2β. The BaBar result is $\sin 2\beta = 0.714 \pm 0.032 \pm 0.018$ [3] while Belle measures $\sin 2\beta = 0.642 \pm 0.031 \pm 0.017$ [4], where the first error is statistical and the second systematic. The current world average is $\sin 2\beta_{WA} = 0.681 \pm 0.025$ [5]. Given the high experimental and theoretical precision this measurement gives the tightest constraints on the ρ,η parameters. Two of the four ambiguities in β have been resolved by measurements of cos2β [6, 7, 8, 9].

Other B decays sensitive to $\sin 2\beta$ are those mediated by the $b \to c\bar{c}d$ transitions [10] (for example $B^0 \to D^{(*)+}D^{(*)-}$) where, besides the dominant tree level amplitudes, there are non negligible penguin contributions with different weak phase. The results found by BaBar and Belle are consistent with the Standard Model expectations. A possible discrepancy has been found by Belle in the mode $B^0 \to D^+D^-$ [11] where there is evidence of direct CP violation at 3.2σ level.

In the Standard Model CP asymmetries in B decays that proceed through $b \to sq\bar{q}$ transitions are expected to give sin2β as the $B^0 \to (c\bar{c})K^{(*)0}$ decays. These channels are dominated by penguin amplitudes and are potentially sensitive to contributions from new Physics (new particles in the loop). Belle and BaBar have measured time-dependent CP asymmetries in several such decays

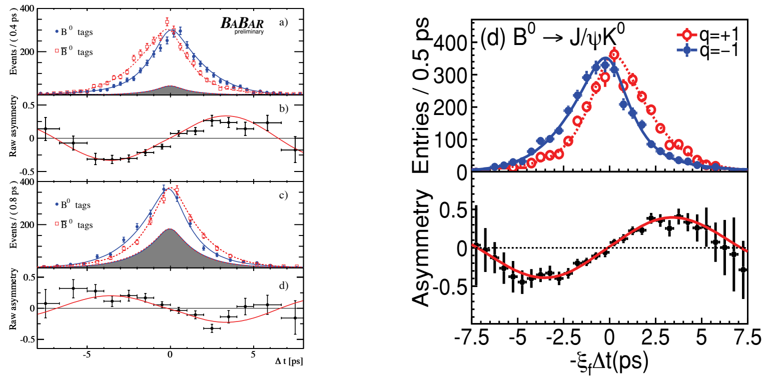


Figure 2: *Left: distribution of the yields and raw* CP *asymmetry as functions of* Δt *for* $J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $\eta_c K^0_S$ *(*CP*-odd, top) and* $J/\psi K^0_L$ *(*CP*-even, bottom), measured by BaBar. Right: distribution of the yields and raw* CP *asymmetry as functions of* $-\xi_f \Delta t$ *for* $J/\psi K^0$*, measured by Belle.* $\xi_f = +1(-1)$ *for* CP*-even (*CP*-odd) final states,* $q = +1(-1)$ *for* $B^0(\bar{B}^0)$ *tag. The solid curves show the fit results.*

like $B^0 \to \phi K_s$ and $B^0 \to \eta' K_s$. A naive average of the S_f coefficients is consistent with the Standard Model expectation [5]. Improving the precisions of these measurement is one of the main goal of future B factories experiments.

4 Measurement of α

The angle α can be measured from the time-dependent rates in modes with a contribution from the tree level $b \to u\bar{u}d$ transition like the charmless decays $B \to h^+h^-$ ($h = \pi$, ρ), where the weak phase difference between the amplitudes of B^0 and $\bar{B}^0$ going into these final states is 2α. If only tree level diagrams were present, the coefficients of the time-dependent CP asymmetry would be $S_f = \sin 2\alpha$, $C_f = 0$. Since sizable penguin contributions are present the previous relations are modified:

