SLAC-PUB-8532
BABAR-CONF-00/10
hep-ex/0008054
August, 2000

Measurement of the time dependence of $B^0\overline{B}^0$ oscillations using inclusive dilepton events

The *BABAR* Collaboration

Abstract

A preliminary study of time dependence of $B^0\overline{B}^0$ oscillations using dilepton events is presented. The flavor of the B meson is determined by the charge sign of the lepton. To separate signal leptons from cascade and fake leptons we have used a method which combines several discriminating variables in a neural network. The time evolution of the oscillations is studied by reconstructing the time difference between the decays of the B mesons produced by the Υ(4S) decay. With an integrated luminosity of 7.7 fb^{-1} collected on resonance by *BABAR* at the PEP-II asymmetric B Factory, we measure the difference in mass of the neutral B eigenstates, Δm_{B^0}, to be $(0.507 \pm 0.015 \pm 0.022) \times 10^{12}\,\hbar\,s^{-1}$.

Submitted to the 30th International Conference on High Energy Physics,
7/27/2000—8/2/2000, Osaka, Japan

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

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1 Introduction

A precision measurement of the $B^0\overline{B}^0$ oscillation frequency is of great importance since it is sensitive to the CKM matrix element $|V_{td}|$ and, in combination with knowledge of the $B_s\overline{B}_s$ oscillation frequency, provides a stringent constraint on the Unitarity Triangle.

The mass difference Δm_{B^0} between the two mass eigenstates of the $B^0\overline{B}^0$ system may be measured by comparing the rate for pairs of neutral B mesons to decay with the same b quark flavor with the rate to decay with the opposite flavor sign at the $\Upsilon(4S)$ in the following time dependent asymmetry:

$$\frac{N(B^0\overline{B}^0)(\Delta t) - (N(B^0B^0)(\Delta t) + N(\overline{B}^0\overline{B}^0)(\Delta t))}{N(B^0\overline{B}^0)(\Delta t) + (N(B^0B^0)(\Delta t) + N(\overline{B}^0\overline{B}^0)(\Delta t))} = \cos(\Delta m_{B^0} \cdot \Delta t), \tag{1}$$

where Δt is the difference between the two B meson decay times in the $\Upsilon(4S)$ center of mass system. The simplest way to determine the b quark flavor of the decaying neutral B is to use leptons as tagging particles. By counting the number of "like" events $(l^+, l^+) + (l^-, l^-)$ and "unlike" events (l^+, l^-), a measurement of Δm_{B^0} may be extracted through the asymmetry :

$$A_{obs}(|\Delta t|) = \frac{N(l^+, l^-) - (N(l^+, l^+) + N(l^-, l^-))}{N(l^+, l^-) + (N(l^+, l^+) + N(l^-, l^-))}. \tag{2}$$

The semileptonic (muon or electron) branching ratio of B mesons is about 20%. Therefore, the dilepton events useful for this analysis represent 4% of the Υ(4S) $\to B\overline{B}$ decays. In statistical terms, the dilepton tagging is more efficient than the semi-exclusive tagging performed at the ARGUS [1] and the CLEO [2] experiments. Moreover the new asymmetric B factories, like PEP-II, allow a time-dependent measurement, which is radically different from measurements of the time-integrated probability χ_d performed at the previous e^+e^- colliders operating at the $\Upsilon(4S)$, where $\chi_d = x_d^2/(2 \cdot (1 + x_d^2))$ and $x_d = \Delta m_{B^0}/\Gamma_{B^0}$. Previous measurements of the time-dependence of $B^0\overline{B}^0$ oscillations have been done by the LEP, SLD and CDF experiments [3].

The present measurement is performed on events collected by the *BABAR* detector at the PEP-II asymmetric B Factory between January and June 2000. The corresponding integrated luminosity is 7.7 fb^{-1} taken on the $\Upsilon(4S)$ resonance and 1.2 fb^{-1} taken 40 MeV below resonance. The *BABAR* detector and its performance are described elsewhere [4]. The event selection and particle identification criteria are described in section 2. The selection of signal events and a study of the fraction of events with the wrong flavor tagging (*mistag*) are detailed in Section 2.4. The method to determine the time-separation of the two B semileptonic decays is explained in Section 3. Section 4.2 shows the details of the fit on data and the result of the Δm_{B^0} measurement. A list of cross-checks of the result is in Section 5, while the evaluation of systematic uncertainties is reported in Section 6.

2 Selection of dilepton events

In this study of the oscillation frequency Δm_{B^0} , the flavor of the B meson at decay is determined by the sign of leptons produced in semileptonic B decays. To reduce the mistag rate, an attempt is made to suppress cascade leptons (produced in $b \to c \to \ell$ transitions).

