Experimental Results on B mesons from the BABAR experiment

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Highlights of a selection of results obtained by the BABAR experiment on the PEP-II collider at SLAC until the spring of 2002 are presented. The phenomenology of CP violation in B decays is briefly reviewed. At that time, CP violation was already significantly established in the decays of neutral B mesons to charmonium and a neutral K: $\sin 2\beta = 0.75 \pm 0.09 \pm 0.04$. The analysis method and its implementation are described. The interpretation of the measurements and future prospects are discussed. Preliminary results on charmless and other rare B decays, that could lead to measurements of the CKM angles α and γ are shown.

1 An overview of CP Violation in B decays

For CP violation to occur in B meson decay[1], at least two amplitudes, with a fundamental phase difference have to contribute. Three types of CP violation are distinguished[2, 3].
In *direct CP violation* the B and $\overline{B}$ decay to CP conjugate final states with different rates. Direct CP violation requires both strong and weak phase differences. It can affect neutral and charged B mesons in contrast with the other types which rely on neutral B mixing.
CP violation in mixing occurs when $\Delta B = 2$ transitions (box diagrams) exist which make mass eigenstates that are different from the CP eigenstates.
Finally *CP violation in the interference between mixing and decay* is the case where a final state built out of a CP self conjugate collection of quarks (which can be a CP eigenstate f_{CP}) is reached either from a B^0 or from a $\overline{B}^0$ after a $B^0 \rightarrow \overline{B}^0$ flavor oscillation.
A very clean theoretical situation is obtained in the last case when a single diagram dominates the $B^0 \rightarrow f_{CP}$ transition (*golden mode*). A time dependent CP asymmetry (see Equation 1 below) follows from the opposite signs

[1]representing the BABAR collaboration.

for the interference terms between the two decay paths starting with a B^0 or a $\overline{B}^0$.
New e^+e^- colliders, the B factories, were built when it was demonstrated they could host experiments sensitive to CP violation in golden modes within the standard model. Since Kobayashi and Maskawa extended the Cabibbo theory of flavor mixing in charged current weak interaction to 3 families of quarks[4], it has been known that the standard model formalism is able to account for CP violation. The unitary quark mixing matrix, called the CKM matrix V, contains an irreducible phase the value of which might explain all CP violating phenomena. More generally, V depends on 4 parameters. A convenient representation due to Wolfenstein[5] is :

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4).$$

The unitarity relation computed with the first and third column is conventionally used to draw a normalised triangle in the complex plane, the unitarity triangle (UT), pictured at the bottom of Fig. 1.
The definition of the CKM angles, α, β and γ is explicit on the picture. The goal of the experiments at B factories is to overdetermine the apex (ρ, η) of the UT, and more generally, the 4 parameters of the CKM matrix.
Nonleptonic b decays[2] mainly proceed via *tree* (T) and *penguin* (P) diagrams (Fig. 2). The powers of λ determine the relative strengths of the terms in the amplitudes, neglecting at this level the effects of color suppression, electroweak penguin and annihilation diagrams.

The first two rows in Table 1 show processes dominated by one amplitude. New physics could be discovered if incompatible β measurements were obtained from golden modes with differing decay mechanism (e.g. T in the first row and P in the second).

Fig. 1 The Unitarity Triangle.

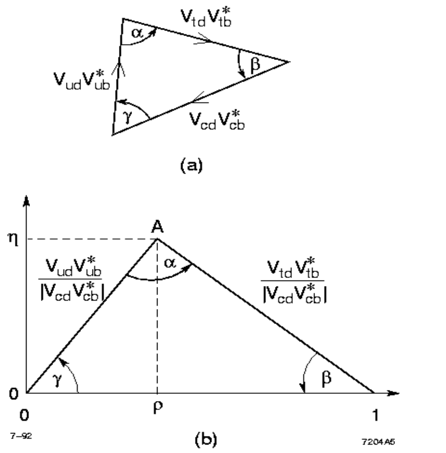
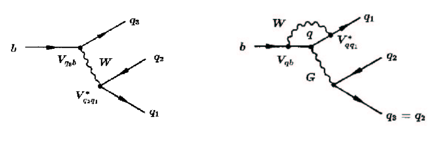


Fig. 2 Tree and Penguin graphs



The rate of such a B^0 decay has interference effects between that amplitude and that of $B^0\overline{B}^0$ mixing which are free from strong interaction complications. When more than two decay paths with comparable strengths contribute, only an effective phase can be obtained.
More complicated processes can be used to search for CP violation at high luminosity. For example cascades[6] where T_{cus} and T_{ucs} transitions lead to a D or $\overline{D}$ meson which decay to a final state they share in common have rates which depend on γ.