$$S_f = \sqrt{1 - C_f^2}\sin 2\alpha_{eff}, C_f \sim 2\mathrm{Im}(P/T)\sin\alpha \qquad (4)$$

where T and P are the parts of the amplitude depending on $V^*_{ub}V_{ud}$ (including the tree diagram) and $V^*_{tb}V_{td}$, respectively, and α_{eff} is unknown and equals α in the limit of $P/T \to 0$. Once that C_f and S_f are measured with a time-dependent analysis similar to that used to determine sin2β, the difference $\Delta\alpha = \alpha - \alpha_{eff}$ can be obtained with an isospin analysis [12], where the penguing contribution is estimated using the isospin-related decays $B^0 \to h^0 h^0$ and $B^+ \to h^0 h^+$. The method determines α with an 8-fold ambiguity.

CP violation is well established in the $\pi\pi$ system and the full isospin analysis has been performed by both the BaBar and the Belle collaborations. The BaBar result, based on 383 million $B\bar{B}$ pairs is $\alpha = (96^{+10}_{-6})^o$ [13] while the Belle result, based on 535 million $B\bar{B}$ pairs is $\alpha = (97 \pm 11)^o$ [14] for the solution that is not removed by other constraints on the unitary plane.

The angle α can be also extracted from the decay $B^0 \to \rho^+\rho^-$ with a similar analysis as in $B^0 \to \pi^+\pi^-$. Penguin pollution is lower with respect to the $\pi\pi$ system allowing a more precise determination of α. The final state $\rho^+\rho^-$ is vector-vector and an angular analysis is in principle necessary to separate the CP-odd and CP-even components. Experimentally it has been found that the state is fully longitudinal polarized (CP-even), so this channel can be analyzed as $B^0 \to \pi^+\pi^-$. BaBar has recently presented the first time-dependent analysis of the $B^0 \to \rho^0\rho^0$ decay [15] on 427 million $B\bar{B}$ pairs. The evidence for the signal is 3.6σ and applying the isospin analysis $\Delta\alpha = 14.6^o$@ 68% C.L. has been obtained. Figure 3 left) shows the confidence level on $\Delta\alpha$. Belle has presented the result of a search of the $B^0 \to \rho^0\rho^0$ decay on 657 million $B\bar{B}$ pairs where no significant signal has been found. The upper limit BR($B^0 \to \rho^0\rho^0$)$<$ 1.0×10^{-6} @ 90% C.L. has been found [16], compatible with the BaBar result. The measurement of the S_f and C_f parameters, together with the branching fractions needed for the isospin analysis, are reported in tab. 1 [17, 18, 19, 20].

A third way to constrain α is the time-dependent Dalitz plot analysis of the decay $B^0 \to \pi^+\pi^-\pi^0$. The decay amplitudes of this process are dominated by the resonances ρ^+, ρ^- and ρ^0, where ρ is the sum of the ground state $\rho(770)$ and the radial excitations $\rho(1450)$ and $\rho(1700)$. The time-dependent Dalitz plot distributions for B^0 and $\bar{B}^0$ decaying in the $\pi^+\pi^-\pi^0$ final state are fitted to a likelihood with 26 physical parameters related to α, tree and penguin amplitudes that are subsequently determined with a least-square fit to the 26 parameters. The BaBar result, based on 375 million $B\bar{B}$ pairs is $\alpha = (87^{+45}_{-13})^o$ [21]. The Belle result, based on 449 million $B\bar{B}$ pairs is $68^o < \alpha < 95^o$ @ 68.3%C.L. [22]. In both cases there are mirror solutions at $+180^o$. Even if with the current data sample this method alone does not constrain α

