SLAC-PUB-8780
BABAR-PROC-00/32
hep-ex/0103036
February, 2001

Studies of CP Violation at *BABAR*

Anders Ryd [1]
California Institute of Technology, 356-48, Pasadena CA 91125
(for the *BABAR* Collaboration)

Abstract

BABAR has studied the time dependent asymmetries in the the decays $B^0 \to J/\psi K^0_S$ and $B^0 \to \psi(2S)K^0_S$ in a data set of 9.0 fb^{-1} taken at the $\Upsilon(4S)$ resonance. In these channels we reconstruct 168 events of which 120 are flavor tagged and used in a likelihood fit where we determine $\sin 2\beta$. The flavor of the other neutral B mesons is tagged using information primarily from identified leptons and Kaons. A neural network is used to recover events without any clear Kaon or lepton signature. A preliminary result of $\sin 2\beta = 0.12 \pm 0.37 \pm 0.09$ is obtained.

Contributed to the Proceedings of the
7^{th} International Conference on B-Physics at Hadron Machines,
9/13/2000—9/18/2000, Sea of Galilee, Isreal

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

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

[1] ryd@hep.caltech.edu

1 Introduction

One of the main goals of the BABAR experiment is to study CP Violation in neutral B-mesons. The neutral B meson system is similar to the neutral Kaon system in that we have two flavor eigenstates that mix. However, the phenomenology is rather different. In the Kaon system the physics is driven by a large difference in the decay widths, such that there are two states, the K_L^0 and the K_S^0, that have substantially different lifetimes. In the B_d system the widths of the two states are very similar and instead the physics is dominated by the mass difference, Δm_{B_d}, which controls the oscillation frequency of the $B^0\bar{B}^0$ system.

In the Standard Model, CP Violation arises from complex phases in the CKM matrix. By studying the interference between decays of B mesons that decays directly to a common final state and those that mix before they decay, we can study the phases of the CKM triangle[1].

Unitarity of the CKM matrix allows the construction of unitarity triangles. Applying the unitarity constraint between the first and third generation gives the least degenerate triangle. The angles of this unitarity triangle are probed in CP Violation in B decays. Figure 1 shows the normalized CKM triangle, the studies of CP Violation in $B \to J/\psi K_S^0$ allow us to determine $\sin 2\beta$.

The decays of primary interest in this presentation are $B^0 \to J/\psi K_S^0$ and the very similar $B^0 \to \psi(2S)K_S^0$. These decays have been dubbed the golden modes for measuring $\sin 2\beta$. These modes are experimentally fairly straight forward to construct, and have branching fractions that allow us to collect samples of events that are sufficiently large to study the time dependent asymmetry. But foremost, they are the golden modes due to the very small theoretical uncertainties as there are no penguin contributions with different weak phases.

The time dependent rate for $B \to J/\psi K_S^0$ is given by

$$f_{\pm}(\Delta t; \Gamma, \Delta m_{B_d}, \sin 2\beta) = \frac{1}{4}\Gamma e^{-\Gamma|\Delta t|}[1 \pm \sin 2\beta \times \sin \Delta m_{B_d}\Delta t], \tag{1}$$

where $+(-)$ indicates that the $B_{\rm tag}$, the other B from the $\Upsilon(4S)$ decay, was tagged as a B^0 ($\bar{B}^0$). To experimentally fit the time distribution we need to account for two effects; finite resolution in the Δt determination and the possibility that the wrong tag was assigned to $B_{\rm tag}$. The time resolution is handled by convoluting Eq. 1 with a resolution function, $\mathcal{R}(\Delta t; \hat{a})$. The fraction of mistags, w, dilutes the $\sin 2\beta$ measurement by $\mathcal{D} = 1 - 2w$. Experimentally we will perform a fit to

$$\mathcal{F}_{\pm}(\Delta t; \Gamma, \Delta m_{B_d}, \mathcal{D}\sin 2\beta, \hat{a}) = f_{\pm}(\Delta t; \Gamma, \Delta m_{B_d}, \mathcal{D}\sin 2\beta) \otimes \mathcal{R}(\Delta t; \hat{a}). \tag{2}$$

The time dependent CP asymmetry for the $B^0 \to J/\psi K_S^0$ and $B^0 \to \psi(2S)K_S^0$ decays is given by

$$a_{CP}(\Delta t) = \frac{N_{B^0}(\Delta t) - N_{\bar{B}^0}(\Delta t)}{N_{B^0}(\Delta t) + N_{\bar{B}^0}(\Delta t)} = \mathcal{D}\sin 2\beta \sin(\Delta m_{B_d}\Delta t), \tag{3}$$

where N_{B^0} ($N_{\bar{B}^0}$) is the number of events where $B_{\rm tag}$ was assigned a B^0 ($\bar{B}^0$) tag. In these expressions $\Delta t = t_{CP} - t_{\rm tag}$ refers to the time difference between the decay of B_{CP} and B_{tag}. At the $\Upsilon(4S)$ where the two B mesons are produced in a coherent state, the flavor of the B decaying to the CP eigenstate is determined by studying the flavor of the other B, as the two

B mesons are in a coherent P-wave state we know that the flavor of B_{CP} is of the opposite flavor of the $B_{\rm tag}$ at the time of the $B_{\rm tag}$ decay. Hence, Δt is the time B_{CP} evolved from when we knew its flavor. Further, at PEP-II the collisions are asymmetric, this allows us to measure the difference between the decay times of the two B mesons by simply measuring the separation in z of the two B decays, $\Delta t \approx \Delta z / c\langle\beta\gamma\rangle$.

