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First Physics Results at *BABAR*

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The *BABAR* detector, which operates at the SLAC PEP-II asymmetric e^+e^- collider at energies near the $\Upsilon(4S)$ resonance, started operation on the 26th of May 1999. We present the first study of $\sin 2\beta$, with samples of $B^0 \to J/\psi K^0_S$ and $B^0 \to \psi(2S)K^0_S$ decays, using $9.0\,\text{fb}^{-1}$ of data recorded between January and July 2000 at the $\Upsilon(4S)$ resonance and $0.8\,\text{fb}^{-1}$ recorded 40 MeV below the $\Upsilon(4S)$ resonance. A preliminary result of $\sin 2\beta = 0.12 \pm 0.37\,(\text{stat}) \pm 0.09\,(\text{syst})$ was obtained. Details of the analysis are given. Moreover, we present measurements of charged and neutral B meson lifetimes and $B^0\overline{B}^0$ oscillation frequency.

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1 Introduction

The primary goal of the *BABAR* experiment at PEP-II is to overconstrain the Unitarity Triangle. The sides of this triangle can be measured through non-*CP* violating physics, such as V_{ub}, V_{cb}, V_{td} measurements [1], while its angles are accessible through *CP* violating processes [1].

2 PEP-II

The PEP-II B Factory [2] is an e^+e^- colliding beam storage ring complex on the SLAC site designed to produce a luminosity of at least $3\text{x}10^{33}\,\text{cm}^{-2}\text{s}^{-1}$ at a center–of–mass energy of 10.58 GeV, the mass of the $\Upsilon(4S)$ resonance. In the 2000 run, the achieved average luminosity was $2.5\text{x}10^{33}\,\text{cm}^{-2}\text{s}^{-1}$, with a daily average integrated luminosity of $135\,\text{pb}^{-1}$. The total collected luminosity was about $22\,\text{fb}^{-1}$. The machine is asymmetric with a High Energy Ring (HER) for the 9.0 GeV electron beam and a Low Energy Ring (LER) for the 3.1 GeV positron beam. This corresponds to $\beta\gamma$=0.56 and makes it possible to measure time dependent *CP* violating asymmetries. It corresponds to an average separation of $\beta\gamma c\tau$=250 μm between the two B mesons vertices.

3 *BABAR*

3.1 Detector description [2]

The volume within the *BABAR* superconducting solenoid, which produces a 1.5 T axial magnetic field, consists of: a five layer silicon strip vertex detector (SVT), a central drift chamber (DCH), a quartz-bar Cherenkov radiation detector (DIRC) and a CsI crystal electromagnetic calorimeter (EMC). Two layers of cylindrical resistive plate counters (RPCs) are located between the barrel calorimeter and the magnet cryostat. All the detectors located inside the magnet have full acceptance in azimuth. The integrated flux return (IFR) outside the cryostat is composed of 18 layers of steel, which successively increase in thickness away from the interaction point, and are instrumented with 19 layers of planar RPCs in the barrel and 18 in the endcaps.

3.2 Event reconstruction [2]

Charged particles are detected and their momentum is measured by a combination of the DCH and SVT. The charged particle momentum resolution is approximately given by $(\delta p_T/p_T)^2 = (0.0015\,p_T)^2 + (0.005)^2$, where p_T is in GeV/c. The SVT, with a typical resolution of 10 μm per hit, provides excellent vertex resolution both in the transverse plane and in z. The vertex resolution in z is typically 50 μm for a fully reconstructed B meson and of order 100 μm for the distance among the two B mesons when only one is fully reconstructed. Leptons and hadrons are identified using a combination of measurements from all the *BABAR* components, including the energy loss $\text{d}E/\text{d}x$ in the helium-based gas of the DCH (40 samples maximum) and in the silicon of the SVT (5 samples maximum). Electrons and photons are identified in the barrel and the forward regions by the EMC, and muons are

identified in the IFR. In the barrel region the DIRC provides excellent kaon identification over the full momentum range above 250 MeV/c.

