SLAC-PUB-8731
BABAR-PROC-00/40
hep-ex/0012037
December, 2000

The *BABAR* Measurement of $\sin 2\beta$ and its Future Prospects

James Weatherall
University of Manchester
Department of Physics and Astronomy, University of Manchester,
Oxford Road, Manchester, M13 9PL, UK
(for the *BABAR* Collaboration)

Abstract

The measurement of $\sin 2\beta$ by the *BABAR* experiment, where β is one of the angles of the Unitarity Triangle, is described. Some prospects for the future of the measurement are also discussed.

Contributed to the Proceedings of the UK Phenomenology Workshop
on Heavy Flavour and *CP* Violation,
9/17/2000—9/22/2000, Durham, UK

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Work supported in part by Department of Energy contract DE-AC03-76SF00515.

1 Introduction

The *BABAR* experiment consists of an asymmetric electron-positron collider operating at the $\Upsilon(4S)$ resonance. More details on the detector can be found in [1]. The aim is to overconstrain the unitarity triangle by measuring its sides and angles. The analysis reviewed here measures $\sin 2\beta$ by studying time-dependent *CP* violating asymmetries in $B^0 \to J/\psi\, K_S^0$ and $B^0 \to \psi' K_S^0$ decays.

2 Overview of the $\sin 2\beta$ analysis

There are five main parts to measuring the *CP* violating asymmetry:

- Selection of signal *CP* events
- Measurement of the distance Δz between the two B^0 decay vertices along the $\Upsilon(4S)$ boost axis
- Determination of the flavour of the tag-side B
- Measurement of dilution factors for the different tagging categories
- Extraction of $\sin 2\beta$ via an unbinned maximum likelihood fit

2.1 Event Selection

The sample used for the analysis is 9.8 fb^{-1} of data recorded between January and July 2000 of which 0.8 fb^{-1} was recorded 40 MeV below the $\Upsilon(4S)$ resonance. Particle identification uses mainly the CsI calorimeter for electrons, the Instrumented Flux Return for muons and the DIRC for kaons. Extra information is provided by dE/dx measured in the tracking system. The selection for the *CP* events proceeds as follows. Pairs of electrons or muons coming from a common vertex are combined to form J/ψ and ψ' candidates. The ψ' is also reconstructed from its decay into $J/\psi\ \pi^+\pi^-$. The K_S candidates are made from either a pair of charged tracks or a pair of π^0 candidates. In addition there are various event shape and topological cuts designed to reduce continuum and $B\overline{B}$ background. Full details of the selection can be found in [2]. The final event sample is shown in figure 1.

There are two other B decay samples. One consists of fully reconstructed semileptonic ($B^0 \to D^{*-} l^+ \nu_l$) and hadronic ($B^0 \to D^{(*)-}\pi^+, D^{(*)-}\rho^+, D^{(*)-}a_1^+$) decays as well as a control sample of $B^+ \to \overline{D}^{(*)0}\pi^+$ events. The selection of this sample is described in [3] and [4]. The other is a charmonium control sample containing fully reconstructed neutral or charged B candidates in two-body decay modes with a J/ψ in the final state (e.g. $B^+ \to J/\psi\ K^+, B^0 \to J/\psi\ K^{*0}(K^{*0} \to K^+\pi^-)$).