The major steps in performing this analysis are

- Reconstruct the CP eigenstates.
- Measure the vertex resolution, $\mathcal{R}(\Delta t; \hat{a})$.
- Determine vertex separation, which gives Δt
- Tag the flavor of the other B, $B_{\rm tag}$.
- Measure the wrong tag fraction, w.
- Perform likelihood fit to the Δt distribution to determine $\sin 2\beta$.

As far as possible we try to determine the resolution function parameters and wrong tag fractions from data.

2 The BABAR experiment

The BABAR experiment is located at the PEP-II storage ring at SLAC. PEP-II collides electrons and positrons with energies of about 9.0 GeV/c^2 and 3.1 GeV/c^2 respectively at the center of mass energy of the $\Upsilon(4S)$ resonance. The produced $\Upsilon(4S)$ mesons have a boost of about $\beta\gamma = 0.56$. Since the first recorded collisions with the BABAR experiment on May 26, 1999, PEP-II has produced excellent luminosity that have allowed BABAR to collect the worlds largest sample of B mesons at the $\Upsilon(4S)$. The analysis presented here is based on 9.0 fb^{-1} recorded on the resonance and 0.8 fb^{-1} taken about 40 MeV/c^2 below the resonance. This corresponds to about 10.5×10^6 produced $B\bar{B}$ pairs. (The 2000 run of BABAR ended on October 30, 2000, and the total recoded luminosity in 2000 was 23 fb^{-1}.)

The BABAR experiment is described in detail elsewhere [2]. Here just a few key points of particular relevance to the measurement presented will be discussed.

One of the key features of this experiment is that the produced B mesons have a boost of about $\beta\gamma = 0.56$, and that the time difference between the B decays is measured by the separation in z position of the B decay vertices. The typical vertex separation between two B meson decays is 250 μm. The BABAR experiment has a 5 layered, double sided, silicon micro strip vertex detector capable of stand-alone tracking for low momentum particles, $p_T < 120$ MeV/c, not detected in the drift chamber. Figure 2 shows the measured track impact parameter resolution in z as a function of momentum. At higher momenta, where multiple scattering is negligible, the resolution is about 40 μm. For an exclusively reconstructed B the vertex resolution in z is typically about 40-60 μm.

Another unique feature of the BABAR experiment is the charged hadron identification system, the DIRC, Detection of Internally Reflected Cherenkov light. The DIRC detects Cherenkov photons that are produced in quartz bars and reflected out to a water tank instrumented with photo multipliers, see Figure 3. The DIRC has proved to work very well, we have achieved better than 3σ $K-\pi$ separation at momenta of 3 GeV/c. Further improvements are possible with a better understanding of the alignment of the DIRC with respect to the tracking system.

Overall the BABAR experiment has performed very well, important for our ability to record data is our efficiency, typically BABAR is live 97% of the time when PEP delivers luminosity. Losses are due to background spikes that cause trips, ramp-up of voltages, and sporadic outages, e.g., of computing resources. After the data is recorded, it is typically reconstructed within 24 hours.

2.1 Reconstruction of event samples

The CP sample consists of events reconstructed in the following modes

$$\begin{array}{ll} B^0 \to J/\psi K^0_S & (K^0_S \to \pi^+\pi^-), \\ B^0 \to J/\psi K^0_S & (K^0_S \to \pi^0\pi^0), \\ B^0 \to \psi(2S) K^0_S & (K^0_S \to \pi^+\pi^-), \end{array}$$

where the J/ψ and the $\psi(2S)$ are reconstructed in both the e^+e^- and $\mu^+\mu^-$ channels, the $\psi(2S)$ is also reconstructed in the $J/\psi\pi^+\pi^-$ channel. In the e^+e^- decays, bremsstrahlung photon recovery is attempted. For more details about the event reconstruction see Ref. [3]. We obtain a total of 168 events in these modes, as shown in Figures 4-6. The yields and purities are summarized in Table 1.

To measure the performance of the tagging, and in particular to determine the wrong tag fraction, a sample of exclusively reconstructed B mesons is used. The modes used and the yields are summarized in Table 2. The reconstruction of these samples are detailed in Ref. [5] and [6].

2.2 Vertex separation

For events where one exclusively reconstructed B meson has been found, the vertex of the other B decay is determined by trying to combine all other tracks in the event. Candidate tracks that form a good separate vertex, e.g., a K^0_S, are combined to form a neutral candidate, which is used instead of the daughter tracks in the vertex determination. Tracks are removed if they contribute more than 6 to the χ^2 of the vertex fit. Events are also rejected if $|\Delta z| > 3$ mm or if $\sigma_{\Delta z} > 400$ μm.

The time resolution function is parametrized as a sum of two Gaussians,

$$\mathcal{R}(\Delta t; \hat{a}) = \sum_{i=1}^{2} \frac{f_i}{\sigma_i \sqrt{2\pi}} \exp(-(\Delta t - \delta_i)^2 / 2\sigma_i^2). \tag{4}$$

The resolution parameters, σ_i, are taken as a scale factor, $\mathcal{S}_i$, times the calculated resolution based on the the tracking errors. The parameters for the second, wider, Gaussian is fixed

from Monte Carlo, the parameters for the first Gaussian is determined from the combined fit for mixing and the wrong tag fractions, see Section 2.3. We also allow for a wide term, f_w, with a resolution of 1.8 ps, and no bias, to handle outliers. The parameters of the resolution function are summarized in Table 5.