4 sin2β measurement

In e^+e^- storage rings operating at the $\Upsilon(4S)$ resonance a $B^0\overline{B}^0$ pair produced in a $\Upsilon(4S)$ decay evolves in a coherent P-wave until one of the B mesons decays. If one of the B mesons (B_{tag}) can be ascertained to decay to a state of known flavor at a certain time t_{tag}, the other B (B_{CP}) is *at that time* known to be of the opposite flavor. For the measurement of sin2β, B_{CP} is fully reconstructed in a CP eigenstate ($J/\psi\, K^0_S$ or $\psi(2S)K^0_S$). By measuring the proper time interval $\Delta t = t_{CP} - t_{tag}$ from the B_{tag} decay time to the decay of the B_{CP} (t_{CP}), it is possible to determine the time evolution of the initially pure B^0 or $\overline{B}^0$ state:

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

where the $+$ or $-$ sign indicates whether the B_{tag} is tagged as a B^0 or a $\overline{B}^0$, respectively. The dilution factor $\mathcal{D}$ is given by $\mathcal{D} = 1 - 2w$, where w is the mistag fraction, *i.e.*, the probability that the flavor of the tagging B is identified incorrectly. A direct CP violation term proportional to $\cos\Delta m_d\,\Delta t$ could arise from the interference between two decay mechanisms with different weak phases. In the Standard Model, we consider that the dominant diagrams for the decay modes have no relative weak phase, so no such term is expected.

To account for the finite resolution of the detector, the time-dependent distributions $f_\pm$ for B^0 and $\overline{B}^0$ tagged events (Eq. 1) must be convoluted with a time resolution function $\mathcal{R}(\Delta t;\hat{a})$:

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

where $\hat{a}$ represents the set of parameters that describe the resolution function.

It is possible to construct a CP-violating observable

$$\mathcal{A}_{CP}(\Delta t) = \frac{\mathcal{F}_+(\Delta t)\,-\,\mathcal{F}_-(\Delta t)}{\mathcal{F}_+(\Delta t)\,+\,\mathcal{F}_-(\Delta t)}\ , \tag{3}$$

which is approximately proportional to sin2β:

$$\mathcal{A}_{CP}(\Delta t) \sim \mathcal{D}\sin 2\beta\times\sin\Delta m_d\,\Delta t\ . \tag{4}$$

Since no time-integrated CP asymmetry effect is expected, an analysis of the time-dependent asymmetry is necessary. At an asymmetric-energy B Factory, the proper decay-time difference Δt is, to an excellent approximation, proportional to the distance Δz between the two B^0-decay vertices along the axis of the boost, $\Delta t \approx \Delta z/\mathrm{c}\,\langle\beta\gamma\rangle$.

Since the amplitude of the time-dependent CP-violating asymmetry in Eq. 4 involves the product of $\mathcal{D}$ and sin2β, one needs to determine the dilution factors $\mathcal{D}_i$ (or equivalently the mistag fractions w_i) in order to extract the value of sin2β. The mistag fractions are determined from the data by studying the time-dependent rate of $B^0\overline{B}^0$ oscillations.