Table 1: *CP parameters and branching fractions of $B \to \rho\rho$.*

	BaBar	Belle
S	$-0.17 \pm 0.20^{+0.05}_{-0.06}$	$0.19 \pm 0.30 \pm 0.08$
C	$0.01 \pm 0.15 \pm 0.06$	$-0.16 \pm 0.21 \pm 0.08$
$\mathcal{B}(\rho^+\rho^-) \times 10^6$	$25.5 \pm 2.1^{+3.6}_{-3.9}$	$22.8 \pm 3.8^{+2.3}_{-2.6}$
$\mathcal{B}(\rho^+\rho^0) \times 10^6$	$16.8 \pm 2.2 \pm 2.3$	$31.7 \pm 7.1^{+3.8}_{-6.7}$
$A_{CP}(\rho^+\rho^0)$	$-0.12 \pm 0.13 \pm 0.10$	$0.00 \pm 0.22 \pm 0.03$
$\mathcal{B}(\rho^0\rho^0) \times 10^6$	$0.84 \pm 0.29 \pm 0.17$	< 1.0 @90%C.L.
$S(\rho^0\rho^0)$	$0.5 \pm 0.9 \pm 0.2$	—
$C(\rho^0\rho^0)$	$0.4 \pm 0.9 \pm 0.2$	—

significantly, the information is useful when added to the results in the $\pi\pi$ and $\rho\rho$ decay modes, in particular to remove some of the ambiguities.

4.1 Global constraint on α

Figure 3 right) shows the probability density function of α, based on a bayesian analysis [23] of the three measurements described above. The corresponding result is $\alpha = (91 \pm 8)^o$ for the solution that is not removed by other constraints on the unitary plane.

5 Measurement of γ

The methods to measure γ exploit the interference between amplitudes corresponding to the CKM allowed $b \to c$ transition and the CKM suppressed $b \to u$ transition, like in the decays $B^- \to D^{(*)0}K^{(*)-}$ and $B^- \to \bar{D}^{(*)0}K^{(*)-}$ with $D^{(*)0}$ and $\bar{D}^{(*)0}$ decaying to a common final state. The sensitivity to γ is driven by the parameter r_B, defined as the magnitude of the ratio between the suppressed over the allowed amplitude. Since r_B, and thus the sensitivity, is in general small ($r_B \sim$ 0.1-0.4 depending on the B decay mode) the results from the different techniques must be combined to obtain a significant constraint on γ. The most stringent constraints come from charged B decays but BaBar has investigated methods that use neutral B decays.

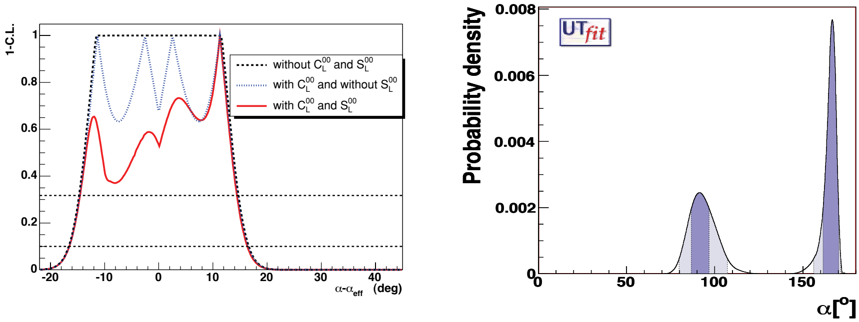


Figure 3: *Left: confidence level on $\Delta\alpha = \alpha - \alpha_{eff}$ obtained from the isospin analysis of the $\rho\rho$ system described in the text. The dotted line corresponds to the usual isospin analysis. The dashed line is obtained without using the CP $S(\rho^0\rho^0)$ and $C(\rho^0\rho^0)$ parameters. The solid line is obtained using also the information from $S(\rho^0\rho^0)$ and $C(\rho^0\rho^0)$. Horizontal lines correspond to the 68% (top) and 90% (bottom) C.L. intervals. Right: probability density function of α obtained from the measurements available combining BaBar and Belle described in the text. Dark and light regions correspond to 68% and 90% probability, respectively.*