2.3 Flavor tagging

Each event with an exclusively reconstructed B^0 decay is assigned a tag as a B^0 or a $\bar{B}^0$ if the rest of the event satisfies the criteria for one of several tagging categories. These tagging categories are constructed such that each event will only belong to one category. The first category uses primary leptons to determine the flavor. If the event contains an identified lepton, electron or muon, with center of mass momentum greater than 1.1 GeV/c the event is tagged as a B^0 ($\bar{B}^0$) if the charge of the lepton is positive (negative). The second category uses charged particles identified as Kaons. If the sum of Kaons charges is positive (negative) the event is assigned a B^0 ($\bar{B}^0$) tag. If the lepton tags and Kaon tags disagree no tag is assigned in these categories. The last two categories, `NT1` and `NT2`, are assigned based on the output of a neural network. The neural network combines information about Kaons, leptons, soft pions and the stiffest track in the event to form an output that distinguishes between B^0 and $\bar{B}^0$ tags. The output from the neural network is shown in Figure 7. The two tagging categories are defined such that `NT1` corresponds to the events which has the best separation and `NT2` to the events that has slightly worse separation. The events, in the middle of Figure 7, which have very little separation are not used.

The figure of merit for each tagging category is the effective tagging efficiency, $Q_i = \epsilon_i(1-2w_i)^2 = \epsilon_i \mathcal{D}_i^2$, where ϵ_i is the fraction of events assigned to category i and w_i is the fraction that had the wrong tag assigned.

To determine the wrong tag fraction we use the sample of exclusively reconstructed hadronic B meson decays. These decays tag the flavor of the decaying B, so by performing a combined tagging and mixing analysis we can determine the wrong tag fraction for each category. For the events in each tagging category we perform a fit to

$$\mathcal{H}_{\pm}(\Delta t; \Gamma, \Delta m_{B_d}, \mathcal{D}, \hat{a}) = \frac{1}{4}\Gamma e^{-\Gamma|\Delta t|}[1 \pm \mathcal{D} \times \cos \Delta m_{B_d} \Delta t] \otimes \mathcal{R}(\Delta t; \hat{a}), \tag{5}$$

where $+$ are unmixed events and $-$ are mixed events. A log-likelihood is formed by

$$\ln \mathcal{L} = \sum_i [\sum_{\text{unmixed}} \ln \mathcal{H}_+(\Delta t; \Gamma, \Delta m_{B_d}, \mathcal{D}_i, \hat{a}) + \sum_{\text{mixed}} \ln \mathcal{H}_-(\Delta t; \Gamma, \Delta m_{B_d}, \mathcal{D}_i, \hat{a})] \tag{6}$$

where i runs over the tagging categories. Additional terms are added to the probability density functions to describe the contributions from backgrounds, details are given in [6].

The results of the fit are shown in Table 3. The total tagging efficiency is $76.7 \pm 0.5\%$ with an effective tagging efficiency, Q, of $27.9 \pm 0.5\%$ (statistical errors only).

When the tagging algorithm is applied to the sample of 168 CP events 120 events were assigned a flavor tag. Table 4 shows a break down per mode and per tagging category of the events in the CP sample. Of the 120 events tagged, 70 were B^0 and 50 were $\bar{B}^0$ tags.

2.4 Systematics

Systematic errors were considered from many different sources; input parameters to the likelihood fit, uncertainties in the time resolution function and wrong tag fractions. The B^0 lifetime was fixed to the PDG [4] value $\tau_{B^0} = 1.548$ ps, Δm_{B_d} was also fixed to the PDG value, $\Delta m_{B_d} = 0.472\ \hbar\text{ps}^{-1}$. Varying the values of these parameters give the uncertainties on $\sin 2\beta$ for τ_{B^0} and Δm_{B_d} of 0.002 and 0.015 respectively.

The time resolution function was determined in a high statistics sample of fully reconstructed B^0 events. We vary the parameters in the time resolution function by 1 statistical standard deviation and assign a systematic error on $\sin 2\beta$ of 0.019. To study the sensitivity on the bias in Δt, we allowed the bias of the second Gaussian to increase to 0.5 ps. This results in a change of 0.047 on $\sin 2\beta$ and is assigned as a systematic uncertainty. The sensitivity to this bias is due to the different number of events that are tagged as B^0 and $\bar{B}^0$.

The mistag fractions are determined from exclusively reconstructed B^0 and $\bar{B}^0$ mesons. Sources of systematic uncertainty come from the presence of backgrounds in these samples and possible differences between the tagging performance in the CP sample and the hadronic samples. The details about the accounting of backgrounds in the hadronic samples are given in Ref. [6]. The systematic uncertainty on $\sin 2\beta$ from the measured mistag fractions is estimated to be 0.053. A rather conservative systematic error of 0.050 on $\sin 2\beta$ is assigned for a possible difference between the tagging performance between the CP sample and the exclusive hadronic sample.