2.1 Lepton identification

Electron and muon candidates are required to pass the *very tight* selection criteria fully described in [4]. Electrons are selected by specific requirements on the ratio of the energy deposited in the Electromagnetic Calorimeter (EMC) and the momentum measured in the Drift Chamber (DCH), on the lateral shape of the energy deposition in the calorimeter, and on the specific ionization density measured in the DCH. Muons are identified by the use of the energy released in the calorimeter, as well as the strip multiplicity, track continuity and penetration depth in the Instrumented Flux Return. The performance of the *very tight* selection criteria are estimated on data control samples, as a function of the particle momentum as well as the polar and azimuthal angles. The electron and muon selection efficiencies are about 92% and 75%, respectively, with pion misidentification probabilities around 0.3% and 3%, respectively. Lepton candidates consistent with the kaon hypothesis as measured in the Detector of Internally Reflected Cherenkov light (DIRC) are rejected. More than 60% of the kaon contamination in the muon sample is rejected with negligible effect on lepton identification efficiency.

2.2 Background rejection

Non $B\bar{B}$ events are suppressed by requiring the Fox-Wolfram ratio of second to zeroth order moments to be less than 0.4.

The residual contamination from radiative Bhabha and two-photon events is reduced by requiring the event squared invariant mass to be greater than 20 $(\mathrm{GeV}/c^2)^2$, the event aplanarity to be greater than 0.01, and the number of charged tracks to be greater than 4.

Electrons from gamma conversions are identified (see [4]) and rejected with a negligible loss of efficiency for signal events. Leptons from J/ψ decays are identified by pairing them with the other oppositely-charged candidates of the same lepton species, selected with looser criteria. We reject the whole event if any combination has an invariant mass within $40\,\mathrm{MeV}/c^2$ of the J/ψ mass.

2.3 Track quality requirements

We finally apply selection criteria on the quality of the tracks, in order to improve the Δz reconstruction, where Δz is the difference between the decay points of the two B mesons along the beam direction. Any lepton candidate must have a distance of closest approach to the nominal beam position in the transverse plane, d_0, less than 1 cm, and a distance of closest approach along the beam direction, $|z_0|$, less than 6 cm, at least 20 hits in the DCH, at least 4 z-coordinate hits in the Silicon Vertex Tracker, a momentum range in the center of mass system between $700\,\mathrm{MeV}/c$ and $2.5\,\mathrm{GeV}/c$, a momentum range in the laboratory system between $500\,\mathrm{MeV}/c$ and $5\,\mathrm{GeV}/c$, and a polar angle in the range between 0.5 and 2.6 radians. We also require the total error on Δz, computed on an event-by-event basis to be less than $175\,\mu$m. When estimating the event-by-event error, it should be noticed that, due to non-zero flight length of the B mesons in the transverse plane, the two leptons do not actually originate from the same point in that plane. The total error is therefore the quadratic sum of the tracking error and of this additional uncertainty. As reported in Section 3, the non-negligible effect of the track quality requirements on signal efficiency yields only a small degradation of the resulting statistical uncertainty in Δm_{B^0}.

2.4 Selection of the direct dileptons

The discrimination between direct and cascade leptons is based on a neural network which combines five discriminating variables, all calculated in the $\Upsilon(4S)$ center of mass system:

- the momenta of the two leptons with highest momenta, p_1^* and p_2^*;
- the total visible energy, E_{tot}, and the missing momentum, p_{miss}, of the event;
- the opening angle between the leptons, θ_{12}.