5.1 γ from charged B decays

The $B^- \to \tilde{D}^{(*)0} K^{(*)-}$ [1] are used and three methods exist, depending on the $\tilde{D}^{(*)0}$ decay: the Gronau-London-Wyler [24)] (GLW) method where $\tilde{D}^{(*)0}$ decays into a CP eigenstate, the Atwood-Dunietz-Soni [25)] (ADS) method where $\tilde{D}^{(*)0}$ decays into a flavor eigenstate and the Giri-Grossman-Soffer-Zupan [26)] (GGSZ) method where $\tilde{D}^{(*)0}$ decays into a three-body final state. The third method is the more effective in constraining γ but it is not discussed here since no new results were available at the time of the conference. See [5)] for recent results.

BaBar recently presented an update for the GLW analysis of the $B^- \to \tilde{D}^0 K^-$ decay on 382 million $B\bar{B}$ pair. The $\tilde{D}^0$ decay modes considered are $\pi^+\pi^-$, K^+K^- (CP even), $K_s\pi^0$ and $K_s\omega$ (CP odd). The result is expressed in terms of the ratios $R_{CP\pm}$ of charge-averaged partial rates and of the partial-rate charge asymmetries $A_{CP\pm}$. These observables are related to γ, the magnitude ratio r_B and the relative strong phase δ. The result is: $A_{CP+} = 0.27 \pm 0.09 \pm 0.04$, $A_{CP-} = -0.09 \pm 0.09 \pm 0.02$, $R_{CP+} = 1.06 \pm 0.10 \pm 0.05$, $R_{CP-} =$

[1] The symbol $\tilde{D}^{(*)0}$ indicates either a $D^{(*)0}$ or a $\bar{D}^{(*)0}$ meson.

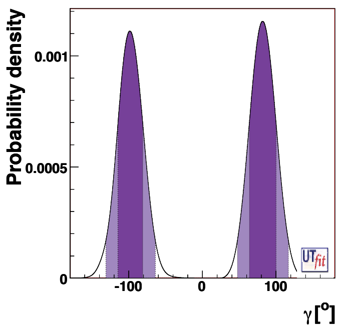
$1.03 \pm 0.10 \pm 0.05$ [27] where the first errors are statistical and the second systematic.

Belle has updated the ADS analysis of the decay $B^- \to \tilde{D}^0 K^-$ with $\tilde{D}^0$ decaying into the flavor eigenstate $K^\pm \pi^\mp$ on a data sample of 657 million $B\bar{B}$ pairs. In this case it is exploited the interference between the CKM-favored $B^- \to D^0 K^-$ decay, followed by the doubly Cabibbo-suppressed $D^0 \to K^+\pi^-$ decay, with the CKM-suppressed $B^- \to \bar{D}^0 K^-$ decay, followed by the Cabibbo-favored $\bar{D}^0 \to K^+\pi^-$ decay. These are called suppressed decay chains. The observables considered are the ratio of the decay rates of the suppressed decay chains over the rates of the favored decay chains (both B and D favored decays) R_{ADS}, and the CP asymmetry A_{ADS} in the suppressed decay chains. These observables are related to γ , r_B, δ_B defined as in the GLW case and r_D, δ_D, the corresponding quantities for the D meson. No signal has been observed for the suppressed decays: $A_{ADS} = -0.13^{+0.97}_{-0.88} \pm 0.26$ and $R_{ADS} = 8.0^{+6.3+2.0}_{-5.7-2.8}$ where the first errors are statistical and the second systematic. The limit $r_B < 0.19$ @90% C.L. has been set [28].