The CP sample is estimated to contain a background fraction of $(5 \pm 3)\%$. Backgrounds from, e.g., u, d, and s continuum events contributes primarily at small values of Δt and hence do not contribute much to the determination of $\sin 2\beta$. We estimate that the effective background is 3% and correct for the background by increasing the apparent asymmetry by 1.03. A fractional systematic error of 3% is assigned on the asymmetry to cover the uncertainty in the size of the background as well as any possible CP asymmetry in the background.

The systematic errors are summarized in Table 7, and a total systematic uncertainty of 0.09 on $\sin 2\beta$ is obtained.

2.5 Results

The analysis was carried out blind to eliminate any possible experimenters bias. The blinding technique hid both the result of the likelihood fit for $\sin 2\beta$, as well as the CP asymmetry in the Δt distribution. The error on the asymmetry was not hidden. The value of $\sin 2\beta$ was hidden by adding an arbitrary offset and flipping the sign. The CP asymmetry in the Δt distribution was hidden by adding an offset and, on an event by event basis, multiply Δt with the sign of the tag.

This allowed us to carry out many systematic studies while keeping the value of $\sin 2\beta$ hidden. In particular, the whole analysis procedure, including event selection, was fixed prior to unblinding the value of $\sin 2\beta$.

Using Eq. 2, we perform a likelihood fit to determine one single parameter, $\sin 2\beta$. The

mistag fractions, w_i, and the resolution function parameters, $\hat{a}$ are taken from Tables 3 and 5 respectively. We obtain

$$\sin 2\beta = 0.12 \pm 0.37 \pm 0.09. \tag{7}$$

Table 6 shows a breakdown of the fit for different modes and tagging categories. Figure 8 shows the Δt distributions for B^0 and $\bar{B}^0$ tagged events, the different yields of B^0 and $\bar{B}^0$ tags is apparent in this plot as well as in Figure 9, which shows the raw asymmetry.

To validate the analysis several cross checks have been made. In particular, we have used the charmonium non-CP samples such as $B^+ \to J/\psi K^+$ and the self tagging B^0 mode, $J/\psi K^{*0}$, $K^{*0} \to K^+\pi^-$, to establish that we do not observe any time dependent asymmetry in these modes. We also use the large samples of exclusively reconstructed charged and neutral B mesons in this check. Table 8 summarizes the fits for an apparent CP asymmetry in these modes. The result is consistent with no time dependent asymmetry in these modes.

Other important validation measurements are the lifetime and mixing measurements [5, 6], also discused in detail in Rainer Bartoldus contributions to this conference.

Figure 10 shows the constraints in the $\rho - \eta$ plane and the preliminary BABAR measurement of $\sin 2\beta$. The allowed area in the plot does not include any constraint from our measurement of $\sin 2\beta$.

3 Conclusion

BABAR has reported preliminary results based on a dataset of 9.0 fb^{-1} recorded at the $\Upsilon(4S)$ resonance from January to July in 2000. The analysis used the modes $B^0 \to J/\psi K^0_S$ and $B^0 \to \psi(2S)K^0_S$ and studied the time dependent asymmetry in events where the flavor of the other B meson was determined. The preliminary result

$$\sin 2\beta = 0.12 \pm 0.37 \pm 0.09 \tag{8}$$

was obtained. An analysis of the full 2000 dataset is now in progress, other modes, including $B^0 \to J/\psi K^0_L$, is to be included to further improve the precision of the measurement of $\sin 2\beta$. Data collected over the next few years should significantly improve the precision of this measurement. BABAR and PEP-II will start running again in February of 2001.

References

[1] P. H. Harrison and H. R. Quinn, eds., "The BABAR Physics Book", SLAC-R-504 (1998) and references therein.

[2] BABAR Collaboration, B. Aubert *et al.*, "The first year of the BABAR experiment at PEP-II", BABAR-CONF-00/17, submitted to the XXXth International Conference on High Energy Physics, Osaka, Japan.

[3] BABAR Collaboration, B. Aubert *et al.*, "Exclusive B decays to charmonium final states", BABAR-CONF-00/05, submitted to the XXXth International Conference on High Energy Physics, Osaka, Japan.

[4] Particle Data Group, D. E. Groom *et al.*, Eur. Phys. Jour. C **15**, 1 (2000)

[5] BABAR Collaboration, B. Aubert *et al.*, "A measurement of the charged and neutral B meson lifetimes using fully reconstructed decays", BABAR-CONF-00/07, submitted to the XXXth International Conference on High Energy Physics, Osaka, Japan.

[6] BABAR Collaboration, B. Aubert *et al.*, "A measurement of the $B^0\bar{B}^0$ oscillation frequency and determination of flavor-tagging efficiency using semileptonic and hadronic B decays", BABAR-CONF-00/08, submitted to the XXXth International Conference on High Energy Physics, Osaka, Japan.

Final state	Yield	Purity (%)
$J/\psi K_S$ ($K_S \to \pi^+\pi^-$)	121	96
$J/\psi K_S$ ($K_S \to \pi^0\pi^0$)	19	91
$\psi(2S)K_S$ ($K_S \to \pi^+\pi^-$)	28	93

Table 1: The yield of events in the different modes for the CP sample.