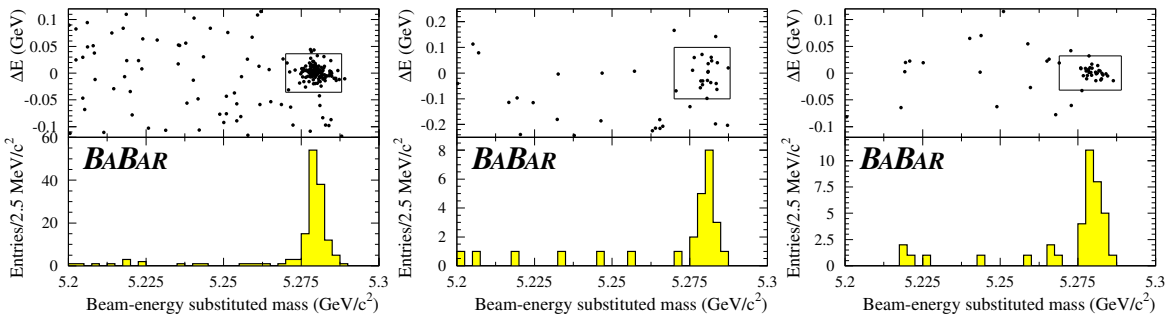

Figure 1: *CP* signal event distributions for $J/\psi K_S(\pi^+\pi^-)$ (left), $J/\psi K_S(\pi^0\pi^0)$ (middle) and $\psi'\ K_S(\pi^+\pi^-)$ (right).

2.2 Measuring Δz

The time-dependent decay rate for the B_{CP} is given by

$$f_\pm(\,\Gamma,\,\Delta m_d,\,\mathcal{D}\sin 2\beta,\,t\,) = \frac{1}{4}\,\Gamma\,\mathrm{e}^{-\Gamma|t|}\,[\,1\,\pm\,\mathcal{D}\sin 2\beta\times\sin\Delta m_d\,t\,] \tag{1}$$

where the + or - sign indicates whether the B_{tag} was tagged as a B^0 or $\overline{B}^0$ respectively. The dilution factor $\mathcal{D}$ is given by $\mathcal{D} = 1 - 2w$, where w is the mistag fraction (the probability that the B_{tag} is identified incorrectly). To account for finite detector resolution, the time distribution must be convoluted with a resolution function:

$$\mathcal{R}(\Delta z;\hat{a}\,) \;=\; \sum_{i=1}^{2}\frac{f_i}{\sigma_i\sqrt{2\pi}}\exp\left(-(\Delta z-\delta_i)^2/2{\sigma_i}^2\right) \quad , \tag{2}$$

which is just the sum of two Gaussians where the f_i, δ_i and σ_i are the normalizations, biases and widths of the distributions. In practice two scale factors $\mathcal{S}_1$ and $\mathcal{S}_2$ are introduced such that $\sigma_i = \mathcal{S}_i \times \sigma_{\Delta t}$ where $\sigma_{\Delta t}$ is an event-by-event calculated error on Δt. They take account of underestimating the uncertainty on Δt due to effects such as hard scattering and possible underestimation of the amount of material traversed by the particles. The resolution function parameters are obtained from a maximum likelihood fit to the hadronic B^0 sample and are shown in table 1. The f_w parameter represents the width of a third Gaussian component, included to accommodate a small ($\sim$1%) fraction of events which have very large values of Δz, mostly caused by vertex reconstruction problems. This Gaussian is unbiased with a fixed width of 8 ps. Further details can be found in [3].

2.3 B flavour tagging

Each event with a *CP* candidate is assigned a B^0 or $\overline{B}^0$ tag if it satisfies the criteria for one of the several tagging categories. The figure of merit for each tagging category is the

Parameter		Value	
δ_1	(ps)	-0.20 ± 0.06	from fit
$\mathcal{S}_1$		1.33 ± 0.14	from fit
f_w	(%)	1.6 ± 0.6	from fit
f_1	(%)	75	fixed
δ_2	(ps)	0	fixed
$\mathcal{S}_2$		2.1	fixed

Table 1: Resolution function parameters. Those, labeled 'from fit' are measured from data and those marked 'fixed' are determined from Monte Carlo.

effective tagging efficiency $Q_i = \epsilon_i(1-2w_i)^2$ where ϵ_i is the fraction of events assigned to category i and w_i is the probability of mis-tagging an event in this category. The statistical error on sin2β is proportional to $1/\sqrt{Q}$ where $Q = \sum_i Q_i$. There are five tagging categories: `Electron, Muon, Kaon, NT1 and NT2`.

