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Several new and updated *BABAR* measurements of $\sin 2\beta$ are presented, together with the latest constraints on the Unitarity Triangle angles α and γ. The higher statistics now available allow more sophisticated analysis techniques, such as time-dependent Dalitz plot fitting. Combined world-average results place tight constraints on the Unitarity Triangle. There is good agreement among the measurements and with the unitarity of the CKM matrix. This represents an impressive verification of the Standard Model description of the quark-flavour sector and of CP violation.

I. INTRODUCTION

The standard model (SM) of electroweak interactions describes CP violation as a consequence of an irreducible phase in the three-family Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]:

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

$V_{\rm CKM}$ describes the couplings between the u, c and t quarks and the d, s and b quarks, mediated by the exchange of a W boson. In B-meson decays the CP-violating (CPV) parameters of the SM are most directly related to the angles and sides of the so-called Unitarity Triangle (UT). The angles α, β and γ are defined as $\alpha \equiv \arg[-V_{\rm td}V^*_{\rm tb}/V_{\rm ud}V^*_{\rm ub}]$, $\beta \equiv \arg[-V_{\rm cd}V^*_{\rm cb}/V_{\rm td}V^*_{\rm tb}]$, and $\gamma \equiv \arg[-V_{\rm ud}V^*_{\rm ub}/V_{\rm cd}V^*_{\rm cb}]$. In the Wolfenstein parameterization [2], the angle γ is the phase of $V_{\rm ub}$, β is the phase of $V_{\rm td}$, and α is the phase difference between $V_{\rm ub}$ and $V_{\rm td}$, constrained to satisfy $\alpha = \pi-\beta-\gamma$ through the unitarity of $V_{\rm CKM}$. In terms of the Wolfenstein parameters $(\bar\rho, \bar\eta)$, the apex of the UT is given by the phase-convention independent definition [3]: $\bar\rho + i\bar\eta \equiv -V_{\rm ud}V^*_{\rm ub}/V_{\rm cd}V^*_{\rm cb}$.

These CPV parameters can be determined from time-dependent asymmetries measured in the decays of $\Upsilon(4S) \to B^0\bar{B}^0$, where one of the two B^0 mesons decays into a CP eigenstate f_{CP} at time t_{CP}, and the other decays into a flavour-specific state $f_{\rm tag}$ at time $t_{\rm tag}$. The time-dependent decay rate is

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \times [1 + q\{S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)\}] \quad (1)$$

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where $\Delta t = t_{CP} - t_{\rm tag}$, τ is the B^0 lifetime, Δm_d is the $B^0\bar{B}^0$ mixing frequency and $q = +1(-1)$ when $f_{\rm tag} = B^0(\bar{B}^0)$. The parameters S_f and C_f are sensitive to mixing-induced and direct CP violation, respectively.

II. *BABAR* DETECTOR AND DATASET

Measurements presented here use data collected with the *BABAR* detector [4] at the PEP-II asymmetric energy e^+e^- collider, located at SLAC. The analyses are based on a data sample of (383 ± 4) million $B\bar{B}$ pairs recorded at the $\Upsilon(4S)$ resonance (center-of-mass (CM) energy $\sqrt{s} = 10.58$ GeV) and 37 fb^{-1} of data collected 40 MeV below the $\Upsilon(4S)$ resonance ("off-resonance"). Results are preliminary unless a journal publication is cited.

The *BABAR* detector provides charged particle tracking through a combination of a 5-layer double-sided silicon vertex tracker and a 40-layer drift chamber, both operating within a 1.5 T magnetic field generated by a superconducting solenoidal magnet. Photons are identified in an electromagnetic calorimeter surrounding a detector of internally reflected Cherenkov light, which associates Cherenkov photons with tracks for charged particle identification (PID). Further PID information is provided by the average energy loss (dE/dx) in the tracking devices. Muon candidates are identified with the use of the instrumented flux return of the solenoid.

III. ANALYSIS OVERVIEW

To discriminate between signal and background, two independent kinematic variables, the beam energy substituted mass $m_{\rm ES} \equiv \sqrt{s/4 - (p^*_B)^2}$ and energy difference $\Delta E \equiv E^*_B - \sqrt{s}/2$ are used. Here E^*_B and p^*_B are the energy and 3-momentum of the B candidate measured in the CM frame. For signal decays $m_{\rm ES}$ (ΔE) peaks at the B mass (zero) with a resolution of a few (few tens of)

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MeV. Event topology is used to reject continuum background, arising primarily from random combinations of particles in $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) events, which have a "jet-like" structure, in contrast to $B\bar{B}$ events, which are more uniform. To improve the separation of signal from background, some of these variables are combined in a multivariate algorithm, such as a Fisher discriminant or Neural Network, which is trained using simulated Monte Carlo (MC) signal and $q\bar{q}$ background events.