Final State	Yield	Purity (%)
$D^{*-}\pi^+$	622 ± 27	90
$D^{*-}\rho^+$	419 ± 25	84
$D^{*-}a_1^+$	239 ± 19	79
$D^-\pi^+$	630 ± 26	90
$D^-\rho^+$	315 ± 20	84
$D^-a_1^+$	225 ± 20	74
Total	2438 ± 57	85
$\bar{D}^0\pi^+$	1755 ± 47	88
$\bar{D}^{*0}\pi^+$	543 ± 27	89
Total	2293 ± 54	88
$D^{*-}\ell^+\nu$	7517 ± 104	84

Table 2: The yield of events in the different modes for B mesons reconstructed in hadronic and semileptonic modes.

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 3: The efficiency and wrong tag fractions in the different tagging categories as determined from the combined tagging and mixing fit to the hadronic and semileptonic event sample.

	$J/\psi K_S$						$\psi(2S)K_S$			CP sample		
	$(K_S \to \pi^+\pi^-)$			$(K_S \to \pi^0\pi^0)$			$(K_S \to \pi^+\pi^-)$			(tagged)		
	B^0	$\bar{B}^0$	all	B^0	$\bar{B}^0$	all	B^0	$\bar{B}^0$	all	B^0	$\bar{B}^0$	all
Electron	1	3	4	1	0	1	1	2	3	3	5	8
Muon	1	3	4	0	0	0	2	0	2	3	3	6
Kaon	29	18	47	2	2	4	5	7	12	36	27	63
NT1	9	2	11	1	0	1	2	0	2	12	2	14
NT2	10	9	19	3	3	6	3	1	4	16	13	29
Total	50	35	85	7	5	12	13	10	23	70	50	120

Table 4: The result of tagging applied to the CP sample and broken down by tagging category and mode.

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_2	(%)	25	fixed
δ_2	(ps)	0	fixed
$\mathcal{S}_2$		2.1	fixed

Table 5: The parameters of the resolution function as determined from the sample of fully reconstructed hadronic B^0 candidates.

sample	$\sin 2\beta$
CP sample	**0.12±0.37**
$J/\psi K_S$ ($K_S \to \pi^+\pi^-$) events	-0.10 ± 0.42
other CP events	0.87 ± 0.81
`Lepton`	1.6 ± 1.0
`Kaon`	0.14 ± 0.47
`NT1`	-0.59 ± 0.87
`NT2`	-0.96 ± 1.30

Table 6: The result of the fit for $\sin 2\beta$ broken down by event and tagging category.

Systematic Error	Uncertainty on $\sin 2\beta$
τ_B^0	0.002
Δm_d	0.015
Δz resolution	0.019
time resolution bias	0.047
measured mistag fraction	0.053
CP versus non-CP sample mistag fraction	0.050
B^0 versus $\bar{B}^0$ mistag fraction	0.005
background in CP sample	0.015
total systematic error	0.091

Table 7: Summary of sources of systematic errors in the determination of $\sin 2\beta$.

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 8: Results of fitting for apparent CP asymmetries in various charged or neutral flavor tagging B samples.

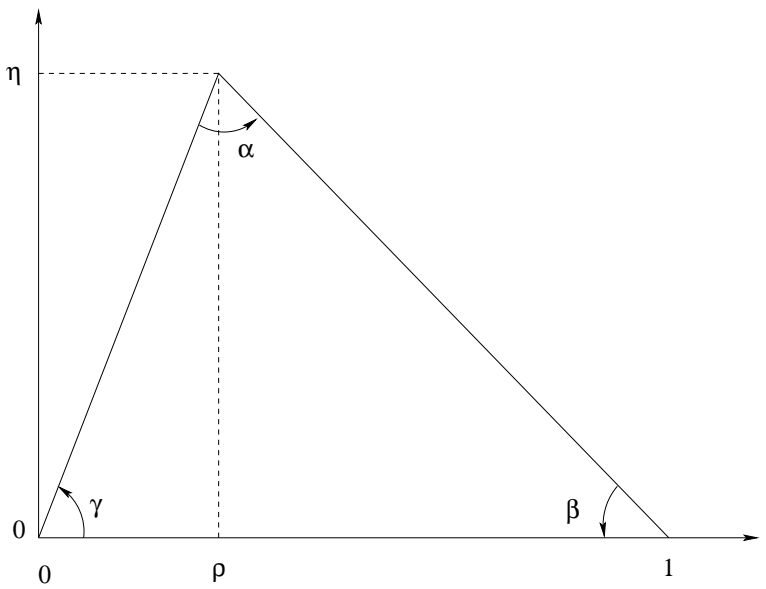

Figure 1: The CKM triangle formed by unitarity between the first and third generation. The study of time dependent asymmetry in $B^0 \to J/\psi K^0_S$ allows us to determine $\sin 2\beta$.

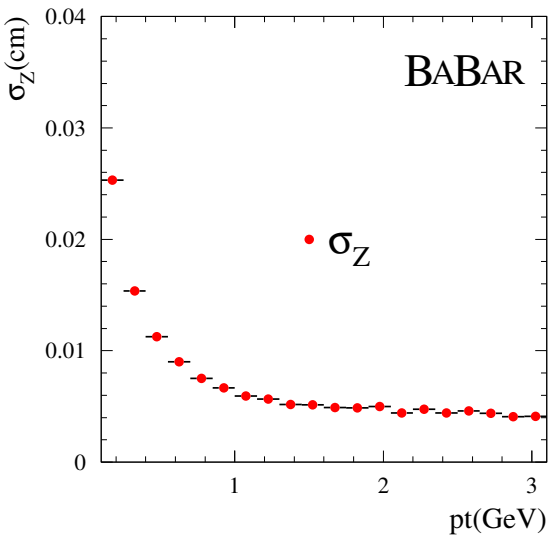

Figure 2: The impact parameter resolution in z for the silicon vertex tracker as measured by cosmic muons.