The first three require the presence of a fast lepton and/or one or more charged kaons in the event and depend on the correlation between the charge of a primary lepton or kaon and the flavour of the b quark. If an event is not assigned to either the `Electron` or `Muon` categories, it is assigned to the `Kaon` category if the sum of the charges of all the identified kaons in the event is different from zero. If both lepton and kaon tags are available but inconsistent the event is rejected from both categories.

NT1 and NT2 are categories from a neural network algorithm, this approach being motivated by the potential flavour-tagging power carried by non-identified leptons and kaons, correlations between leptons and kaons and more generally the momentum spectrum of charged particles from B meson decays. The output of the neural network tagger x_{NT} can be mapped onto the interval [-1,1] with $x_{NT} < 0$ representing a B^0 tag and $x_{NT} > 0$ a $\overline{B}^0$ tag. Events with $|x_{NT}| > 0.5$ are classified in the `NT1` category and events with $0.2 < |x_{NT}| < 0.5$ in the `NT2` category. Events with $|x_{NT}| < 0.2$ are excluded from the final analysis sample.

2.4 Measurement of tagging performance

The effective tagging efficiencies and mistag fractions for all the categories are measured from data using a maximum likelihood fit to the time distributions of the B^0 hadronic event sample. The procedure uses events which have one B fully reconstructed in a flavour eigenstate mode. The tagging algorithms are then applied to the rest of the event, which represents the potential B_{tag}. Events are classified as *mixed* or *unmixed* depending on whether the B_{tag} is tagged with the same or opposite flavour as the B_{CP}. One can express the time-integrated fraction of mixed events χ as a function of the $B^0\overline{B}^0$ mixing probability, $\chi = \chi_d + (1-2\chi_d)w$ where $\chi_d = \frac{1}{2}x_d^2/(1+x_d^2)$, with $x_d = \Delta m_d/\Gamma$. Thus an experimental value of the mistag fraction w can be deduced from the data.

A more accurate estimate of w comes from a time-dependent analysis of the fraction of mixed events. The mixing probability is smallest at low Δt so that this region is governed

by the mistag fraction. Figure 2 shows the fraction of mixed events versus Δt. The resultant tagging performances are shown in table 2.

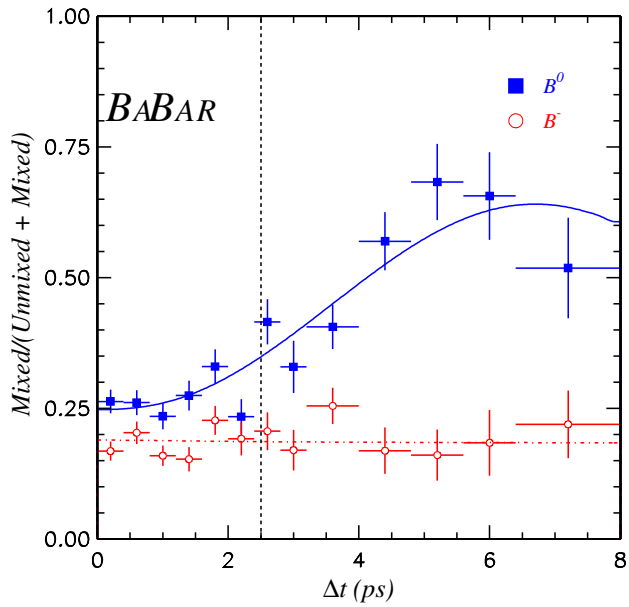

Figure 2: The fraction of mixed events as a function of $|\Delta t|$ for data events in the hadronic sample for neutral B mesons (full squares) and charged B mesons (open circles). The dot-dashed line at $t_{cut} = 2.5$ ps indicates the bin boundary for the time-integrated single-bin method.