Table 1: CKM structure of non leptonic b decay amplitudes. The amplitude for a $b \rightarrow q_1\bar{q}_2q_3$ transition is written in terms of T and/or P amplitudes with the CKM factors shown explicitely. The power of λ governing the first and second terms are given. A golden channel leads to a pure measurement of a CKM phase. Only *effective phases* are accessible from the non golden channels.

quark process	1st term	2nd		example	UT angle
$A_{ccs} \approx V_{cb}V_{cs}^*T_{ccs} + V_{ub}V_{us}^*P_s$	λ^2	λ^4	golden	$J/\psi\, K_{S,L}$	β
$A_{sss} \approx V_{cb}V_{cs}^*P_s + V_{ub}V_{us}^*P_s'$	λ^2	λ^4	golden	$\Phi\ K_S^0$	β
$A_{ccd} \approx V_{cb}V_{cd}^*T_{ccd} + V_{tb}V_{td}^*P_d$	λ^3	λ^3		D^+D^-	$\beta+\theta$
$A_{uud} \approx V_{ub}V_{ud}^*T_{uud} + V_{tb}V_{td}^*P_d$	λ^3	λ^3		$\pi^+\pi^-$	α_{eff}

2 Experimental setup and analysis tools

2.1 PEP-II and BaBar

CP violation in the interference between mixing and decay produce time dependent CP-asymmetries. For a CP eigenstate f_{CP}:

$$\begin{aligned} A_{f_{CP}} &= \frac{\Gamma(\overline{B}^0_{phys}(t) \rightarrow f_{CP}) - \Gamma(B^0_{phys}(t) \rightarrow f_{CP})}{\Gamma(\overline{B}^0_{phys}(t) \rightarrow f_{CP}) + \Gamma(B^0_{phys}(t) \rightarrow f_{CP})} \\ &= C_{f_{CP}} cos(\Delta m_d t) + S_{f_{CP}} sin(\Delta m_d t). \end{aligned} \tag{1}$$

In Eq. (1), t is the proper time elapsed between the production of a B meson with known flavor (beauty) and its decay. $B_{phys}(t)$ is the evolved B state after t. Neglecting C[redacted]*ing*, the coefficients can be written:

$C_{f_{CP}}$ [redacted] $1+|\lambda_{f_{CP}}|$ [redacted]

$$S_{f_{CP}} = \frac{-2Im(\lambda_{f_{CP}})}{1+|\lambda_{f_{CP}}|^2}. \qquad (2)$$

where $\lambda_{f_{CP}} = \frac{q}{p} \times \frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} \times \eta_{CP}$, q and p are the mixing parameters, A [redacted] $\overline{A}$) are the B^0 (resp. $\overline{B}^0$) $\to$ f_{CP} amplitudes and η_{CP} is the CP par[redacted] f_{CP} state. A non-zero $C_{f_{CP}}$ is evidence for *direct CP violation*. [redacted] mode $|A| = |\overline{A}|$, and $|S_{f_{CP}}|$ is the sine of [redacted] in Table 1, $S_{f_{CP}} = \eta_{CP} \times \sin 2\beta$[redacted]
To be capable of measurin[redacted] fulfill the following req[redacted]
Since the f_{CP} branc[redacted] charmo-nium + kaon mode[redacted] is required to detect a signif[redacted]cays[redacted]ries, PEP-II at SLAC and KEK[redacted]ate[redacted]ance which decays exclusively to B[redacted] section above a man-ageable backgr[redacted]
High perform[redacted] are required to reconstruct pure samples o[redacted]tates.
To tag the initi[redacted]**cle identification** is needed.
To measure the[redacted]ave to fly far enough in the lab[redacted]tory. This is ach[redacted]$\Upsilon(4S)$, using **different electro**[redacted] **positron energi**[redacted]n asymmetric B Factory, o[redacted] measure Δt, the t[redacted]s of the two B me[redacted] decay point is no[redacted]
With 9 GeV e^- a[redacted] average mean dis[redacted] laboratory. The [redacted] 10^{33} cm[redacted]

The results presented here are based on an integrated luminosity of 56.4 fb^{-1}, of which 6.5 were taken at an energy below that of the $\Upsilon(4S)$ resonance.