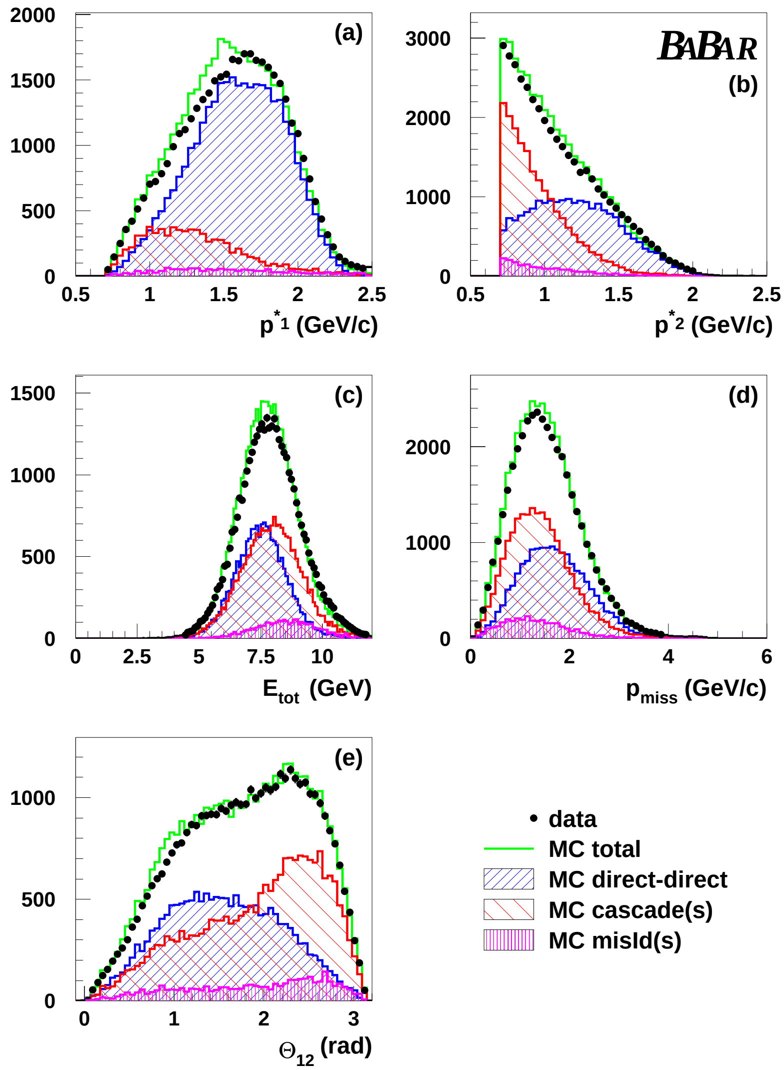

Figure 1: Distributions of the discriminating variables (a) p_1^*, (b) p_2^*, (c) E_{tot}, (d) p_{miss}, and (e) θ_{12}, for data (points) and Monte Carlo (histograms). The contributions from direct-direct pairs, direct-cascade pairs, and pairs with one or more fake leptons, are shown for the Monte Carlo simulation.

The distributions of these variables are shown in Figure 1, for data and Monte Carlo simulation. The first two variables, p_1^* and p_2^*, are very powerful in discriminating between direct and cascade leptons. The last variable, θ_{12}, efficiently removes direct-cascade lepton pairs coming from the same B and further rejects gamma conversions. Some additional discriminating power is also provided by the other two variables. The chosen neural network architecture (5:5:2) is composed of 3 layers, with 2 outputs in the last layer (one for each lepton). The network is trained with 40,000 dileptons from generic B^0 and $B^{\pm}$, and the outputs are chosen to be 1 and 0 for direct and cascade leptons respectively. Figure 2 shows good agreement between data and simulation for the neural network

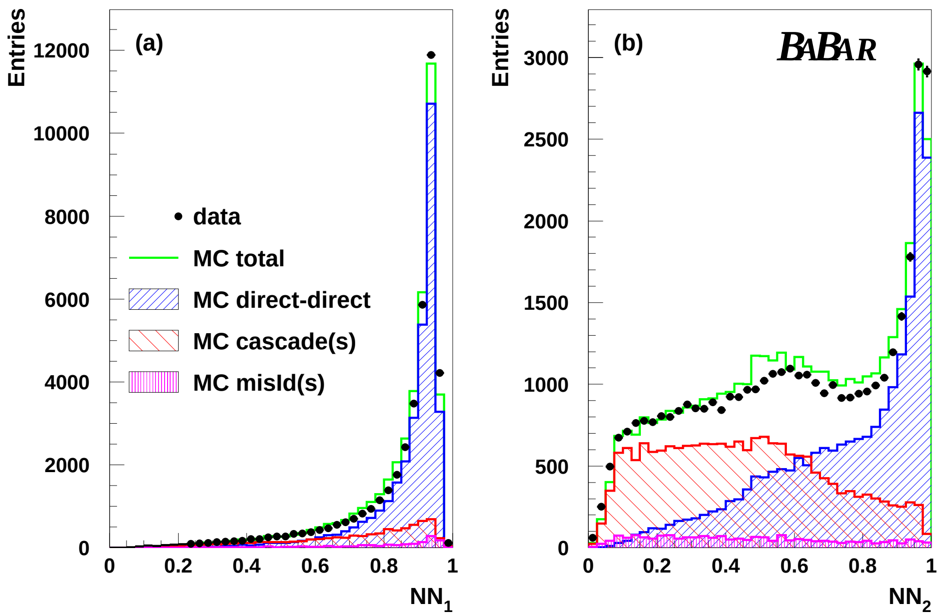

Figure 2: Neural network outputs distributions for the (a) highest and (b) second-highest momentum leptons, for data and Monte Carlo simulation. The various Monte Carlo contributions are shown separately.

outputs of the two leptons. We require both outputs to be greater than 0.8.