2.5 Extracting $\sin 2\beta$

A blind analysis technique was adopted for the extraction of $\sin 2\beta$ to eliminate possible experimenter bias. The technique hides both the result of the likelihood fit and the visual CP asymmetry in the Δt distribution. This method allows systematic studies to be performed while keeping the numerical value of $\sin 2\beta$ hidden.

Possible systematic effects due to uncertainty in the input parameters to the fit, incomplete knowledge of the time resolution function, uncertainties in the mistag fractions and possible limitations in the analysis procedure were all studied. Details can be found in [2]. The systematic errors are summarized in table 3.

2.6 Results and checks

The maximum likelihood fit for $\sin 2\beta$, using the full tagged sample of 120 $B^0 \to J/\psi K^0_S$ and $B^0 \to \psi' K^0_S$ events yields:

Tagging category	ϵ (%)	w (%)	Q (%)
`Lepton`	11.2 ± 0.5	$9.6 \pm 1.7 \pm 1.3$	7.3 ± 0.3
`Kaon`	36.7 ± 0.9	$19.7 \pm 1.3 \pm 1.1$	13.5 ± 0.3
`NT1`	11.7 ± 0.5	$16.7 \pm 2.2 \pm 2.0$	5.2 ± 0.2
`NT2`	16.6 ± 0.6	$33.1 \pm 2.1 \pm 2.1$	1.9 ± 0.1
all	76.7 ± 0.5		27.9 ± 0.5

Table 2: Tagging performance as measured from data.

Source of uncertainty	Uncertainty on sin2β
uncertainty on τ_B^0	0.002
uncertainty on Δm_d	0.015
uncertainty on Δz resolution for *CP* sample	0.019
uncertainty on time-resolution bias for *CP* sample	0.047
uncertainty on measurement of mistag fractions	0.053
different mistag fractions for *CP* and non-*CP* samples	0.050
different mistag fractions for B^0 and $\overline{B}^0$	0.005
background in *CP* sample	0.015
total systematic error	**0.091**

Table 3: Summary of systematic uncertainties. The different contributions are added in quadrature.

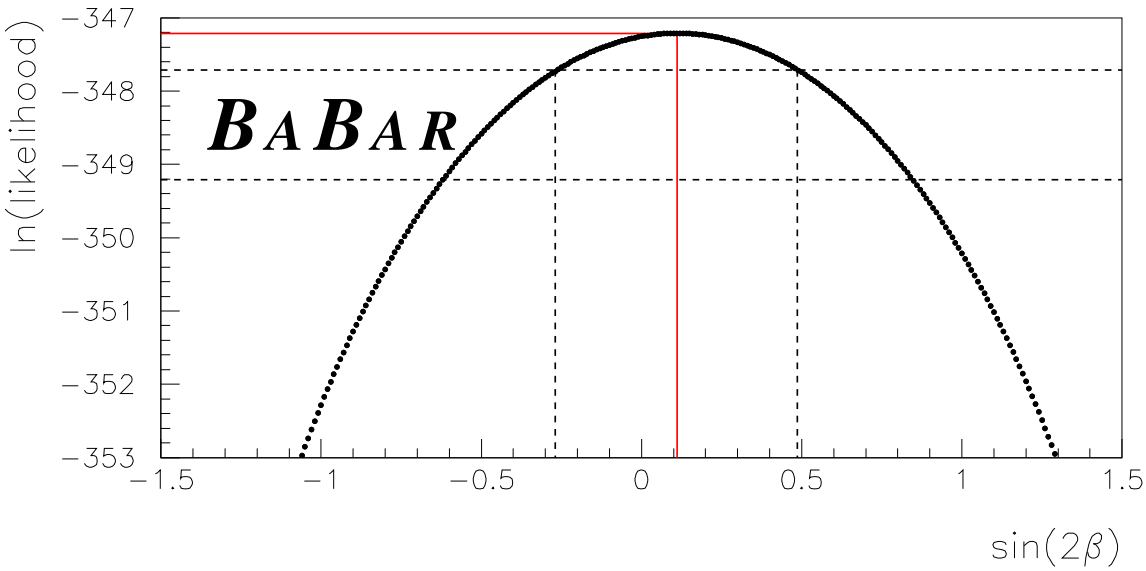

Figure 3: Variation of the log likelihood as a function of sin2β. The two horizontal dashed lines indicate changes in the log-likelihood corresponding to one and two statistical standard deviations.