2.2 Experimental technique

Time dependent CP-asymmetries are studied in samples of $B^0\overline{B}^0$ events where one B meson decays to a completely reconstructible exclusive non leptonic final state and the other, to a flavor specific mode. Before any decay, the $B\overline{B}$ pair is in a coherent L=1 quantum state i.e. it remains a particle-antiparticle pair. When the flavor specific decay occurs, the other B has the opposite flavor. It then evolves in the way prescribed by $B\overline{B}$ mixing. This argument holds whatever the time ordering of the two decays[2, 3]. To analyse CP-asymmetries, the experimental technique[8] consists in implementing the exclusive B meson reconstruction, the B flavor tagging and the vertexing algorithm for the determination of Δt.
Very pure samples (see section 3) are selected for f_{CP} as well as flavor eigenstates using two kinematic variables ΔE and m_{ES}. ΔE is the difference in the center of mass frame between the energy of the B candidate and the beam energy. m_{ES} is the invariant mass of the B candidate computed from the candidate momentum and the beam energy which is much more precisely known than the candidate energy.
To determine Δt, the projection Δz along the electron beam of the vector joining the decay points of the two B mesons is measured. The vertex of the fully reconstructed B is obtained from a geometric and kinematic fit of the candidate. The other B decay point is obtained iteratively from the charged tracks which remain after removal of those belonging to the reconstructed candidates and those with which a V^0 (K^0_s or Λ) can be constructed. That vertex is constrained to be compatible with the flight path of that B j 4(w)T85 0 Td (the) with the charged)2971 0 Td (v)Tj 5.7491 0 Td Td (j 4(w)Tj 8.0325 11.9

the Δt resolution is needed with parameters to be fitted from the data.
A hierarchical B flavor tagging algorithm using four non overlapping sets of criteria (categories) exploits the charge correlations between the b quark and the leptons or kaons produced in the CKM-favored $b \to c(\to s)$ quark decay chain. More global information (e.g. charged particle momentum spectrum, soft pions from D^* decays, etc.) are input to neural networks used to complete the tagging algorithm. The efficiency $\varepsilon \approx 0.7$ and the mistag fraction w characterize the performance. The overall effective efficiency is $Q = \varepsilon \times (1-2w)^2 = 0.251 \pm 0.008$.
To validate the experimental techniques, the lifetimes of the B mesons and the $B^0\overline{B}^0$ oscillation frequencies are measured using appropriate reconstructed samples. The Δt distributions obtained for charged and neutral B s are shown on Fig. 3. The measured lifetimes: $\tau_0 = 1.546 \pm 0.032(stat.) \pm 0.022(syst.)$ ps, $\tau_\pm = 1.673 \pm 0.032 \pm 0.023$ ps, are compatible with previous measurements[10] and have smaller errors. The lifetime ratio measurement[9], $\tau_\pm/\tau_0 = 1.082 \pm 0.026 \pm 0.012$ promises an ultimate error at the level of 1 %. Similarly, samples of reconstructed neutral B mesons decaying to flavored final states enabled to extract the averaged mistag fraction and also showed compatibility of the measured $B^0\overline{B}^0$ oscillation frequency Δm_d with previous measurements.

3 The measurement of $\sin 2\beta$.

Table 2: Yields in the B reconstruction f_{CP} modes after tagging. Note that for the $J/\psi\, K^{*0}$ final state a partial wave analysis is needed to separate the CP-even and CP-odd contributions.

Mode	N_{tagged}	Purity
$(c\bar{c})K^0_S$	995	94%
$J/\psi\, K^0_L$	742	57%
$J/\psi\, K^{*0}$	113	83%
All CP	1850	79%

Some of the yields measured for the golden modes $B^0 \to$charmonium K^0_S as well as $\to$ charmonium K^0_L (more difficult to select because the K^0_L energy is not measured) are shown on Fig. 4 and summarized in Table 2. Since the tagging performance is the same for both samples, the Δt distributions for tagged flavored B and f_{CP} samples are simulataneously fit keeping τ_0 and Δm_d fixed at the previous pre-BaBar values[10]. The result for a sine-wave only $A_{CP}(\Delta t)$ is: $\sin 2\beta = 0.75 \pm 0.09 \pm 0.04$.