The combined effect of the above cuts gives, from simulated events, signal purity and efficiency of 78% and 9%, respectively. The remaining background consists of 12% direct-cascade events (8% with the wrong tagging), 5% $B\overline{B}$ events with one or more fake leptons, 2% $B\overline{B}$ events with one or more non-prompt leptons, a negligible contribution from cascade-cascade events, and 3% from continuum events. The latter was determined in data by rescaling the number of off-resonance events that pass the selection with the ratio of on- and off-resonance luminosities. The total number of selected on-resonance events is 36631 (10742 electron pairs, 7836 muon pairs, and 18053 electron-muon pairs).

3 Determination of Δt

A determination of the z coordinate of the B decay vertex using only the lepton track can be obtained, to first approximation, by taking the z of the point of closest approach between the track and the beam spot in the transverse plane. This estimator is a fairly good way to determine the z position of the B^0 decays vertices since the selected direct leptons have rather high momenta. However, it is possible to use the two lepton tracks and a beam spot constraint in a simple χ^2

vertex fit to obtain a better estimate of the primary vertex of the event in the transverse plane, and to compute the points of closest approach of the two tracks to this new point. The corresponding z coordinates represent a better approximation of the z coordinate of the B decay vertices, and the corresponding Δz resolution function has much reduced tails. For this reason we adopt the latter method to compute the Δz.

Further studies show that a requirement on the total error to be less than $175\,\mu$m reduces the tails of the Δz resolution function by a factor four and reduces the signal efficiency by 30%. However, due to the improved resolution, the total statistical uncertainty on Δm_{B^0} is degraded only by 3% despite the loss of efficiency. A two-Gaussian fit to the resulting Δz resolution function from simulated dilepton events gives $\sigma_n = 87\,\mu$m and $\sigma_w = 195\,\mu$m for the narrow and wide Gaussian, respectively, and 76% of the events in the narrow Gaussian.

The time difference between the two B decay times is defined as $\Delta t = \Delta z/(<\beta\gamma> c)$, with $<\beta\gamma>= 0.554$. This approximation neglects the B meson motion in the $\Upsilon(4S)$ rest frame. In this inclusive approach it is not possible to determine the exact boost. Therefore, the effect of this shift was studied with Monte Carlo by comparing the fitted value of Δm_{B^0} with the true Δt and with $\Delta z/(<\beta\gamma> c)$. This study shows that the effect is negligible compared to the current level of accuracy of this analysis.

4 Fitting procedure

4.1 Time dependence of the fraction of mistagged events

Even after a cut on the neural net output, a non-negligible fraction of events are mistagged (i.e. a true $B^0\overline{B}^0$ pair is tagged as a B^0B^0 or $\overline{B}^0\overline{B}^0$ pair and vice versa for B^0B^0 or $\overline{B}^0\overline{B}^0$ events). The fraction of mistagged events is directly determined in the fit. However we have to take into account that the time dependence of cascade leptons from the same B, or from the other B, are different. In the case of a cascade from a same B (Fig. 3(a)), we observe a peak at low Δz, due the flight length of the charm hadron, which is fitted by an exponential decay. For the cascade leptons from the other B, (circles in Fig. 3(b)), the fraction of mistagged events as a function of the true Δz between the two leptons shows a linear dependence which comes from the fact that the Δz measured between the two leptons contains the additional flight length of the charm hadron. The same distribution, determined using the z distance of the true B vertices, is flat to first order (squares in Figure 3). Actually, the linear dependence on Δz can be explained by considering the time distribution of the cascade lepton. Assuming that the flight length of the charmed hadron is small compared to that of the B, the time distribution of the cascade lepton from the other B can be approximated by:

$$\eta\, e^{-t/(\tau_B+<\tau_c>)} \simeq \eta\,(1+\frac{<\tau_c>}{\tau_B^2}\cdot t)\, e^{-t/\tau_B},$$

where τ_B and $<\tau_c>$ are the B meson lifetime and an average lifetime of the D mesons, respectively. In the final fit procedure, the linear dependence is taken into account by a free parameter; the time shape of the cascade lepton from a same B is determined from the Monte Carlo simulation.