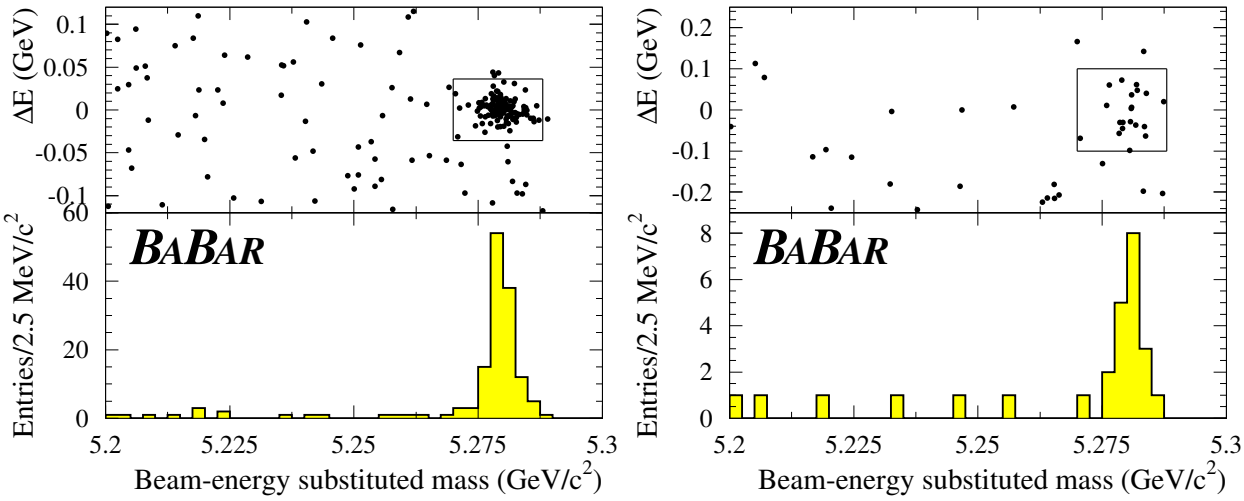

Figure 1: *$J/\psi K^0_S$ ($K^0_S \to \pi^+\pi^-$) signal (left). $J/\psi K^0_S$ ($K^0_S \to \pi^0\pi^0$) signal (right).*

The value of the single free parameter $\sin 2\beta$ is extracted from the tagged B_{CP} sample by maximizing the likelihood function

$$\ln \mathcal{L}_{CP} = \sum_i \left[\sum_{B^0\,\mathrm{tag}} \ln \mathcal{F}_+(\,\Delta t\,;\,\Gamma,\,\Delta m_d,\,\hat{a},\,\mathcal{D}_i \sin 2\beta\,) + \sum_{\overline{B}^0\,\mathrm{tag}} \ln \mathcal{F}_-(\,\Delta t\,;\,\Gamma,\,\Delta m_d,\,\hat{a},\,\mathcal{D}_i \sin 2\beta\,) \right] , \tag{5}$$

where the outer summation is over tagging categories i.

4.1 Analysis

For this analysis we use a sample of $9.8\,\mathrm{fb}^{-1}$ of data recorded between January and the beginning of July 2000, of which $0.8\,\mathrm{fb}^{-1}$ was recorded 40 MeV below the $\Upsilon(4S)$ resonance (off-resonance data).

The measurement of the *CP*-violating asymmetry has five main components :

- Selection of the signal $B^0/\overline{B}^0 \to J/\psi K^0_S$ and $B^0/\overline{B}^0 \to \psi(2S)K^0_S$ events, as described in detail in [3].

  Distributions of ΔE, the difference between the reconstructed and expected B meson energy measured in the center–of–mass frame, and m_{ES}, the beam–energy substitued mass, are shown in Fig. 1 for the $J/\psi K^0_S$ ($K^0_S \to \pi^+\pi^-$) and $J/\psi K^0_S$ ($K^0_S \to \pi^0\pi^0$) samples. Signal event yields and purities, determined from a fit to the m_{ES} distributions after selection on ΔE, are summarized in Table 1.

- Measurement of the distance Δz between the two B^0 decay vertices along the $\Upsilon(4S)$ boost axis, as described in detail in [4] and [5].

Table 1: Event yields for the different samples used in this analysis, from the fit to $m_{\rm ES}$ distributions after selection on ΔE. The purity is quoted for $m_{\rm ES} > 5.270\,{\rm MeV}/c^2$.

Final state	Yield	Purity (%)
$J/\psi K^0_S$ ($K^0_S \to \pi^+\pi^-$)	124±12	96
$J/\psi K^0_S$ ($K^0_S \to \pi^0\pi^0$)	18±4	91
$\psi(2S)K^0_S$	27±6	93

From the measurement of Δz , Δt can be computed.

The time resolution function is described accurately by the sum of two Gaussian distributions, which has five independent parameters:

$$\mathcal{R}(\,\Delta t;\,\hat{a}\,) \;=\; \sum_{i=1}^{2} \frac{f_i}{\sigma_i\sqrt{2\pi}} \exp\left(-(\Delta t-\delta_i)^2/2{\sigma_i}^2\right)\,. \tag{6}$$

A fit to the time resolution function in Monte Carlo simulated events indicates that most of the events ($f_1 = 1 - f_2 = 70\%$) are in the core Gaussian, which has a width $\sigma_1 \approx 0.6\,$ps. The wide Gaussian has a width $\sigma_2 \approx 1.8\,$ps. Tracks from forward-going charm decays included in the reconstruction of the B_{tag} vertex introduce a small bias, $\delta_1 \approx -0.2\,$ps, for the core Gaussian.