Physical quantities, such as signal yields or CPV parameters, are determined using extended and unbinned maximum likelihood (ML) fits. The likelihood function includes probability density functions (PDF) with shapes based on MC or data (sidebands or off-resonance). Their most important parameters are left free. In addition to signal and continuum background, B-background categories are also included in the fits. Systematic errors arise from several sources, such as uncertainties in signal PDF shape parameters, B-background estimates and the effects of interference between resonances. In all the CP-violation measurements reported here the statistical errors dominate.

IV. RESULTS

New or updated measurements are reported of the UT angles β, α and γ. The most precisely determined is β, and consistency among the various measurements of this angle from different B decay modes is an important test of the SM.

A. Measurements of angle β

1. $\sin 2\beta$ from $b \to c\bar{c}s$ decays; $B^0 \to$ Charmonium $K^{(*)0}$

In the CKM framework, neutral B decays to CP eigenstates containing a charmonium meson and a $K^{(*)0}$ meson are dominated by processes involving tree diagrams. They provide a direct and clean measurement of $\sin 2\beta$ [5]. The B^0 candidates are reconstructed from the final states $J/\psi K^0_S$, $J/\psi K^0_L$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $\eta_c K^0_S$ and $J/\psi K^{*0}$. We reconstruct $K^0_S \to \pi^+\pi^-$ (and also $K^0_S \to \pi^0\pi^0$ for $J/\psi K^0_S$). Charmonium mesons are reconstructed in the decays $J/\psi \to e^+e^-$, $\mu^+\mu^-$; $\psi(2S) \to e^+e^-$, $\mu^+\mu^-$, $J/\psi\mu^+\mu^-$; $\chi_{c1} \to J/\psi\gamma$ and $\eta_c \to K^0_S K^+\pi^-$. A new $\eta_c K^0_S$ event selection is included, based on the Dalitz plot (DP) structure of the $\eta_c \to K^0_S K^+\pi^-$ decay. We have performed a more detailed study of the CP properties of background events, resulting in reduced systematic errors. Figure 1 shows the Δt distributions and asymmetries in yields between events with B^0 tags and $\bar{B}^0$ tags as functions of Δt, with projections of the likelihood fit results overlaid. We measure $\sin 2\beta = 0.714 \pm 0.032 \pm 0.018$ and the parameter $C = 0.049 \pm 0.022 \pm 0.017$, where the first errors are statistical and second errors are systematic [6].

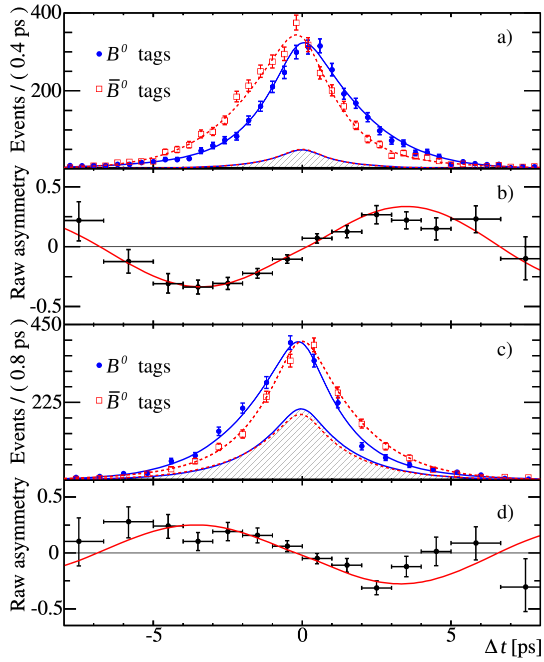

FIG. 1: a) Number of candidates in the signal region, with CP-odd final states, with a B^0 tag (N_{B^0}) and with a $\bar{B}^0$ tag ($N_{\bar{B}^0}$), and b) the raw asymmetry, $(N_{B^0} - N_{\bar{B}^0})/(N_{B^0} + N_{\bar{B}^0})$, as functions of Δt. Figures c) and d) are the corresponding distributions for CP-even final states. The solid (dashed) curves represent the fit projections in Δt for $B^0(\bar{B}^0)$ tags.

These results provide an improved model-independent constraint on the position of the apex of the UT [7] and form a benchmark against which to compare other measurements of $\sin 2\beta$.

2. $\sin 2\beta$ from $b \to c\bar{c}d$ decays: $B^0 \to D^{(*)+}D^{(*)-}$

Colour-allowed $b \to c\bar{c}d$ decays provide another way to measure $\sin 2\beta$. Within the SM, the amplitudes are dominated by tree-level processes and time-dependent CP asymmetries in $B^0 \to D^{(*)+}D^{(*)-}$ decays are directly related to $\sin 2\beta$, if corrections due to penguin diagram contributions are neglected. The penguin-induced corrections have been estimated in models based on the factorization approximation and heavy quark symmetry and are predicted to be a few percent. A significant deviation between $\sin 2\beta$ measured in $b \to c\bar{c}d$ decays and that from $b \to c\bar{c}s$ decays would be evidence for new physics (NP) beyond the SM [8].