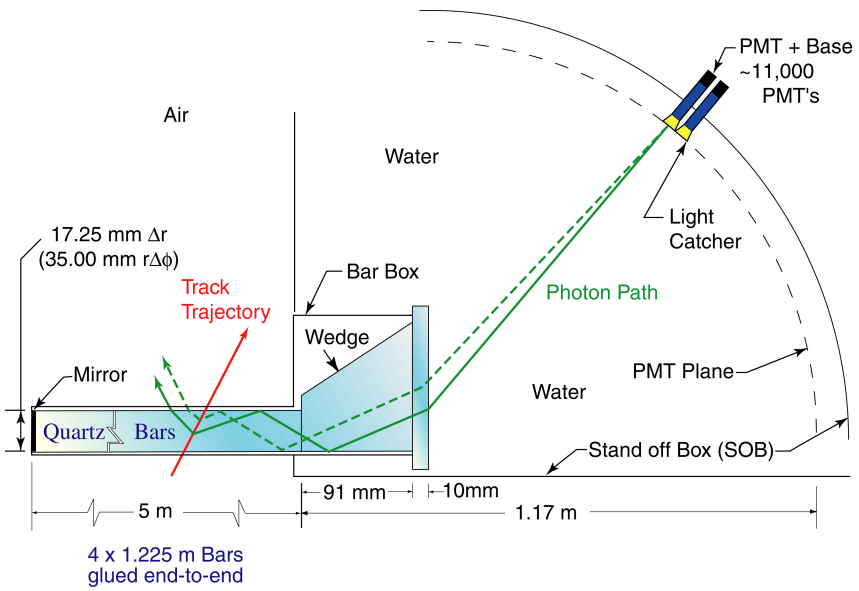

Figure 3: The principle of the DIRC; incident charged particles emits Cherenkov radiation as they pass through the quarts bars. The Cherenkov photons are reflected to the end of the quartz bar and out in a water tank, which is instrumented with photomultipliers to detect the light.

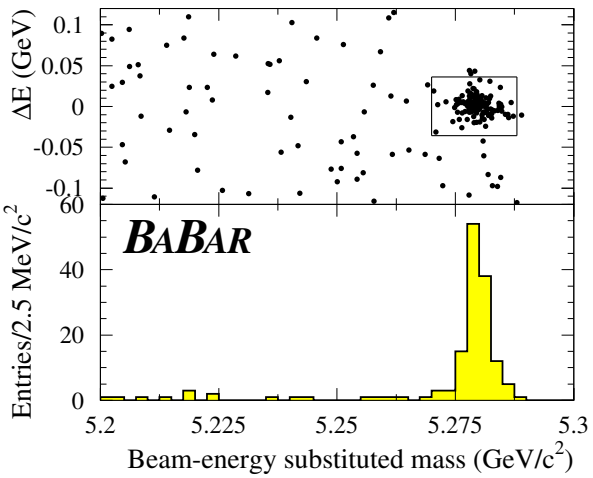

Figure 4: The signal in the $B^0 \to J/\psi K^0_S$, $K^0_S \to \pi^+\pi^-$ mode.

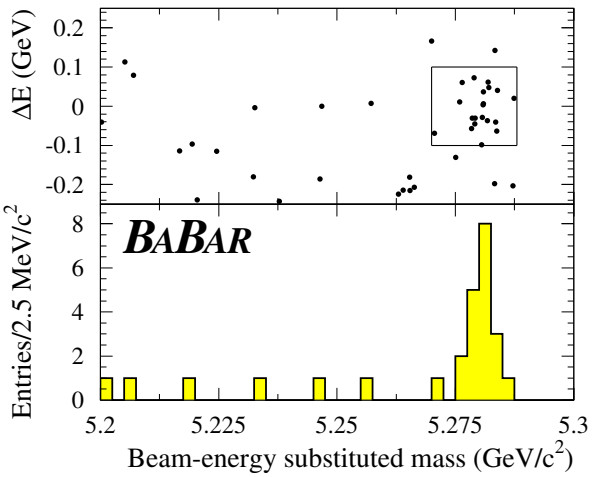

Figure 5: The signal in the $B^0 \to J/\psi K^0_S$, $K^0_S \to \pi^0\pi^0$ mode.

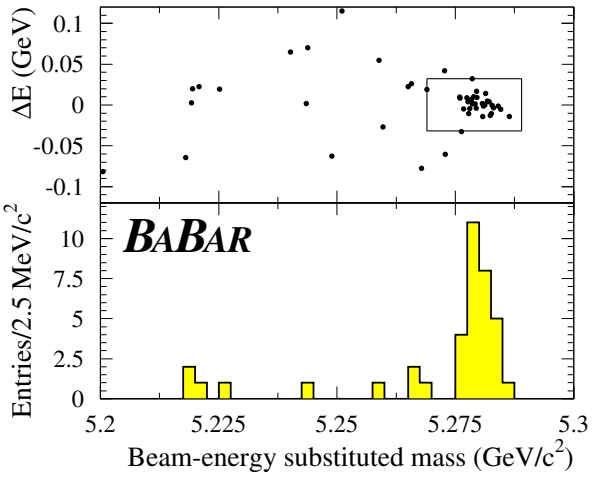

Figure 6: The signal in the $B^0 \to \psi(2S)K^0_S$, $K^0_S \to \pi^+\pi^-$ mode.