The CP asymmetries as a function of Δt are shown on Fig. 5 for CP-odd and CP-even channels with the likelihood projections superimposed. Out of phase sine waves are observed as expected. Since the conference, that measurement has been updated[11] to $\sin 2\beta = 0.741 \pm 0.067 \pm 0.033$. A similar result[12] $0.719 \pm 0.074 \pm 0.035$ is obtained by the BELLE experiment. Consistent results are obtained in BaBar by doing fits looking at one decay channel only.
Control samples (e.g. flavored B s) with null expectations indeed give results compatible with zero. A fit allowing both sine and cosine waves in the A_{CP} time dependence gives $\lambda_{f_{CP}} = 0.92 \pm 0.06 \pm 0.02$. That value being compatible with 1, there is no evidence for direct CP violation.

Fig. 4 Charmonium K^0_S and $J/\psi K^0_L$ yields.

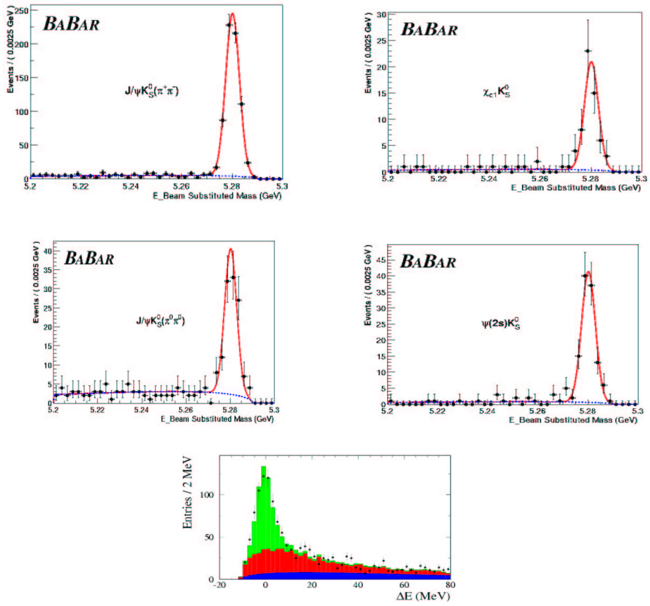
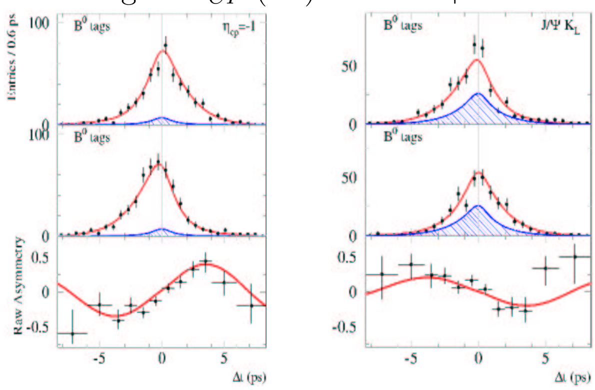


Fig. 5 A_{CP} (Δt) for CP=∓1.



The 1 and 2-standard deviation zones for $\sin 2\beta$ in the (ρ, η) plot are shown on Fig. 6. There is a four-fold trigonometric ambiguity. One solution agrees with previous non-CP measurements. The standard model is resilient.
A preliminary result on $B^0 \to \eta_c K^0_S$ (first line of Table 1) was shown at the conference: $\sin 2\beta = 0.43 \pm 0.46 \pm 0.08$. Although signals were seen in $B \to \Phi K$ channels, no result was available for the pure penguin A_{CP}.

The S_{DD} and C_{DD} coefficients of Eq.(1), for $B \to D^{(*)+}D^{(*)-}$ decays are summarized in Table 3. More data are needed before any conclusions can be drawn from these measurements.

In summary, CP violation has been discovered by the experiments at the B factories. At the current level of precision, all the data are compatible with the standard (CKM) model.