Updated measurements of CP-violating asymmetries in $B^0 \to D^+D^-$ are presented [9], with $D^\pm \to K^\mp\pi^\pm\pi^\pm$. A major source of background is from continuum $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) events, which are suppressed using the Fisher Discriminant. An unbinned ML fit to $m_{\rm ES}$ and Δt distributions yields 131 ± 14 (stat.) signal events, and CPV parameters $S = -0.54 \pm 0.34$(stat.)± 0.06(syst.) and

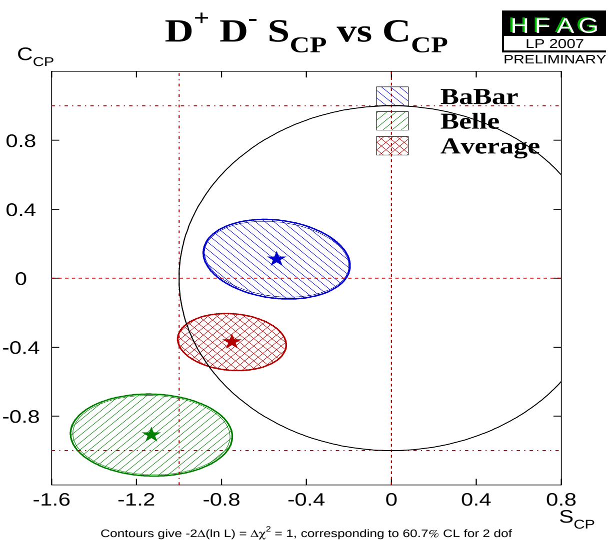

FIG. 2: Comparison between *BABAR* and Belle measurements of CPV parameters in $B^0 \to D^+D^-$ decays [11].

$C = 0.11 \pm 0.22(\text{stat.}) \pm 0.07(\text{syst.})$. The time-dependent asymmetries are consistent with SM predictions. No evidence is found for large direct CP violation, as reported by the Belle Collaboration [10]. A comparison between *BABAR* and Belle results is shown in Fig. 2, provided by HFAG [11].

The decay $B^0 \to D^{*+}D^{*-}$ is similar to $B^0 \to D^+D^-$, but results in a vector-vector final state. It proceeds through the CP-even S and D waves and through the CP-odd P wave. A combined analysis of the time-dependent flavour-tagged decays and the one-dimensional angular distribution of the decay products gives an improved measurement of the CP-odd fraction $R_\perp$ and the time-dependent CP-asymmetry parameters [12]. The D^{*+} is reconstructed in its decay to $D^0\pi^+$ and $D^+\pi^0$ with $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$, $K^0_S\pi^+\pi^-$ and $D^+ \to K^-\pi^+\pi^+$. An unbinned ML fit to m_{ES} extracts the signal yield as $617 \pm 33(\text{stat.})$. The CP-odd fraction $R_\perp$ is measured in a simultaneous unbinned ML fit to $\cos\theta_{tr}$ and m_{ES} distributions, as shown in Fig. 3, where θ_{tr} is one of the angles in the transversity framework [13], giving $R_\perp = 0.143 \pm 0.034(\text{stat.}) \pm 0.008(\text{syst.})$. A combined analysis of the $\cos\theta_{tr}$ distribution and its time dependence results in the CPV parameters $S = -0.66 \pm 0.19 \pm 0.04$ and $C = -0.02 \pm 0.11 \pm 0.02$. These results are consistent with SM predictions, with no evidence for direct CP violation.

3. $\sin 2\beta_{\text{eff}}$ *from* $b \to q\bar{q}s$ $(q = s, d, u)$ *decays*

The decays $b \to q\bar{q}s$ $(q = s, d, u)$ are dominated by penguin-diagram processes. In the SM, the CPV parameters S_f and C_f are expected to be near the values from

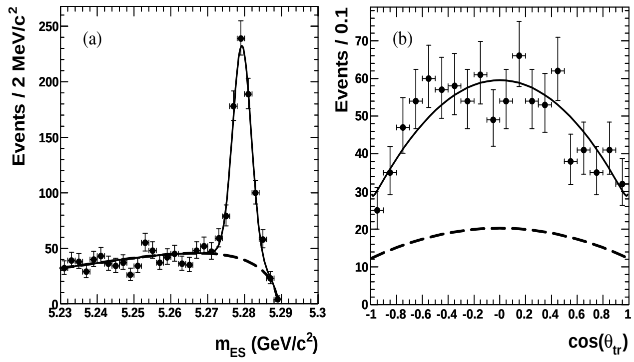

FIG. 3: Distributions of (a) m_{ES} and (b) $\cos\theta_{tr}$, with $m_{\text{ES}} > 5.27$ GeV/c^2. The solid line is the projection of the fit result. The dotted line represents the background component.