$$\sin 2\beta = 0.12 \pm 0.37\,(stat) \pm 0.09\,(syst)\ (preliminary). \tag{3}$$

The log likelihood is shown as a function of sin2β in figure 3. The raw asymmetry as a function of Δt is shown in figure 4

The probability of obtaining a statistical uncertainty of 0.37 is estimated by generating a large number of toy Monte Carlo experiments with the same number of tagged *CP* events as in the data sample. The errors are distributed around 0.32 with a standard deviation of 0.03, meaning that the probability of obtaining a larger statistical error that the one observed is 5%. From a large number of full Monte Carlo simulated experiments, we estimate that the probability of finding a lower value of the likelihood than the one observed is 20%.

Several cross-checks are performed to validate the main analysis. The charmonium and fully-reconstructed hadronic control samples are composed of events that should exhibit no time-dependent asymmetry. These events are fitted in the same way as the signal *CP* events to extract an "apparent *CP* asymmetry". The results are shown in table 4.

2.7 Constraints on the Unitarity Triangle

The Unitarity Triangle in the $(\overline{\rho}, \overline{\eta})$ plane is shown in figure 5. The two solutions corresponding to the measured central value are shown as straight lines. The cross-hatched

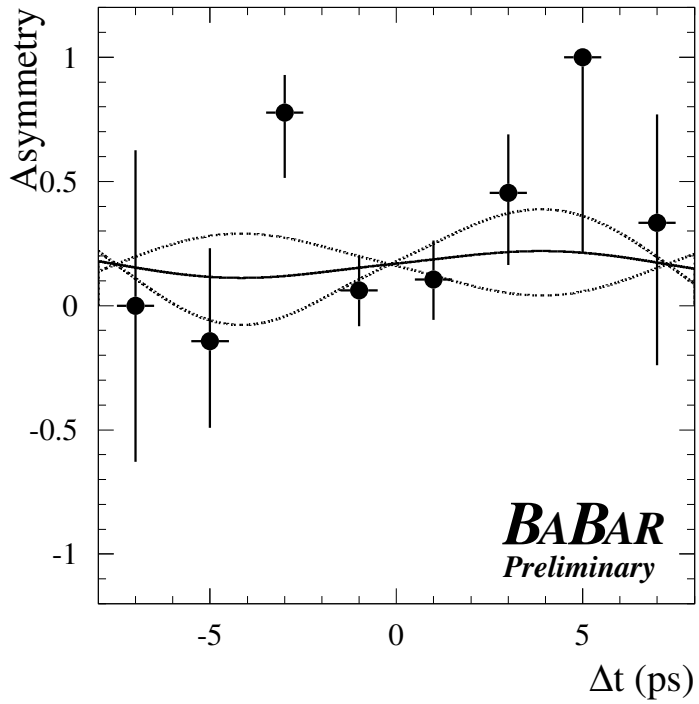

Figure 4: The raw $B^0 - \overline{B}^0$ asymmetry $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$. The time-dependent asymmetry is represented by a solid curve for the central value of $\sin 2\beta$, and by two dotted curves for the values at plus and minus one statistical standard deviation from the central value. The curves are not centered at (0,0) because the CP sample contains an unequal number of B^0 and $\overline{B}^0$ events (70 B^0 versus 50 $\overline{B}^0$). The χ^2 between the binned asymmetry and the result of the maximum likelihood fit is 9.2 for 7 degrees of freedom.