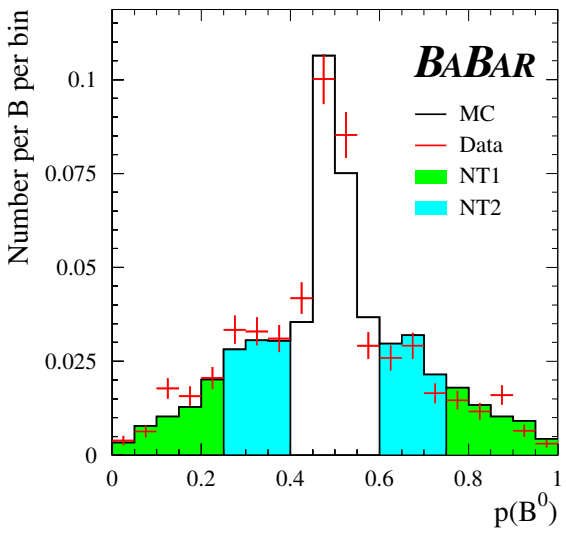

Figure 7: The output from the neural network for B flavor tagging. The data is shown as points with error bars and the histogram shows the Monte Carlo. Events close to 1 (0) are likely to be B^0 ($\bar{B}^0$) tags. Events near 0.5 provide no taging information and are not used.

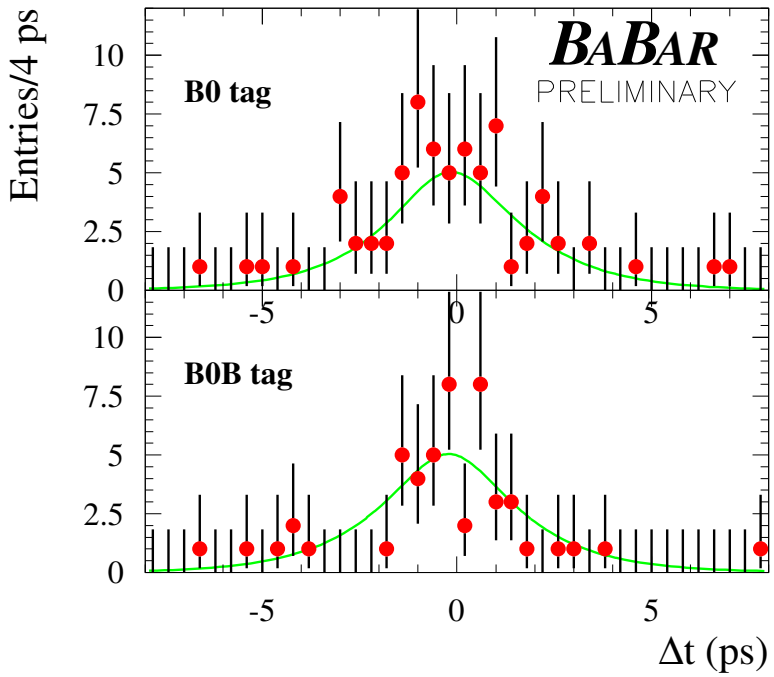

Figure 8: The Δt distributions for events in the CP sample tagged as B^0 and $\bar{B}^0$ respectively. The asymmetry in the number of B^0 and $\bar{B}^0$ tags are apparent in the plot. The shift to negative values of Δt is due to the small bias, about 0.2 ps, in the time resolution.

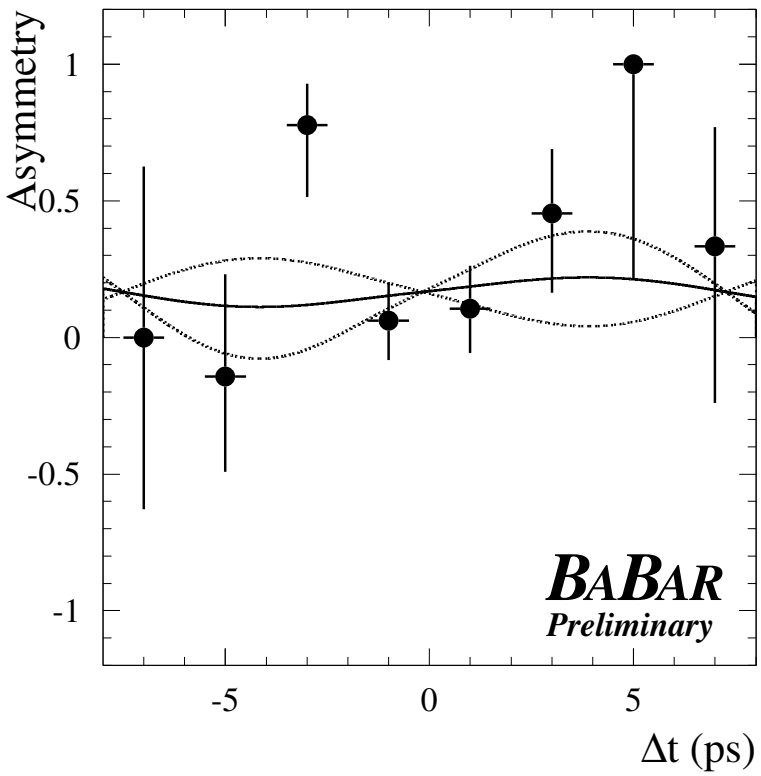

Figure 9: The raw $B^0 - \bar{B}^0$ asymmetry $(N_{B^0} - N_{\bar{B}^0})/(N_{B^0} + N_{\bar{B}^0})$, with binomial errors, as a function of Δt. The solid line is the asymmetry for our central value of $\sin 2\beta$. The dotted lines represents one statistical standard deviations from the central value.