4.2 Measurement of Δm_{B^0}

The value and statistical error for Δm_{B^0} are extracted with a χ^2 minimization fit to the dilepton asymmetry (see Eq. 2). The fit function, $A_{fit}(\Delta t)$, takes into account the various time distributions

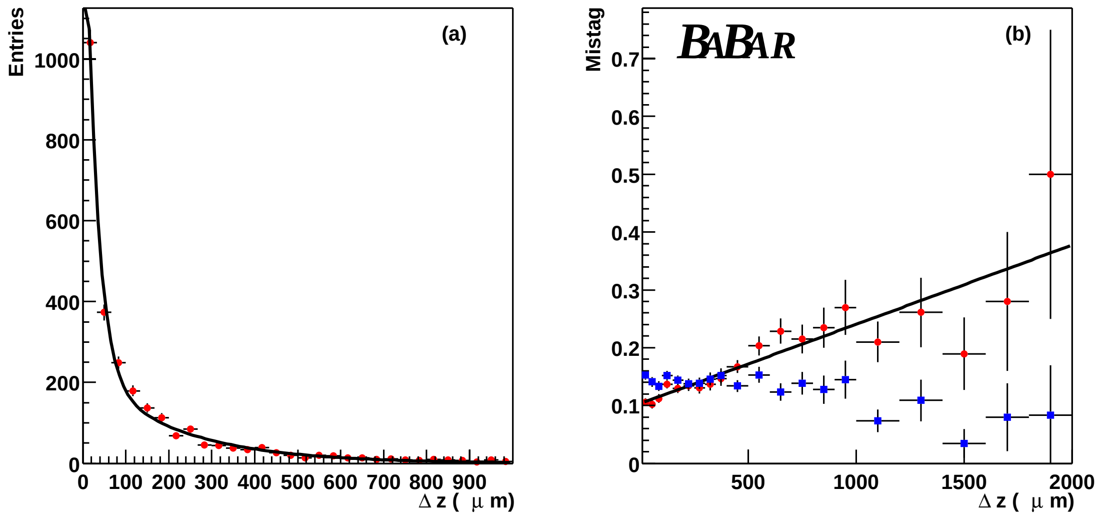

Figure 3: (a) Distribution of Δz between direct and cascade leptons that come from the same B. (b) Fraction of mistagged events for cascade leptons coming from the other B, as a function of the true Δz between the two leptons (circles) and the true Δz between the B mesons (squares).

of the dilepton signal ($f^{unmix}(\Delta t)$, $f^{mix}(\Delta t)$), the cascade lepton and the non-$B\overline{B}$ backgrounds ($f^{OS}_{other}(\Delta t)$, $f^{SS}_{other}(\Delta t)$):

$$A_{fit}(\Delta t) = \frac{(f^{OS} - f^{SS}) \otimes f_{reso}(\Delta t) + (f^{OS}_{other}(\Delta t) - f^{SS}_{other}(\Delta t))}{(f^{OS} + f^{SS}) \otimes f_{reso}(\Delta t) + (f^{OS}_{other}(\Delta t) + f^{SS}_{other}(\Delta t))},$$

where $\otimes$ stands for the convolution product with the resolution function $f_{reso}(\Delta t)$ (see Section 3), and the f-functions are expressed in terms of the various signal and background contributions as

$$\begin{aligned} f^{OS}(\Delta t) &= f^{unmix}(\Delta t) \cdot (1 - (1 + f_c)\eta_0) + f^{SB}_{mistag}(\Delta t) \cdot f_c \cdot \eta_0 \\ &\quad + f^{mix}(\Delta t) \cdot (\eta_0 + \alpha \Delta t) \\ f^{SS}(\Delta t) &= f^{mix}(\Delta t) \cdot (1 - (1 + f_c)\eta_0) + f^{unmix}(\Delta t) \cdot (\eta_0 + \alpha \Delta t), \end{aligned}$$

The signal contributions for unmixed and mixed events are given respectively by

$$\begin{aligned} f^{unmix}(\Delta t) &= \frac{1}{2(1+R)}[\Gamma^0 e^{-\Gamma^0|\Delta t|}(1 + \cos(\Delta m_{B^0} \Delta t)) + 2R \cdot \Gamma^+ \cdot e^{-\Gamma^+|\Delta t|}], \\ f^{mix}(\Delta t) &= \frac{1}{2(1+R)}[\Gamma^0 e^{-\Gamma^0|\Delta t|}(1 - \cos(\Delta m_{B^0} \Delta t))], \end{aligned}$$

where R is proportional to the ratio $(b_+^2 f_{+-})/(b_0^2 f_{00})$ (b_+ and b_0 are respectively the semileptonic branching ratio of charged and neutral B, and f_{+-}/f_{00} is the production ratio of charged and neutral B pairs at the $\Upsilon(4S)$).

The time distribution of direct-cascade events where both leptons originate from the same B is represented by $f^{SB}_{mistag}(\Delta t) = [< \Gamma^c > e^{-<\Gamma^c>|\Delta t|}]$, with $< c/\Gamma^c >= 60\,\mu$m as determined from simulated events (Fig. 3). The difference in the fraction of direct-cascade events between the cascade lepton from the same B and from the other B (due, for instance, to the cut on the angle between the 2 leptons) is estimated by the parameter f_c, determined to be 0.6 from simulated events (Fig. 3).