$b \to c\bar{c}s$ decays (namely, $C_f \sim 0$ and $S_f \sim \sin 2\beta$). Additional CKM suppressed contributions to the amplitudes can induce only small deviations, whereas additional loop contributions from NP processes may produce large observable deviations [8, 14]. There are many decay modes available for CP studies e.g. $\eta' K^0_S$, $\rho^0 K^0_S$, $\pi^0 K^0_S$, $\pi^0\pi^0 K^0_S$ etc. There has been a tendency for the effective values of $\sin 2\beta$ ($\sin 2\beta_{\text{eff}}$) derived from $b \to q\bar{q}s$ decay modes to lie below the reference value from $b \to c\bar{c}s$ decays. Until August 2007, the HFAG "naïve average" of $\sin 2\beta_{\text{eff}}$ measurements from $b \to q\bar{q}s$ penguin modes was roughly two standard deviations below the reference value [11]. However, this naïve average neglects the theoretical and experimental differences among the various $b \to q\bar{q}s$ decay modes, and so it should be treated with extreme caution.

BABAR has a new preliminary measurement of CPV parameters in $B^0 \to K^0_S\pi^+\pi^-$ decays, based for the first time on a full time-dependent Dalitz plot analysis. Earlier studies have been reported using a quasi-two-body (Q2B) approach, in which, for example, $f_0(980)K^0_S$ or $\rho^0 K^0_S$ decays are reconstructed from the three-body final state $K^0_S\pi^+\pi^-$, but the interference between resonances is not fitted, and is accounted for as part of the systematic error. Therefore, more precise results can be obtained using a DP fit to $B^0 \to K^0_S\pi^+\pi^-$. Furthermore the interference terms allow the cosine of the effective weak phase difference between mixing and decay amplitudes to be determined, thus helping to resolve ambiguities that arise from Q2B analyses. Also the observation of direct CP violation in $B^0 \to K^+\pi^-$ decays [15] motivates a search for possible similar effects in $B^0 \to K^{*+}\pi^-$.

A time-dependent DP analysis of $B^0 \to K^0_S\pi^+\pi^-$ has been used to extract the CPV parameters of $f_0(980)K^0_S$ and $\rho^0(770)K^0_S$ and the direct CP asymmetries (A_{CP}) of $K^{*+}(892)\pi^-$. The DP model consists of the following $\pi\pi$ and $K^0_S\pi$ resonances, a non-resonant term, and interferences among all of them: $\rho^0(770)$, $f_0(980)$, $K^*(892)$, $f_2(1270)$, $f_0(1300)$, $\chi_{c0}(1P)$, $K^*(1430)$. A neural network (NN) is used to separate the signal from the continuum background. MC simulated events are used to study the background from other B decays. We per-

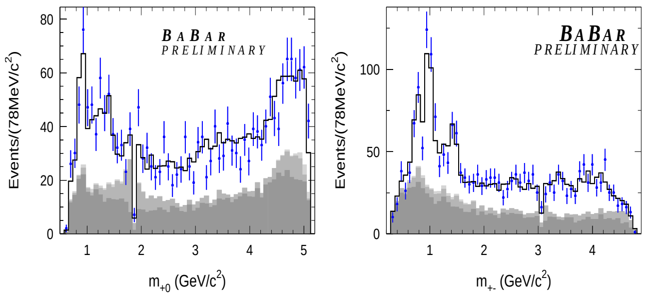

FIG. 4: Distributions of $m(K_S^0\pi^+)$ (left) and $m(\pi^+\pi^-)$ (right) for samples enhanced in $B^0 \to K_S^0\pi^+\pi^-$ signal. The solid histogram shows the projection of the fit result. The dark, medium, and light shaded areas represent respectively the contribution from continuum events, the sum of continuum events and the B background expectation, and the sum of these and the mis-reconstructed signal events. The last contribution is hardly visible due to its small fraction.

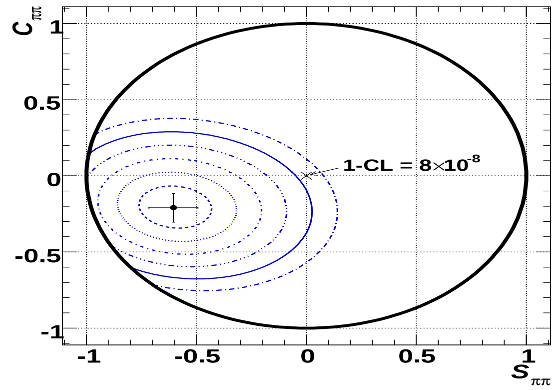

FIG. 5: $S_{\pi\pi}$ and $C_{\pi\pi}$: the central values, errors and confidence level (C.L.) contours for $1 - \text{C.L.} = 0.317\ (1\sigma)$, $4.55 \times 10^{-2}(2\sigma)$, $2.70 \times 10^{-3}(3\sigma)$, $6.33 \times 10^{-5}(4\sigma)$, $5.73 \times 10^{-7}(5\sigma)$, and $1.97 \times 10^{-9}(6\sigma)$, calculated from the square root of the change in the value of $-2\ln\mathcal{L}$ compared with its value at the minimum. The systematic errors are included.