- Determination of the flavor of the B_{tag}, as described in detail in [4].

  Each event with a CP candidate is assigned a B^0 or $\overline{B}^0$ tag if the rest of the event (*i.e.*, with the daughter tracks of the B_{CP} removed) satisfies the criteria from one of several tagging categories. In other words, a B^0 tag indicates that the B_{CP} candidate was in a $\overline{B}^0$ state at $\Delta t = 0$; a $\overline{B}^0$ tag indicates that the B_{CP} candidate was in a B^0 state.

  Three tagging categories rely on the presence of a fast lepton (`Lepton` categories) and/or one or more charged kaons in the event (`Kaon` category). Two categories, called neural network categories (`NT1` and `NT2`), are based upon the output value of a neural network algorithm applied to events that have not already been assigned to lepton or kaon tagging categories.

- Measurement of the dilution factors $\mathcal{D}_i$ from the data for the different tagging categories, as described in detail in [4].

  The figure of merit for each tagging category is the effective tagging efficiency $Q_i = \varepsilon_i\,(1-2w_i)^2$, where ε_i is the fraction of events assigned to category i and w_i is the mistag fraction.

  The mistag fractions are measured directly in events in which one B^0 candidate, called the B_{rec}, is fully reconstructed in a flavor eigenstate mode. The flavor-tagging algorithms are applied to the rest of the event, which constitutes the potential B_{tag}, assuming the B_{rec} is properly tagged.

  The mistag fractions and the tagging efficiencies obtained by combining the results from maximum likelihood fits to the time distributions in the B^0 hadronic and semileptonic samples are summarized in Table 2.

Table 2: Mistag fractions measured from a maximum-likelihood fit to the time distribution for the fully-reconstructed B^0 sample. The `Electron` and `Muon` categories are grouped into one `Lepton` category. The uncertainties on ε and Q are statistical only.

Tagging Category	ε (%)	w (%)	Q (%)
`Lepton`	11.2 ± 0.5	$9.6 \pm 1.7 \pm 1.3$	7.3 ± 0.7
`Kaon`	36.7 ± 0.9	$19.7 \pm 1.3 \pm 1.1$	13.5 ± 1.2
`NT1`	11.7 ± 0.5	$16.7 \pm 2.2 \pm 2.0$	5.2 ± 0.7
`NT2`	16.6 ± 0.6	$33.1 \pm 2.1 \pm 2.1$	1.9 ± 0.5
all	76.7 ± 0.5		27.9 ± 1.6

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

Source of uncertainty	Uncertainty on $\sin 2\beta$
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**

- Extraction of the amplitude of the *CP* asymmetry and the value of $\sin 2\beta$ with an unbinned maximum likelihood fit.

  The maximum-likelihood fit for $\sin 2\beta$, using the full tagged sample of $B^0/\overline{B}^0 \to J/\psi K_S^0$ and $B^0/\overline{B}^0 \to \psi(2S)K_S^0$ events, gives:

$$\sin 2\beta = 0.12 \pm 0.37\,(\text{stat}) \pm 0.09\,(\text{syst}). \tag{7}$$

  For this result, the B^0 lifetime and Δm_d are fixed to the current best values [6]. The log likelihood is shown as a function of $\sin 2\beta$ and the Δt distributions for B^0 and $\overline{B}^0$ tags are shown in Fig. 2. The contributions to the systematic uncertainty are summarized in Table 3. They are added in quadrature to obtain the total systematic error.

  Improvements in the $\sin 2\beta$ measurement are expected in the near future with the accumulation and analysis of more data and further systematic studies.