Sample	Apparent CP asymmetry
Hadronic charged B decays	0.03 ± 0.07
Hadronic neutral B decays	-0.01 ± 0.08
$J/\psi K^+$	0.13 ± 0.14
$J/\psi K^{*0}(K^{*0} \to K^+\pi^-)$	0.49 ± 0.26

Table 4: Summary of systematic uncertainties. The different contributions are added in quadrature.

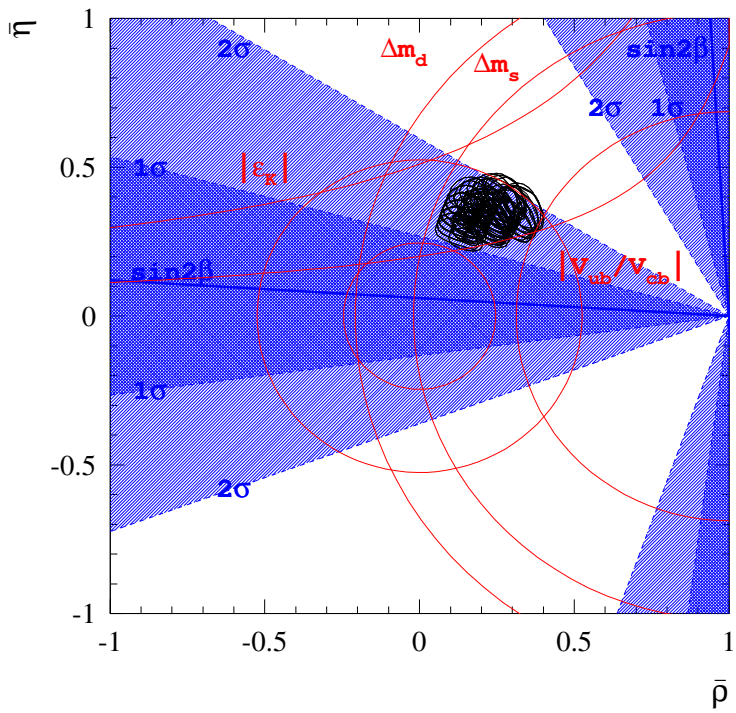

Figure 5: Present constraints on the position of the apex of the Unitarity Triangle with the *BABAR* result indicated by the cross-hatched regions.

regions correspond to one and two times the one-standard-deviation experimental uncertainty. The ellipses represent regions allowed by all other measurements that constrain the triangle. They are shown for a variety of choices of theoretical parameters. More details can be found in [5].

3 Future prospects

The preceding pages describe only a preliminary measurement of sin2β by the *BABAR* experiment. More data will allow extra channels to be included in the final fit as well as providing more events for the currently used decay modes. The new channels will bring extra experimental and theoretical challenges with them. Such present and future issues are discussed in the sections that follow.

3.1 Available Modes

The B decay modes that have been used to measure sin2β up to now are clean in that they are vector-scalar, $b \to ccs$ transitions which have no significant pollution from penguin diagrams. The next step is to add vector-vector modes such as $B^0 \to J/\psi K^*$. These modes

require an angular analysis of the vector meson decay products, due to the different partial waves and therefore admixture of *CP* odd and *CP* even that is present in the final state. Such an angular analysis has already yielded preliminary results for the $J/\psi K^*$ modes. Once one has measured the polarizations in these modes, they are as clean, theoretically, as the vector-scalar modes. Another obvious addition is $B^0 \to J/\psi K_L$ decays where the challenge here is to understand the background well enough to make the channel feasible. Work is ongoing in this area.

A different kind of difficulty is presented by channels with a significant degree of penguin contamination, such as $b \to ccd$ scalar-scalar modes (e.g. $B^0 \to D^+D^-$). Here the fit must take into account the fact that the true value of $\sin 2\beta$ is shifted by an amount proportional to the ratio of tree to penguin contributions. This ratio is model dependent and subject to large theoretical uncertainties.