form an unbinned extended ML fit to extract the inclusive $B^0 \to K_S^0\pi^+\pi^-$ event yield and the resonant amplitudes. The fit uses the variables m_{ES}, ΔE, the NN output and the Dalitz plot coordinates. The Δt information allows measurement of mixing-induced CP violation and provides additional continuum background rejection. Figure 4 shows the distributions for $m(K_S^0\pi^+)$ and $m(\pi^+\pi^-)$ and indicates the good quality of the fit. The relative magnitudes and phases of the different components of the signal model are fitted directly, and we obtain the Q2B parameters and the UT angle $2\beta_{\text{eff}}$. The measured values of $2\beta_{\text{eff}}$ in B^0 decays to $f_0(980)K_S^0$ and $\rho^0(770)K_S^0$ are $(89^{+22}_{-20} \pm 5 \pm 8)^\circ$ and $(37^{+19}_{-17} \pm 5 \pm 6)^\circ$, respectively, where the first quoted uncertainty is statistical, the second is systematic and the third is the Dalitz plot signal model uncertainty. Both results are consistent with SM predictions, but in the case of $B^0 \to f_0(980)K_S^0$ it is 2.1 standard deviations *higher* than 2β derived from $b \to c\bar{c}s$ decays. This is opposite to the trend found from other results in $b \to q\bar{q}s$ transitions. Also, $2\beta_{\text{eff}}(f_0(980)K_S^0) = 0$ is excluded at the 4.3σ level. In the decays to $K^*(892)\pi$ we find $A_{CP} = -0.18 \pm 0.10 \pm 0.03 \pm 0.03$. The measured phase difference between decay amplitudes of $B^0 \to K^{*+}(892)\pi^-$ and $\bar{B}^0 \to K^{*-}(892)\pi^+$ is $(-164 \pm 24 \pm 12 \pm 15)^\circ$. The details of this analysis are described in Ref. [16].

B. Measurement of angle α from $b \to u\bar{u}d$ decays

1. *Observation of CP violation in $B^0 \to h^+h^-$ decays*

The proper-time evolution of the asymmetry between B^0 and $\bar{B}^0$ decays to $\pi^+\pi^-$ is characterized by sine and cosine terms with amplitudes $S_{\pi\pi}$ and $C_{\pi\pi}$, respectively. $S_{\pi\pi}$ arises from interference between decays with and without B^0-$\bar{B}^0$ mixing, and $C_{\pi\pi}$ is due to interference between $b \to u$ tree and $b \to d$ penguin decay amplitudes. Similarly, the direct CP-violating asymmetry $\mathcal{A}_{K\pi}$ between the $\bar{B}^0 \to K^-\pi^+$ and $B^0 \to K^+\pi^-$ decay rates arises from interference between $b \to u$ tree and $b \to s$ penguin amplitudes. Negligible contributions to these asymmetry parameters are expected from CP violation purely in B^0-$\bar{B}^0$ mixing, which has been determined to be very small [7]. The quantity $\sin 2\alpha_{\text{eff}} = S_{\pi\pi}/\sqrt{1 - C_{\pi\pi}^2}$ can be related to the UT angle α through a model-independent analysis that uses the isospin-related decays $B^\pm \to \pi^\pm\pi^0$ and $B^0 \to \pi^0\pi^0$ [17]. The unbinned ML fit [18] uses as input m_{ES}, ΔE, the Fisher discriminant, dE/dx, the Cherenkov angle and Δt. We find $4372 \pm 82(\text{stat.})$ $B^0 \to K^+\pi^-$ decays and measure $\mathcal{A}_{K\pi} = -0.107 \pm 0.018(\text{stat.})^{+0.007}_{-0.004}(\text{syst.})$, which excludes the CP conserving hypothesis with a significance of 5.5 standard deviations. In the same sample, we find $1139 \pm 49(\text{stat.})$ $B^0 \to \pi^+\pi^-$ decays and measure the CPV parameters $S_{\pi\pi} = -0.60 \pm 0.11(\text{stat.}) \pm 0.03(\text{syst.})$ and $C_{\pi\pi} = -0.21 \pm 0.09(\text{stat.}) \pm 0.02(\text{syst.})$. CP conservation in $B^0 \to \pi^+\pi^-(S_{\pi\pi} = C_{\pi\pi} = 0)$ is excluded at a confidence level $1 - \text{C.L.} = 8 \times 10^{-8}$, corresponding to 5.4 standard deviations. A contour plot of the $(S_{\pi\pi}, C_{\pi\pi})$ confidence level is shown in Fig. 5. The correlation between $S_{\pi\pi}$ and $C_{\pi\pi}$ is -0.07. Combining these new preliminary *BABAR* measurements with $B^0 \to \pi^0\pi^0$ and $B^\pm \to \pi^\pm\pi^0$ [19] constrains the value of $|\Delta\alpha| = |\alpha - \alpha_{\text{eff}}| < 39^\circ$.