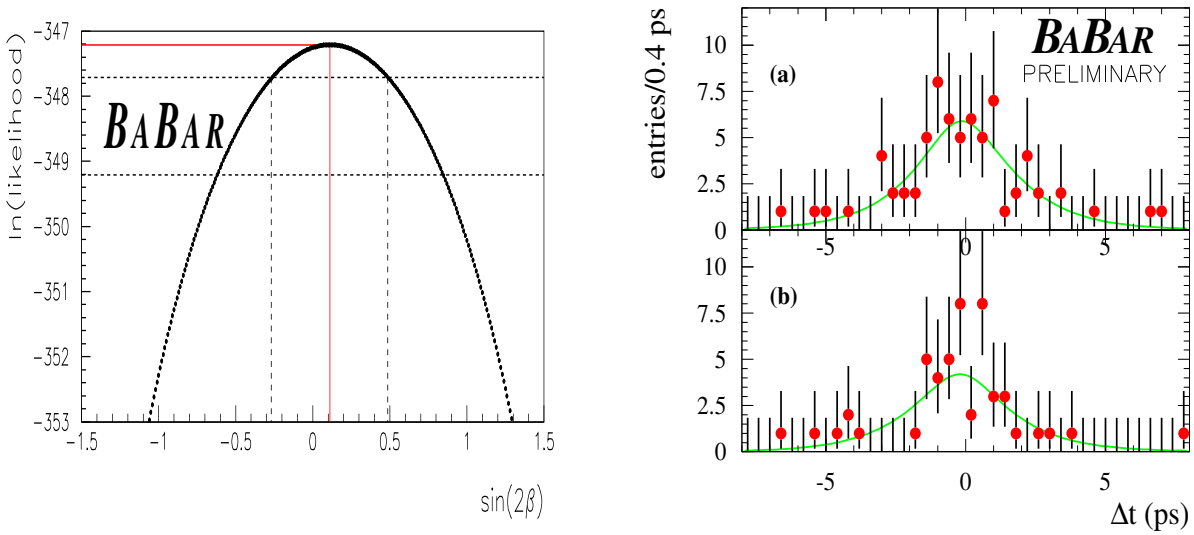

Figure 2: *Variation of the log likelihood as a function of* $\sin 2\beta$ *(left). The two horizont al dashed lines indicate changes in the log likelihood corresponding to one and two statistical standard deviations. Distribution of* Δt *for (a) the* B^0 *tagged events and (b) the* $\overline{B}^0$ *tagged events in the CP sample (right).*

5 Measurements of charged and neutral B meson lifetimes and $B^0\overline{B}^0$ oscillations

These measurements can be used to test theoretical models of heavy–quark decays and to constrain the Unitarity Triangle (via the sensitivity to the value of the CKM matrix element V_{td}).

One B (B_{rec}) is fully reconstructed in an all-hadronic ($B^0 \to D^{(*)-}\pi^+$, $D^{(*)-}\rho^+$, $D^{(*)-}a_1^+$, $J/\psi K^{*0}$ and $B^+ \to \overline{D}^{(*)0}\pi^+$, $J/\psi K^+$, $\psi(2S)K^+$) or semileptonic decay mode ($B^0 \to D^{*-}\ell^+\nu$) [1]. A total of about 2600 B^0 and a similar number of charged B are reconstructed in the hadronic modes, with a mean purity of $\sim 90\%$. The background is mainly combinatorial. About 7500 B^0 are reconstructed in the semileptonic modes, with a mean purity of $\sim 84\%$. Backgrounds to the semi-leptonic mode are due to combinatorics, wrong leptons, $c\bar{c}$ events, and charged B decays from $B^+ \to D^{**0}l^+\nu$.

The separation between the two B vertices (z_{rec} and z_{TAG} for the reconstructed and tagged vertex, respectively) along the boost direction, $\Delta z = z_{rec} - z_{tag}$, is measured and used to estimate the decay time difference, $\Delta t = \Delta z/\beta_z c$. The Δt resolution is dominated by the precision on the B_{tag} vertex, and has little dependence on the decay mode of the B_{rec}.

[1] Throughout this paper, conjugate modes are implied.