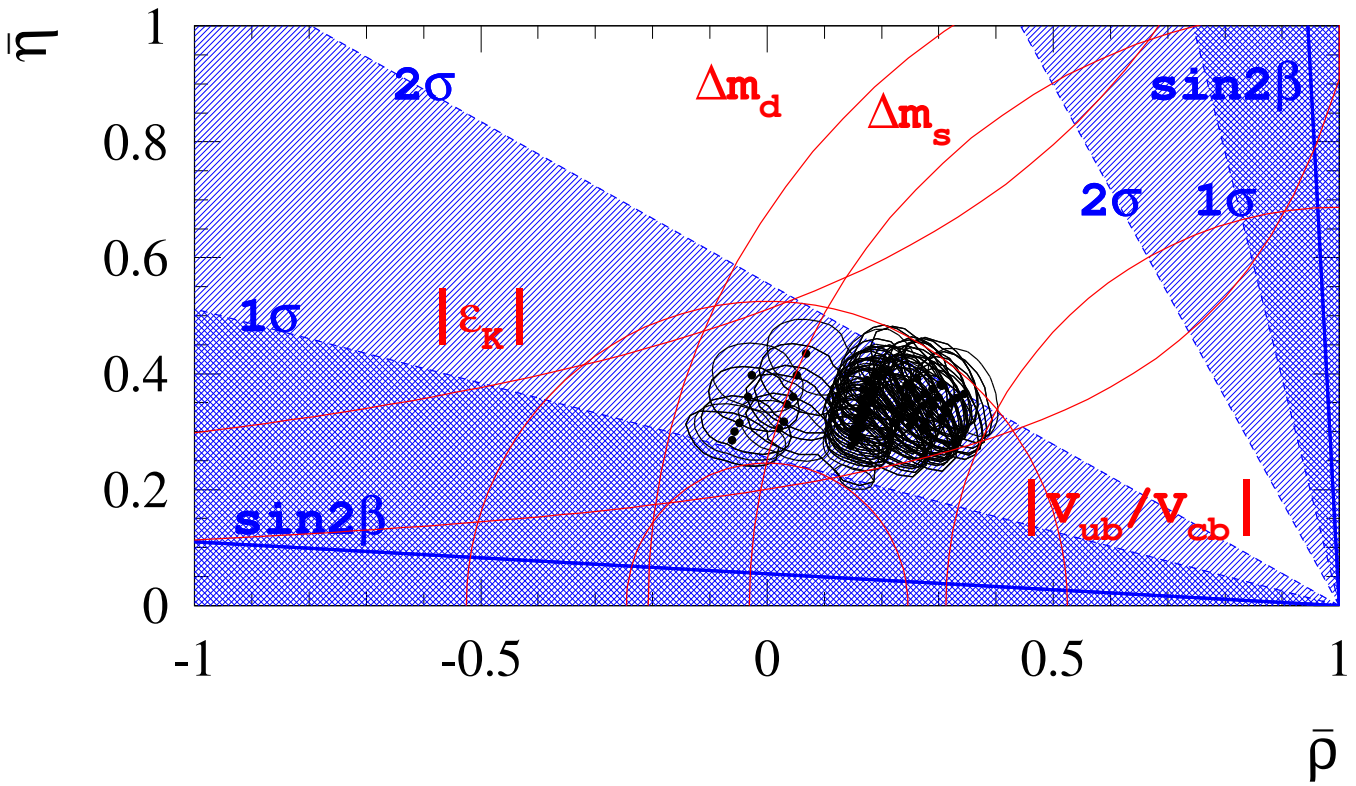

Figure 10: The constraints in the $\hat{\rho} - \hat{\eta}$ planes, and the result of our determination of $\sin 2\beta$ overlayed. The following measurements are used: $|V_{cb}| = 0.0402 \pm 0.017$, $|V_{ub}/V_{cb}| = \langle |V_{ub}/V_{cb}| \rangle \pm 0.0079$, $\Delta m_{B_d} = 0.472 \pm 0.017\,\hbar\mathrm{ps}^{-1}$ and $|\epsilon_K| = (2.271 \pm 0.017) \times 10^{-3}$, and for Δm_{B_s} the set of amplitudes corresponding to a 95%CL limit of $14.6\,\hbar\mathrm{ps}^{-1}$. We scan the model-dependent parameters $\langle |V_{ub}/V_{cb}| \rangle$, B_K, $f_{B_d}\sqrt{B_{B_d}}$ and ξ_s, in the range $[\,0.070,\, 0.100\,]$, $[\,0.720,\, 0.980\,]$, $[\,185,\, 255\,]$ MeV and $[\,1.07,\, 1.21\,]$, respectively. $\sin 2\beta = 0.12 \pm 0.37(\mathrm{stat})$ is represented by cross-hatched regions corresponding to one and two statistical standard deviations.