2. *Constraints on α from $B^0 \to \rho^+\rho^-$ decays*

The flavour transitions in the decay $B^0 \to \rho^+\rho^-$ are the same as those in $B^0 \to \pi^+\pi^-$. Isospin relations [17], and measurements of the $B^+ \to \rho^+\rho^0$ [20] and $B^0 \to \rho^0\rho^0$ [21] branching fractions, show that the penguin contribution in $B \to \rho\rho$ is smaller than the

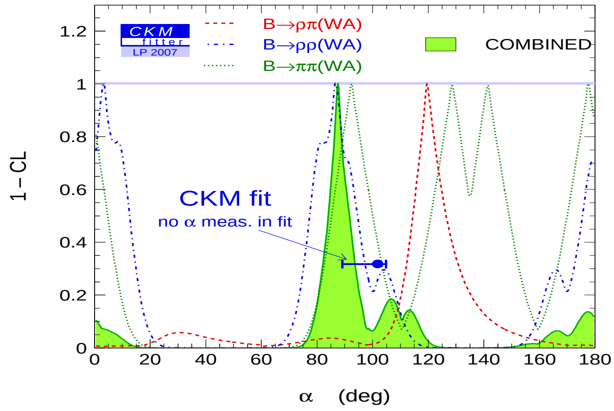

FIG. 6: World average of UT angle α obtained from various measurements of $B \to \pi\pi$, $B \to \rho\rho$ and $B \to \rho\pi$ [7].

leading tree diagram, resulting in tighter constraints on $\alpha_{\rm eff}$ than those obtained from $B^0 \to \pi^+\pi^-$. The decay $B^0 \to \rho^+\rho^-$ leads to a vector-vector final state, so the CP analysis is complicated by the presence of one amplitude with longitudinal polarization (CP even) and two amplitudes with transverse polarization (CP even and CP odd). The decay is observed to be dominated by the longitudinal polarization, with a fraction f_L, defined as the fraction of the helicity-zero state in the decay. For longitudinal polarization the parameters $S = S_{long}$ and $C = C_{long}$ describe the B-mixing induced and direct CP violation, respectively. In the absence of penguin contributions $S_{long} = \sin 2\alpha$ and $C_{long} = 0$. The presence of penguin contributions, with different weak phases to the tree level amplitude, shifts the experimentally measurable parameter: $\alpha_{\rm eff} = \alpha + \delta\alpha$, where $S_{long} = \sqrt{1 - C_{long}^2}\sin 2\alpha_{\rm eff}$, and C_{long} can be non-zero.

From the ML fit we obtain [22] 729 ± 60(stat.) signal events and measure $\mathcal{B}(B^0 \to \rho^+\rho^-) = (25.5 \pm 2.1^{+3.6}_{-3.9}) \times 10^{-6}$, the longitudinal polarization fraction $f_L = 0.992 \pm 0.024 \pm^{+0.026}_{-0.013}$ and the CPV parameters $S_{long} = -0.17 \pm 0.20 \pm^{+0.05}_{-0.06}$ and $C_{long} = 0.01 \pm 0.15 \pm 0.06$, where the first errors are statistical and the second errors are systematic. The correlation between S_{long} and C_{long} is -0.035. We constrain the CKM angle α and the penguin contribution $\delta\alpha$ from an isospin analysis of $B \to \rho\rho$: $|\Delta\alpha| = |\alpha - \alpha_{\rm eff}| < 16.5°$ (90% C.L.). The latest world average constraints on α from various measurements (provided by [7]) can be seen in Fig. 6.