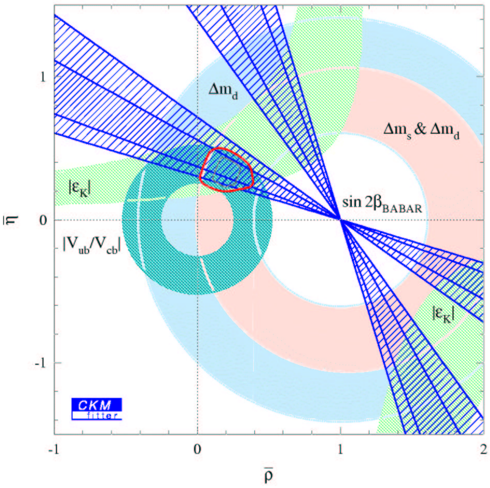


Fig. 6 1 and 2 $\sigma_{\sin 2\beta}$ bands on UT plot.

Table 3: Preliminary results on the $B^0 \to D^{(*)+}D^{(*)-}$ coefficients S_{DD} and C_{DD}.

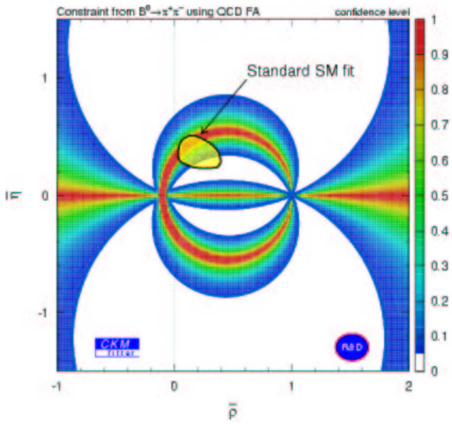
Mode	S_{DD}	C_{DD}
$D^{*+}D^{*-}$	$-0.05 \pm 0.45 \pm 0.07$	$0.12 \pm 0.30 \pm 0.03$
$D^{*+}D^{-}$	$-0.43 \pm 1.41 \pm 0.20$	$0.53 \pm 0.74 \pm 0.13$
$D^{*-}D^{+}$	$0.38 \pm 0.88 \pm 0.05$	$0.30 \pm 0.50 \pm 0.08$

4 Towards $\sin 2\alpha_{eff}$

B decays to two-body final states without charmed hadrons (*charmless 2-body channels*) could give access to the α and γ angles of the UT. Originally, the $B^0 \to \pi^+\pi^-$ channel looked like a golden mode for $\sin 2\alpha$. But it was soon realized that penguin graphs P_d competed with the T_{uud} at $O(\lambda^3)$ (see the last line of Table 1). Unless $|P/T| << 1$, three amplitudes interfere, P, T, and that of mixing. A fit to $A_{CP}^{\pi^+\pi^-}$, pretending that it is a golden channel, can at best determine (the sine of) an effective phase α_{eff}. The present analyses fit for the $C_{\pi\pi}$ and $S_{\pi\pi}$ coefficients defined in Eq. (2). With more theoretical input like isospin invariance, SU(3) symmetry or relying on QCD inspired models[13, 14] to compute the P and T amplitudes, conclusions on CKM angles can be reached. They are however subject to theoretical errors. It is much harder to implement the experimental technique for charmless

decays because the branching ratios of these CKM or penguin suppressed decays are tiny (in the 10^{-5} or 10^{-6} range) and because the final states have much weaker kinematical or topological constraints. Particle identification at high momenta where the DIRC is effective and methods to efficiently remove the continuum $e^+e^- \rightarrow q\bar{q}$ are employed on top of tagging and vertexing.
The final states including charged pions and kaons are treated simultaneously. On top of m_{ES} and ΔE, other discriminating variables are used, namely a Fischer discriminant which characterizes the event energy flow and the DIRC Cherenkov angles of the charged particles. The analyses are performed in two steps. In the first, the CP-averaged branching ratios and the time integrated CP asymmetries are determined. The results of the first step are injected as fixed quantities in the time dependent analyses (second step) which apply tagging and vertexing. All results are preliminary. They are constantly refined. The time integrated results are summarized in Table 4.
The experiment is becoming sensitive to the final states with π^0 s which are needed in isospin constructions. In May 2002, the fit to $A_{CP}^{\pi^+\pi^-}(\Delta t)$ gave: $C_{\pi\pi} = -0.01 \pm 0.37 \pm 0.07$, $S_{\pi\pi} = -0.02 \pm 0.29 \pm 0.07$. The numbers have since moved within errors. For fun, the (ρ, η) plot assuming the validity of a model[13] is pictured on Fig. 7. Any conclusions about the CKM angles are premature.