The time dependence observed for the mistag fraction of direct-cascade events where the cascade lepton comes from the other B, as discussed in Section 4.1, is parametrized by a constant term, η_0, and a slope, α. The same functional dependences as for signal events, $f^{unmix}(\Delta t)$ and $f^{mix}(\Delta t)$, are used.

The time distributions of the non-$B\overline{B}$ background, $f^{OS}_{other}(\Delta t)$ and $f^{SS}_{other}(\Delta t)$, and their absolute normalizations, are obtained from off-resonance data.

Four parameters, Δm_{B^0}, η_0, R, and α, are fitted directly to the observed asymmetry. The lifetimes of the charged and neutral B, Γ^+ and Γ^0, are fixed to their world average values [5].

The off-resonance data is used to measure the fraction of the non-$B\overline{B}$ background to be $(0.7 \pm 0.1)\%$ for same-sign dileptons and $(2.2 \pm 0.3)\%$ for opposite-sign dileptons, respectively. A fit to the time distribution of these events yields an effective lifetime equal to $130\,\mu$m and $135\,\mu$m for same-sign and opposite-sign dileptons, respectively.

The fit to the measured asymmetry $A_{fit}(\Delta t)$ shown in Fig. 4 and obtained with an integrated luminosity of $7.73\,fb^{-1}$, yields the following values: $\Delta m_{B^0} = (0.507 \pm 0.015) \times 10^{12}\,\hbar\,s^{-1}$, $\eta_0 = 0.109 \pm 0.004$, $R = 1.34 \pm 0.11$ and $\alpha = (-1.7 \pm 3.3) \times 10^{-5}$, with a χ^2 of 20.8 for 21 degrees of freedom.

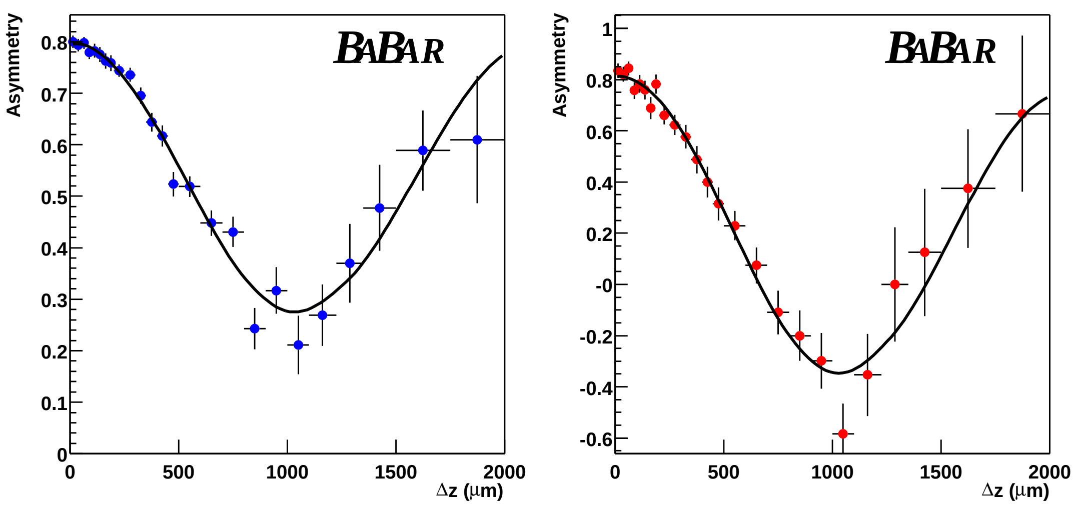

Figure 4: Distribution of the measured asymmetry $A_{obs}(|\Delta t|)$ between unlike-sign events (l^+, l^-) and like-sign events $(l^+, l^+) + (l^-, l^-)$ for (a) the inclusive dilepton sample and (b) the dilepton sample enriched with soft pions, which is discussed in Section 5. The curve represents the result of the fit.

5 Cross-checks and stability of the Δm_{B^0} measurement

5.1 Enrichment of the neutral B with a soft pion

In the inclusive approach proposed in this analysis, the final dilepton sample contains both charged and neutral mesons B in almost equal proportions. Therefore, the observed oscillation amplitude is reduced by the presence of the non-oscillating charged B. To enrich the B^0 fraction, the direct lepton can be correlated with the soft pion produced by a D^{*+} decay. Charged B mesons can only produce a direct lepton and a charged D^* through the D^{**} decay or through the non-resonant 4 body decay $B^- \to D^{*+}\pi^-\ell^-\overline{\nu}$. The branching fractions of these modes are not perfectly measured, but they should represent roughly 10-20% of the semileptonic decays.