Finally, modes such as $B^0 \to D^*D^*$ and $B \to J/\psi\rho^0$ which are vector-vector, $b \to ccd$ transitions face the theoretical challenges of the penguin contaminated modes described above, as well as requiring an angular analysis to solve the vector-vector *CP* admixture problem.

3.2 Experimental Considerations

There are also experimental analysis issues which need to be resolved or studied in greater depth in the future. The tagging algorithms that *BABAR* uses should be developed and extended to include extra tagging categories such as the using the soft pion from D^* decays and incorporating leptons at an intermediate momentum (i.e. from a cascade). It would be useful to take account of correlations within an event, such as when two different tagging categories report an answer. This can give more information about the event if the correlations are well understood. There is also an open question when it comes to measuring the tagging performance from the hadronic or semileptonic B decay samples. One then needs to be absolutely sure that using exactly the same numbers for the *CP* signal event sample is a valid thing to do.

The measurement of Δz is another crucial part of the analysis and it is important that the errors and biases to this distribution are understood. The distribution tends to be biased by the decays of particles which fly significantly from the original B decay vertex, such as D^0s. These can be rejected by looking explicitly for cascade decays. The parameterization of the resolution function incorporates detector effects such as misalignments and electronics readout effects. All contributions to the width should be studied in order to fully understand the error on Δz.

Backgrounds to the various *CP* modes can also be a problem. The channels vary in terms of how much background they experience and this background can be particularly dangerous if it has a significant structure in Δz. For charmonium channels, much of the background comes from events containing a real J/ψ. In that case, one needs to study exactly which modes contribute and what their shape is in the final distributions (if they cannot be removed otherwise). Non-resonant backgrounds to vector-vector modes such as the $J/\psi K^0\pi^0$ contribution to $J/\psi K^{*0}(K^{*0} \to K^0\pi^0)$ are in principle dangerous since they

can have *CP* violating properties but no angular structure. However, the branching ratios for these non-resonant modes are typically poorly known and consistent with zero making it difficult to simulate them in the correct proportions.

3.3 Study of Statistical Error

It seems anomalous that both *BABAR* and Belle record higher statistical errors than one would expect. The fitting procedure is, and continues to be a vigorously studied part of the analysis as we need to be certain that the likelihood function is of exactly the correct form for the final fit.

4 Conclusions

A preliminary measurement of $\sin 2\beta$ by *BABAR* has been presented. The errors on the final result make it difficult to express its significance in terms of constraints on the Unitarity Triangle. However, results based on a much larger data sample ($\sim$20 fb^{-1}) will soon be available. Combined with a better understanding of systematic effects, this should make the next measurement of $\sin 2\beta$ even more interesting than the current one. It is also expected that other *CP* modes will soon be available for analysis including $B^0 \to J/\psi K^{*0}(K^{*0} \to K_S\pi^0)$ and $B^0 \to J/\psi K_L$. The larger data sample with additional *CP* modes should yield a value of $\sin 2\beta$ for which the statistical and systematic errors are about one-half of their current values.

References

[1] M. Verderi [BABAR Collaboration], hep-ex/0010076.

[2] D. G. Hitlin [BABAR Collaboration], in hep-ex/0011024.

[3] B. Aubert *et al.* [BABAR Collaboration], decays," hep-ex/0008052.

[4] B. Aubert *et al.* [BABAR Collaboration], hep-ex/0008060.

[5] P. F. Harrison and H. R. Quinn [BABAR Collaboration], SLAC-R-0504 (section 14 and references therein) *Papers from Workshop on Physics at an Asymmetric B Factory (BaBar Collaboration Meeting), Rome, Italy, 11-14 Nov 1996, Princeton, NJ, 17-20 Mar 1997, Orsay, France, 16-19 Jun 1997 and Pasadena, CA, 22-24 Sep 1997.*