Fig. 7 (ρ, η) for $B^0 \rightarrow \pi\pi$ with model[13].



5 Rare decays

At the conference, preliminary results were mentioned very briefly on rare decays, like the $B^{\pm} \rightarrow DK^{\pm}$ where the D decays to K^+K^-, a CP eigenstate shared by the D and the $\overline{D}$ (see the very end of section 1). Results on a host of (two-body and quasi two-body) charmless modes were listed. The high branching ratios of $\eta' K$ channels is confirmed. No significant direct CP asymmetries have been found in charged B decays. The status of electroweak

Table 4: Preliminary results on $B \to$ charmless 2-body decays as of May 2002. CP averaged branching ratios and time integrated CP asymmetries (direct CP violation) are presented. Most of these results have been updated since then. The $B^+ \to K^0\pi^+$ asymmetry, all the $B^+ \to \pi^+\pi^0$ and $B^0 \to \pi^0\pi^0$ results were recent. The K^0 π^0 and K^0 $\overline{K}^0$ are based on 20.6 fb^{-1} of data only.

$B \to$	Yield	Signif.	BR (10^{-6})	A$_{direct}$
$K^+ \pi^-$	403 ± 24		$17.8 \pm 1.1 \pm 0.8$	
$K^+ \pi^0$	$149 \pm 17^{+8}_{-7}$		$11.1^{+1.3}_{-1.2} \pm 1.0$	
$K^0 \pi^+$	$172 \pm 17 \pm 9$	17.8	$17.5^{+1.8}_{-1.7} \pm 1.8$	$-0.17 \pm 0.10 \pm 0.02$
$K^0 \pi^0$	$17.9^{+6.8}_{-5.8} \pm 1.9$	4.5	$8.2^{+3.2}_{-2.7} \pm 1.2$	$0.00 \pm 0.11 \pm 0.02$
$\pi^+ \pi^-$	125^{+16}_{-15}		$5.4 \pm 0.7 \pm 0.5$	
$\pi^+ \pi^0$	$62^{+17}_{-16}{}^{+10}_{-11}$	5.2	$4.1^{+1.1}_{-1.0}{}^{+0.8}_{-0.7}$	$-0.02^{+0.27}_{-0.26} \pm 0.10$
$\pi^0 \pi^0$	9.8 ± 8.7	1.3	< 3.4	
$K^+ K^-$	$0.6^{+8.0}_{-7.4}$		< 1.1	
$K^+ \overline{K}$	$-5.6^{+2.8}_{-5.5} \pm 2.5$		< 3.8	
$K^0 \overline{K}^0$	$3.5^{+3.4}_{-2.4}$	1.5	< 13	

penguin decays branching ratios was given:
$Br(B \to K\ell^+\ell^-) = 0.84^{+0.30}_{-0.24}{}^{+0.10}_{-0.18}\times10^{-6}$ $Br(B \to K^*\ell^+\ell^-) < 3.5\times10^{-6}$at 90 % c.l.

6 Summary and outlook

The BaBar measurement of sin2β had reached a precision of 0.09 at the time of the conference and of 0.067 since then[11]. There is still headroom before it becomes dominated by the systematic errors (at the level of 0.03).
Charmless B decays are the focus of many analyses. There is steady progress towards significant measurements of sin2α_{eff} in two and now three pion final states.
Many modes testing the same standard model parameters via different graphs will be constantly scrutinized, looking for new physics.
The abundant harvest of experimental data on many branching ratios and asymmetries will help to refine the theoretical knowledge of B decays.
Scenarios to accelerate progress towards higher luminosities and reach ab^{-1} samples sooner than presently planned are actively studied.

Acknowledgments

I am grateful for the superb achievements of the PEP-II staff. I am delighted to present so many excellent pieces of physics worked out by my *BaBar* colleagues. I wish to warmly thank the organizers of the conference who prepared a full, diverse and exciting program and very smoothly managed the event. I will remember many participants for their talks and for the friendly discussions we enjoyed together.

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