5.2 γ from neutral B decays

The angle γ can also be constrained using the decay $B^0 \to \tilde{D}^0 K^{*0}$. The K^{*0} is reconstructed in the $K^+\pi^-$ final state (charge conjugation is implied) where the flavor of the B meson is identified by the kaon electric charge. Neutral D mesons are reconstructed in the $K_s\pi^+\pi^-$ final state and analyzed with a Dalitz technique. The final states reconstructed can be reached through the $B^0 \to \bar{D}^0 K^{*0}$ decay ($b \to c$ mediated) and the $B^0 \to D^0 K^{*0}$ decay ($b \to u$ mediated). The natural width of the K^{*0} resonance has been considered by using effective variables obtained by integrating over a region of the $B^0 \to \bar{D}^0 K^+\pi^-$ Dalitz plot. BaBar has presented a result based on 371 million $B\bar{B}$ pairs. An unbinned maximum likelihood technique has been applied to separate signal from background events and extract γ and r_B. A bias in the estimation of the error on γ has been observed on simulation. For this reason an external information on r_B has been combined [29]. The result is $\gamma = (162 \pm 56)^o$ or $\gamma = (342 \pm 56)^o$, $r_B < 0.55$ at 95% probability, $\delta = (62 \pm 57)^o$ or $\delta = (242 \pm 57)^o$ [30] where δ is the strong phase difference between the two interfering amplitudes.

Another decay mode sensitive to γ is $B^0 \to D^\mp K^0 \pi^\pm$. The three body final state is reached predominantly through the intermediate $B^0 \to \tilde{D}^{**0} K_s$



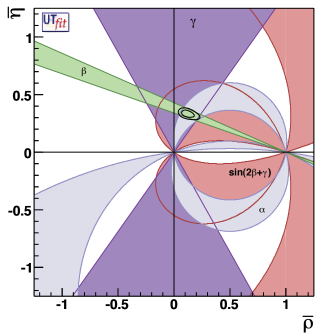


Figure 4: *Left: probability density function of γ obtained from the all measurements available from BaBar and Belle. Dark and light regions correspond to 68% and 90% probability, respectively. Right: constraints in the $\bar{\rho} - \bar{\eta}$ plane from the measurements of the angles α, β and γ.*

and $B^0 \to D^- K^{*+}$ decays. In the first case, $\tilde{D}^{**0}$ indicates a $D_0^*(2400)$ or a $D_2^*(2460)$ state produced through $b \to u$ and $b \to c$ color-suppressed transitions. In the second case the K^* resonances are produced through $b \to c$ transitions. A full time-dependent Dalitz analysis is performed and since the interference proceeds through mixing the effective measured quantity is $2\beta + \gamma$. The BaBar result, based on 347 million $B\bar{B}$ pairs is: $\gamma = (83 \pm 53 \pm 20)^o$ or $\gamma = (263 \pm 53 \pm 20)^o$ [31] where the first errors are statistical and the second systematic. With the current dataset it is not possible to determine the magnitude of the suppressed $b \to u$ decays. Therefore the r_B parameter is fixed in the fit to 0.3 (expected value based on naive calculations) and varied by ± 0.1 in the systematic error.

5.3 Combined result of γ

Figure 4 left) shows the global constraint on γ obtained by combining all the measurements available using the bayiesian approach of ref. [23]. The result is $\gamma = (82 \pm 17)^0$ up to a π ambiguity.

6 Conclusions

The Standard Model description of CP violation is well established and the measurements of the CKM angles are constantly improving in precision. sin2β

is determined with a precision of 4% while the uncertainties on α and γ are 10 and 20 degrees respectively. The most precisely determined angle is β whose measurement is nevertheless still statistics limited. Figure 4 right) shows the constraint on $\bar{\rho}, \bar{\eta}$ ($\bar{\rho} = \rho(1 - \lambda^2/2 + o(\lambda^2))$, $\bar{\eta} = \eta(1 - \lambda^2/2 + o(\lambda^2))$) in the complex plane obtained by combining all the CKM angle measurements.

The B factories offer also a unique window on possible new Physics which have not been found so far. BaBar has recently stopped to take data while Belle will run to $1ab^{-1}$ and then turn off. The future of B physics will depend on future facilities (e.g super B factories).

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