The identification of an event with a soft pion is based on a method proposed by the CLEO Collaboration [2]: only tracks with momentum less than $190\,\mathrm{MeV}/c$ in the center-of-mass system are considered. The direction of motion of the D^* is very close to that of the soft pion (the D^0 and the soft pion are produced almost at rest in the D^* system) and the energy $E^*_{D^*}$ of the D^* in the $\Upsilon(4S)$ system is approximated by using the energy of the soft pion E^*_π in the $\Upsilon(4S)$ system and the energy of the soft pion $E^{D^*}_\pi$ in the D^* system: $E^*_{D^*} \simeq (E^*_\pi/E^{D^*}_\pi) \cdot M_{D^*}$. With the four-vector of the lepton and the D^*, one can compute the missing mass squared M^2_m of the neutrino. In the analysis, events are kept if $|M^2_m| \leq 1.0(\,\mathrm{GeV}/c^2)^2$.

The fit of this sub-sample gives $\Delta m_{B^0} = (0.518 \pm 0.017) \times 10^{12}\,\hbar\,s^{-1}$, in good agreement with the value obtained with the dilepton sample. Even though the fraction of events with the additional soft pion represents only 16.5% of the total dilepton sample, the statistical errors are comparable. While, for the moment, this preliminary method constitutes an excellent cross-check, it may later become an alternative approach in its own right.

5.2 Stability studies

We have investigated the stability of the fit results against various changes in selection criteria. The fit was performed in several ranges of azimuthal angles, as well as for a range of values for the cut on the neural network outputs, $(0.6 \leftrightarrow 0.9)$, on the total error of the Δz $(150\,\mu\mathrm{m} \leftrightarrow 300\,\mu\mathrm{m})$ and for a range in Δz. Subsamples composed of only $\mu\mu$, ee and $e\mu$ were also considered. In all cases, variations in Δm_{B^0} were found to be small or consistent with the nominal value within statistical errors.

6 Systematic uncertainties

In this analysis the fraction of mistagged events η_0 is directly extracted from the fit of the asymmetry but a time dependence of this component, as well as the fraction of misidentified leptons, may induce a bias in the Δm_{B^0} determination. These effects are corrected by using the time distribution of the mistagged events determined from the Monte Carlo, and by fitting a slope to the mistag fraction time dependence. The systematic error is determined by assuming that the Monte Carlo corrections are known at the 30% level.

A conservative estimate of the uncertainty due to fake leptons is taken to be the difference between the results of the fit to Monte Carlo with perfect and simulated particle identification.

Another important source of systematic errors comes from the determination of the resolution function, which is taken from simulated events. To estimate the uncertainty involved in this procedure, we have compared the Δz resolution between data and Monte Carlo using J/ψ events, where the leptons are known to come from the same vertex. From this comparison, shown in Figure 5, we estimate an uncertainty on the width of the narrow and wide Gaussians of the resolution function of 5% and 10%, respectively.