C. Measurement of angle γ

1. CP violation in $B^\pm \to D^0_{CP} K^\pm$ decays

The decays $B^\pm \to D^0 K^\pm$ are central to some of the proposed methods for extracting the UT angle γ in a theoretically clean way [23]. Two direct CP asymmetries need to be measured

$$A_{CP\pm} \equiv \frac{\mathcal{B}(B^- \to D^0_{CP\pm}K^-) - \mathcal{B}(B^+ \to D^0_{CP\pm}K^+)}{\mathcal{B}(B^- \to D^0_{CP\pm}K^-) + \mathcal{B}(B^+ \to D^0_{CP\pm}K^+)} = \frac{\pm 2r \sin\delta \sin\gamma}{1 + r^2 \pm 2r\cos\delta\cos\gamma} \quad (2)$$

as well as two ratios of charge-averaged branching fractions in D^0 decays to $CP = +1$ and $CP = -1$ eigenstates

$$R_{CP\pm} \equiv \frac{\mathcal{B}(B^- \to D^0_{CP\pm}K^-) + \mathcal{B}(B^+ \to D^0_{CP\pm}K^+)}{[\mathcal{B}(B^- \to D^0 K^-) + \mathcal{B}(B^+ \to \bar{D}^0 K^+)]/2} = 1 + r^2 \pm 2r\cos\delta\cos\gamma \quad (3)$$

where $r \equiv |A(B^- \to \bar{D}^0 K^-)/A(B^- \to D^0 K^-)| \approx \mathcal{O}(0.1)$ is the magnitude of the ratio of the amplitudes for $B^- \to \bar{D}^0 K^-$ and $B^- \to D^0 K^-$ decays and δ is the difference between their strong phases. The asymmetries $A_{CP\pm}$ are also of interest because, if significantly different from zero, they would indicate direct CP violation in charged B decays. To measure $R_{CP\pm}$ and $A_{CP\pm}$, $B^\pm \to D^0_{CP\pm}K^\pm$ decays are reconstructed, with $D^0_{CP\pm}$ decaying to two CP-odd ($K^0_S\pi^0$, $K^0_S\omega$) and two CP-even (K^+K^-, $\pi^+\pi^-$) eigenstates. Also $B^- \to D^0 K^-$ and $B^- \to D^0\pi^-$ decays are reconstructed with D^0 decaying to a non-CP state. The signal and background yields for each D^0 decay mode are determined from a two-dimensional extended ML fit to selected data events. The input variables to the fit are ΔE and a PID probability for each track based on the Cherenkov angle. We measure [24] the CP asymmetries $A_{CP+} = 0.35 \pm 0.09 \pm 0.05$ and $A_{CP-} = -0.19 \pm 0.12 \pm 0.02$, where the errors are statistical and systematic. The result for A_{CP+} is 3.4σ away from zero, giving the first evidence for direct CP violation in $B^- \to D^0 K^-$ decays. The double ratios of branching fractions are measured to be $R_{CP+} = 1.07 \pm 0.10 \pm 0.04$ and $R_{CP-} = 0.81 \pm 0.10 \pm 0.05$.

This GLW method (M. Gronau, D. London and D. Wyler [23]), combined with previous measurements of γ using a Dalitz analysis of $B^\pm \to D^{(*)0}K^\pm$ with $D^0 \to K^0_S\pi^+\pi^-$, and the ADS method (D. Atwood, I. Dunietz and A. Soni [23]), improves the constraints on angle γ, as shown in Fig. 7.

V. CONCLUSION

Results have been presented from several new or updated measurements of $\sin 2\beta$ made by the *BABAR* Collaboration, showing reasonable self-consistency. There are also improved constraints on the UT angles α and γ. The higher statistics now available allow more sophisticated analysis techniques, such as time-dependent Dalitz plot fitting.

Fig. 8 shows the combined world-average constraints on the apex of the Unitarity Triangle in the $\bar{\rho}$-$\bar{\eta}$ plane. In addition to the direct measurements of the angles, from CP violation in B decays, there are also direct

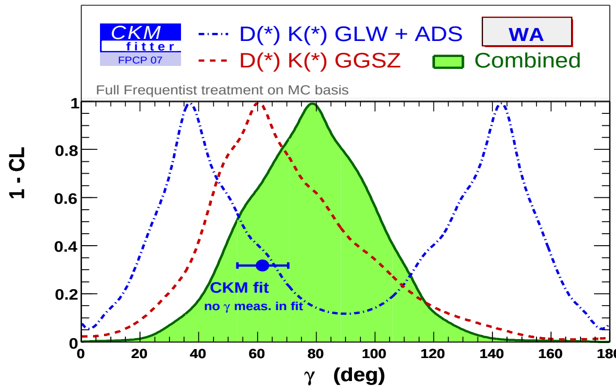

FIG. 7: World-average constraints on γ from $B \to D^{(*)}K$ decays (GLW+ADS) and Dalitz analyses compared to the prediction from the global CKM fit [7].