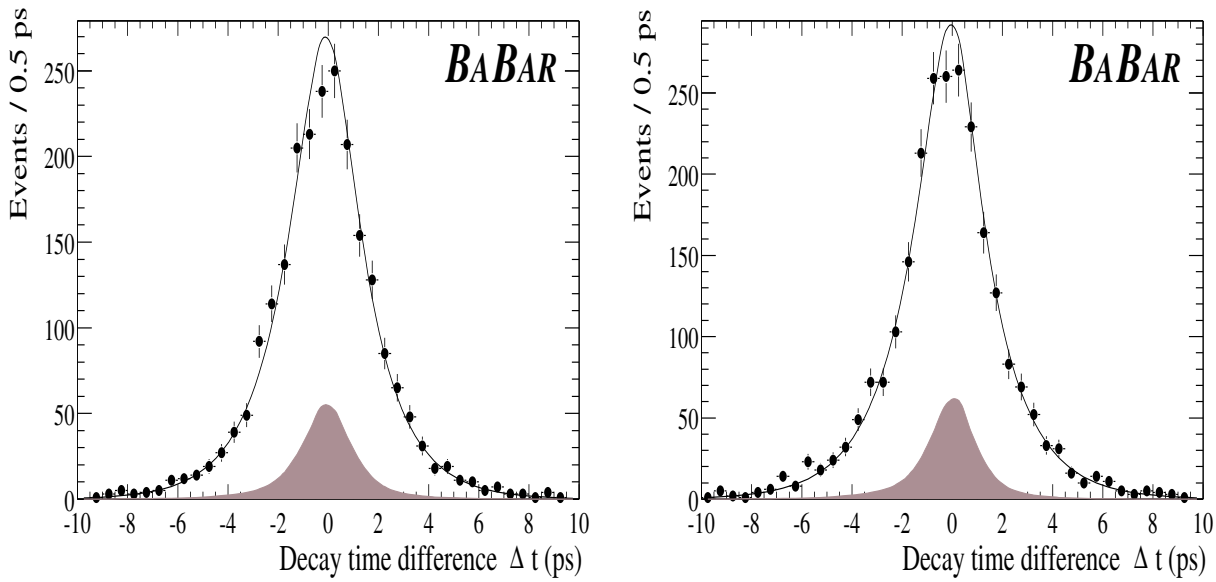

Figure 3: *Δt distributions for $B^0/\overline{B}^0$ (left) and B^+/B^- (right) candidates in the signal region ($m_{\rm ES}>$ 5.27 GeV/c^2). The result of the lifetime fit is superimposed. The background is shown by the hatched area.*

5.1 Lifetime Measurements

The B^0 and B^+ lifetimes are extracted from a simultaneous unbinned maximum likelihood fit to the Δt distributions of the signal candidates, assuming a common resolution function. Only hadronic modes have been used. An empirical description of the Δt background shape is assumed, using $m_{\rm ES}$ sidebands with independent parameters for neutral and charged mesons. Fig. 3 shows the Δt distributions with the fit result superimposed.

5.2 Time–dependent $B^0\overline{B}^0$ mixing

A time-dependent $B^0\overline{B}^0$ mixing measurement requires the determination of the flavor of both B mesons. Considering the $B^0\overline{B}^0$ system as a whole, one can classify the tagged events as *mixed* or *unmixed* depending on whether the B_{tag} is tagged with the same flavor as the B_{rec} or with the opposite flavor.

From the time-dependent rate of mixed (N_{mix}) and unmixed (N_{unmix}) events, the mixing asymmetry $a(\Delta t) = (N_{unmix} - N_{mix})/(N_{unmix} + N_{mix})$ is calculated as a function of Δt and fit to the expected cosine distribution. A simultaneous unbinned likelihood fit to the mixing asymmetry frequency and its amplitude allows the determination of both Δm_d and the mistag rates, w_i, for the different tagging categories. The fit is performed simultaneously in each tagging category, assuming a common resolution function. Fig. 4 shows the $a(\Delta t)$ distributions with the fit result superimposed.