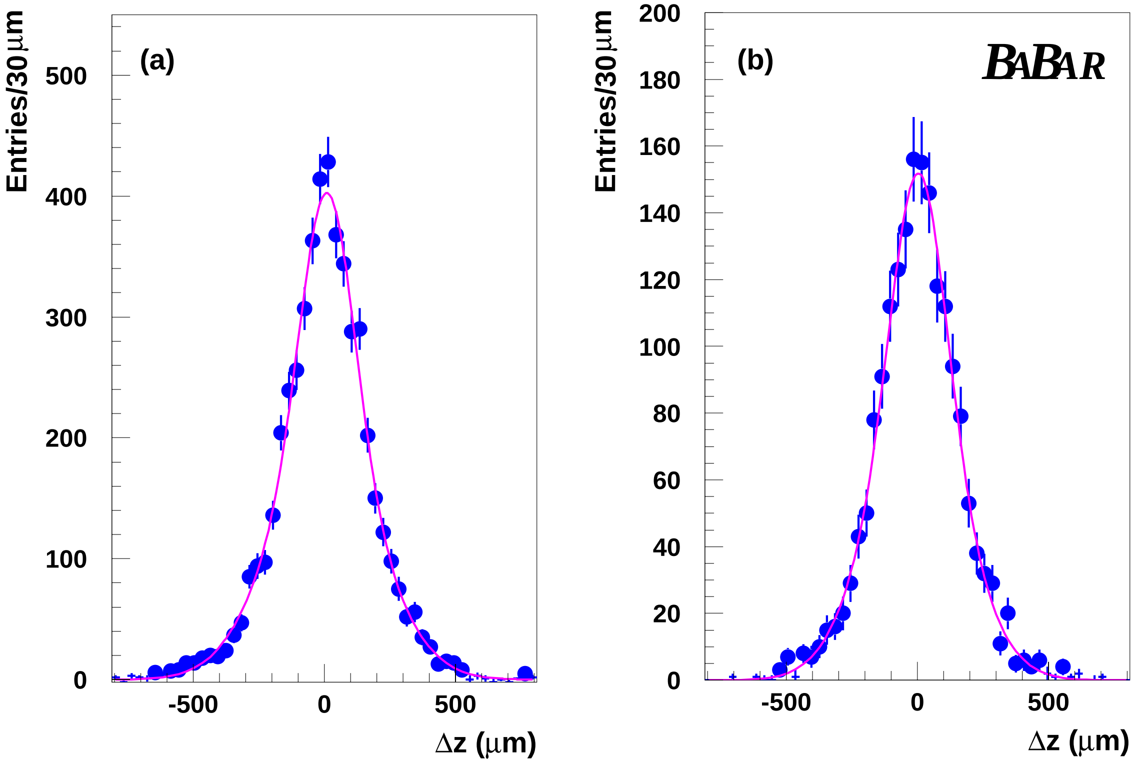

Figure 5: Δz distribution for lepton pairs in the J/ψ mass window in (a) data and (b) Monte Carlo events. The distributions are fitted with a sum of two Gaussians. The resolutions for the narrow and wide Gaussians are $101\,\mu$m and $205\,\mu$m in data, $102\,\mu$m and $184\,\mu$m in Monte Carlo, respectively.

The effect of a charge asymmetry in the identification of the lepton ($\varepsilon^+ \neq \varepsilon^-$) or a mistag asymmetry $\eta^+ \neq \eta^-$ on the Δm_{B^0} measurement is negligible since the effects cancel in the asymmetry. However, the mistag probability η may be different for the charged and neutral B. The impact of such an effect on the Δm_{B^0} measurement is negligible because the bias is fully absorbed by the parameter R, which implies that the fitted value of this ratio need not necessarily be unity.

The list of systematic effects is summarized in Table 1. The sum of the different contributions gives a total systematic uncertainty of $0.022 \times 10^{12}\,\hbar\, s^{-1}$.

7 Conclusions

We present a preliminary study of the $B^0\overline{B}^0$ oscillation frequency with an inclusive sample of dilepton events corresponding to a total luminosity of $7.73\, fb^{-1}$ collected by the *BABAR* experiment. We obtain $\Delta m_{B^0} = (0.507 \pm 0.015 \pm 0.022) \times 10^{12}\,\hbar\, s^{-1}$. The accuracy is already comparable with the current world average.

Table 1: Summary of the contributions to the systematic uncertainty in Δm_{B^0}.

Source of systematic uncertainty	$\sigma(\Delta m_{B^0})$ ($10^{12}\,\hbar\,s^{-1}$)
Non-$B\overline{B}$ background	0.005
Mis-Identification	0.011
Time-dependence of the cascade events	0.009
Correction of the boost approximation	0.001
y-motion of the beam spot ($\leq 20\,\mu$m)	0.001
Δz resolution function	0.009
Tails of the Δz resolution function	0.004
Time-dependence of the resolution function	0.006
Sensitivity to Γ^+ (PDG 98 $\pm 1\sigma$)	0.007
Sensitivity to Γ^0 (PDG 98 $\pm 1\sigma$)	0.007
Total	0.022

8 Acknowledgments

We are grateful for the contributions of our PEP-II colleagues in achieving the excellent luminosity and machine conditions that have made this work possible. We acknowledge support from the Natural Sciences and Engineering Research Council (Canada), Institute of High Energy Physics (China), Commissariat à l'Energie Atomique and Institut National de Physique Nucléaire et de Physique des Particules (France), Bundesministerium für Bildung und Forschung (Germany), Istituto Nazionale di Fisica Nucleare (Italy), The Research Council of Norway, Ministry of Science and Technology of the Russian Federation, Particle Physics and Astronomy Research Council (United Kingdom), the Department of Energy (US), and the National Science Foundation (US). In addition, individual support has been received from the Swiss National Foundation, the A. P. Sloan Foundation, the Research Corporation, and the Alexander von Humboldt Foundation. The visiting groups wish to thank SLAC for the support and kind hospitality extended to them.

References

[1] ARGUS Collaboration, H. Albrecht *et al.*, Phys. Lett. **B374**, 256 (1996).

[2] CLEO Collaboration, J. Bartelt *et al.*, Phys. Rev. Lett. **71**, 1680 (1993).

[3] "Combined results on b-hadron production rates, lifetimes, oscillations and semileptonic decays", ALEPH, CDF, DELPHI, L3, OPAL, and SLD Collaborations, SLAC-PUB-8492, CERN-EP-2000-096, June 2000.

[4] *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.

[5] C. Caso *et al.*, Eur. Phys. Jour. C **3**, 1 (1998).