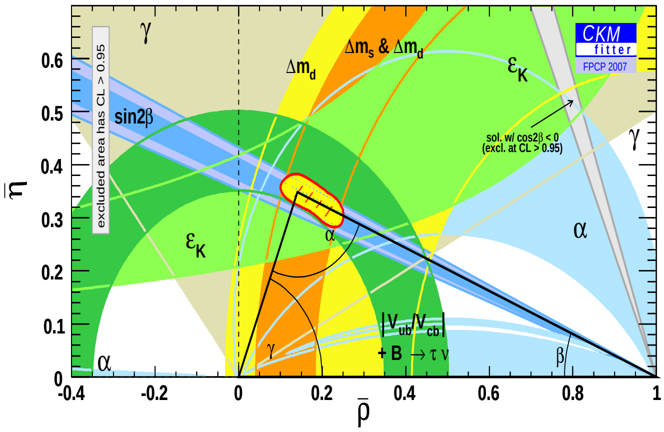

FIG. 8: Constraints in the $\bar{\rho} - \bar{\eta}$ plane [7].

measurements of the sides, from charmless B decays ($|V_{\rm ub}| \,/\, |V_{\rm cb}|$), from B^0_s-$\bar{B}^0_s$ mixing (Δm_s) and from B^0-$\bar{B}^0$ mixing (Δm_d), and a constraint from CP violation in neutral kaon decays (ϵ_K). All of these results, coming from a diverse range of flavour-physics measurements made by many different experiments, show good agreement among themselves and with the unitarity of the CKM matrix. This represents an impressive verification of the Standard Model description of the quark-flavour sector and of CP violation.

The *BABAR* experiment has one further year of data-taking, up to September 2008. We expect to collect a final dataset more than twice as large as that used for the results presented here. This will improve all the measurements, which are statistics-limited, and allow the study of more rare B decay modes. The resulting constraints on the Unitarity Triangle will be a legacy from the B-Factory experiments and will focus the continued search for new physics in the flavour sector.

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[1] N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Th. Phys. **49**, 652 (1973).
[2] L. Wolfenstein, Phys. Rev. Lett. **51**, 1945 (1983).
[3] A.J. Buras, M.E. Lautenbacher, and G. Ostermaier, Phys. Rev. **D 50**, 3433 (1994).
[4] B. Aubert *et al.* (*BABAR* Collaboration), Nucl. Instrum. Meth. **A 479**, 1 (2002).
[5] A.B. Carter and A.I. Sanda, Nucl. Phys. **193**, 85 (1981).
[6] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **99**, 171803 (2007).
[7] UTfit collaboration (M. Bona *et al.*), Phys. Rev. Lett. **97**, 151803 (2006); CKMFitter Group (J. Charles *et al.*), Eur. Phys. Jour. **C 41**, 1-131 (2005).
[8] Z.Z. Xing, Phys. Lett. **B 443**, 365 (1998); Z.Z. Xing, Phys. Rev. **D 61**, 014010 (1999); Y. Grossman and M.P. Worah, Phys. Lett. **B 395**, 241 (1997).
[9] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **99**, 071801 (2007).
[10] S. Fratina *et al.* (Belle Collaboration), Phys. Rev. Lett. **98**, 221802 (2007).
[11] E. Barberio *et al.*, arXiv:0704.3575 [hep-ex] and online update at http://www.slac.stanford.edu/xorg/hfag.
[12] B. Aubert *et al.* (*BABAR* Collaboration), arXiv:0708.1549 [hep-ex] (submitted to Phys. Rev. D).
[13] I. Dunietz, H.R. Quinn, A. Snyder, W. Toki and H.J. Lipkin, Phys. Rev. **D 43**, 2193 (1991).
[14] M. Ciuchini, E. Franco, G. Martinelli, A. Masiero and L. Silvestrini, Phys. Rev. Lett. **79**, 978 (1997).
[15] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **93**, 113801 (2004); K. Abe *et al.* (Belle Collaboration), Phys. Rev. Lett. **93**, 191802 (2004).
[16] B. Aubert *et al.* (*BABAR* Collaboration), arXiv:0708.2097 [hep-ex]

[17] M. Gronau and D. London, Phys. Rev. Lett. **65**, 3381 (1990); B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **94**, 181802 (2005).
[18] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **99**, 021603 (2007).
[19] B. Aubert *et al.* (*BABAR* Collaboration), arXiv:0707.2798 [hep-ex] (submitted to Phys. Rev. D).
[20] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **97**, 026801 (2006); J. Zhang *et al.* (Belle Collaboration), Phys. Rev. Lett. **91**, 0221801 (2003).
[21] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **98**, 111801 (2007).
[22] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. **D 76**, 052007 (2007).
[23] M. Gronau and D. Wyler, Phys. Lett. **B 265**, 172 (1991); M. Gronau and D. London, Phys. Lett. **B 253**, 483 (1991); D. Atwood, I. Dunietz and A. Soni, Phys. Rev. Lett. **78**, 3257 (1997); A. Giri, Y. Grossman, A. Soffer, J. Zupan, Phys. Rev. **D 68**, 054018 (2003).
[24] B. Aubert *et al.* (*BABAR* Collaboration), arXiv:0708.1534 [hep-ex].