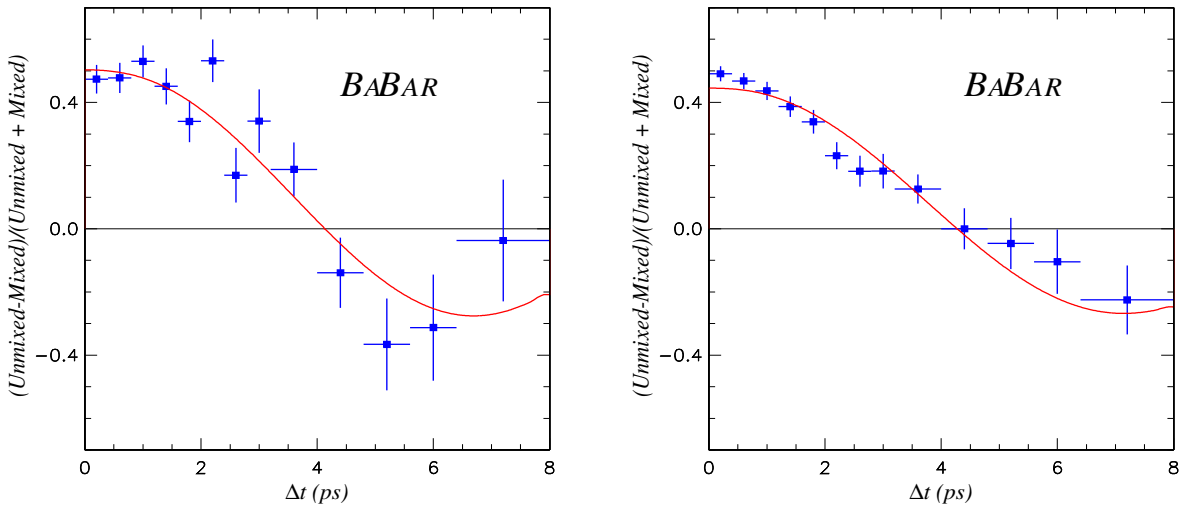

Figure 4: *Time-dependent asymmetry $a(\Delta t)$ between unmixed and mixed events for (left) hadronic B candidates with $m_{\rm ES} > 5.27\,{\rm GeV}/c^2$ and (right) for $B \to D^* \ell \nu$ candidates.*

5.3 Results

The preliminary results for the B meson lifetimes are $\tau_{B^0} = 1.506 \pm 0.052\,(\text{stat}) \pm 0.029\,(\text{syst})$ ps and $\tau_{B^+} = 1.602 \pm 0.049\,(\text{stat}) \pm 0.035\,(\text{syst})$ ps and for their ratio is $\tau_{B^+}/\tau_{B^0} = 1.065 \pm 0.044\,(\text{stat}) \pm 0.021\,(\text{syst})$.

From the hadronic B^0 sample we measure the $B^0\overline{B}^0$ oscillation frequency: $\Delta m_d = 0.516 \pm 0.031\,(\text{stat}) \pm 0.018(\text{syst})\ \hbar\text{ps}^{-1}$ and from the $D^{*-}\ell^+\nu$ sample the result is $\Delta m_d = 0.508 \pm 0.020\,(\text{stat}) \pm 0.022(\text{syst})\ \hbar\text{ps}^{-1}$ Combining the two Δm_d results, we obtain the preliminary result: $\Delta m_d = 0.512 \pm 0.017(\text{stat}) \pm 0.022(\text{syst})\ \hbar\text{ps}^{-1}$. The mistag rates and Δt resolution function extracted from these fits to the data are used in the *BABAR* *CP* violation asymmetry analysis [7]. The above results are consistent with previous measurements [6] and are of similar precision. The mixing result is compatible with a *BABAR* measurement using di–leptons [8].

6 Conclusions

We have presented *BABAR*'s first measurement of the *CP*-violating asymmetry parameter $\sin 2\beta$ in the B meson system:

$$\sin 2\beta = 0.12 \pm 0.37\,(\text{stat}) \pm 0.09\,(\text{syst}). \tag{8}$$

Our measurement is consistent with the world average $\sin 2\beta = 0.9 \pm 0.4$ [6], and is currently limited by the size of the *CP* sample.

We have presented also the time–dependent mixing and lifetime measurements, performed for the first time at the $\Upsilon(4S)$.

Other important competitive measurements have been achieved by *BABAR*.

All measurement are foreseen to be improved in the near future, with the accumulation and study of more data and further systematic studies.

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