$B_d$ mixing measurements with the BABAR detector

C. Voena
Universit`a “La Sapienza” and INFN Roma
P.le Aldo Moro 2 00185 Rome, Italy
(for the BABAR Collaboration)

Abstract

The $B^0\overline{B}^0$ oscillation frequency $\Delta m_d$ has been measured with the BABAR detector at the PEP-II asymmetric $B$ factory with different experimental techniques. The discussion here is focused on the recent simultaneous measurement of $\Delta m_d$ and $\tau_{B^0}$ with exclusively reconstructed $B^0 \rightarrow D^*-\ell^+\nu_\ell$ decays, based on 23 million $BB$ pairs collected by BABAR. The measurements of $\Delta m_d$ with fully reconstructed hadronic decays and with dilepton events are also reviewed. The average BABAR result is $\Delta m_d = 0.500 \pm 0.008 \pm 0.006$ ps$^{-1}$.

Contributed to the Proceedings of the 31st International Conference on High Energy Physics, 7/24/2002—7/31/2002, Amsterdam, the Netherlands

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

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

Particle-antiparticle oscillations or mixing, has been observed in the neutral $B\bar{B}$ meson system almost fifteen years ago [1]. This quantum-mechanical behavior is originated by the flavor eigenstates $B^0$ and $\bar{B}^0$ not being Hamiltonian eigenstates. The frequency of the oscillation is the mass difference between the mass eigenstates, $\Delta m_d$. In the Standard Model, $B^0\bar{B}^0$ mixing occurs through second-order weak diagrams involving the exchange of up-type quarks, with the top quark contributing the dominant amplitude. A measurement of $\Delta m_d$ is therefore sensitive to the value of the Cabibbo-Kobayashi-Maskawa matrix element $V_{td}$ [2]. The oscillation frequency $\Delta m_d$ has been measured with both time-integrated and time-dependent techniques [3]. Asymmetric $B$ factory experiments like BABAR can perform high statistics time dependent measurements of $\Delta m_d$.

2 Measurements of $\Delta m_d$ with the BABAR detector

The BABAR detector [4] collects data at the PEP-II asymmetric $e^+e^-$ collider operated at or near the $\Upsilon(4S)$ resonance. $B\bar{B}$ pairs from $\Upsilon(4S)$ decay move along the high-energy beam direction ($z$) with a nominal Lorentz boost $<\beta\gamma> = 0.55$. Therefore, the two $B$ decays vertices are separated by about 260 $\mu m$ on average. The two $B$ mesons are produced in a coherent $P$-wave state and their proper decay-time difference $\Delta t$ distribution is governed by the following probabilities to observe mixed(-) or unmixed(+) events:

$$Prob(B^0\bar{B}^0 \rightarrow B^0\bar{B}^0, B^0\bar{B}^0 or \bar{B}^0B^0) \propto e^{-\Delta m_d|t|} (1 \pm \cos\Delta m_d \Delta t).$$

(1)

Therefore, a measurement of $\Delta t$ together with the identification of the $b$-flavor of both $B$ mesons at their time of decay, allows to observe the oscillations and to extract $\Delta m_d$.

In the following sections the simultaneous measurement of $\Delta m_d$ and $\tau_{B^0}$ with exclusively reconstructed $B^0 \rightarrow D^{*-}\ell^+\nu_l$ decays [5], the measurement of $\Delta m_d$ with fully reconstructed hadronic $B^0$ decays [6] and with inclusively reconstructed dilepton events [7], will be discussed.

3 Measurement of $\Delta m_d$ and $\tau_{B^0}$ with exclusively reconstructed $B^0 \rightarrow D^{*-}\ell^+\nu_l$ decays

The analysis is based on a sample of approximately 14,000 exclusively reconstructed $B^0 \rightarrow D^{*-}\ell^+\nu_l$ decays selected from 23 million $B\bar{B}$ pairs recorded in the years 1999-2000 by BABAR. The purity of the sample is 65-89% depending on the decay mode of the $\bar{D}^0$ from the $D^{*}$. One of the two $B$ produced by the $\Upsilon(4S)$ decay is reconstructed in the semileptonic mode and the charge of the final-state particles identifies the flavor of the $B$. $D^{*-}$ candidates are reconstructed using the decay $D^{*-} \rightarrow \bar{D}^0\pi^-$, while $\bar{D}^0$ candidates are reconstructed in the modes $K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$ and $K^0_S\pi^+\pi^-$. $D^{*-}$ candidates are then combined with oppositely charged high-energy electrons or muons in the event and the $D^{*-}\ell^+$ pair is required to pass kinematic cuts that enhance the contribution of $B^0 \rightarrow D^{*-}\ell^+\nu_l$ decays. The $B$ mass and energy cannot be reconstructed because of the presence of the neutrino, thus the distribution $\delta m$ of the difference between the $D^{*-}$ and the $D^0$ masses is used to select $B$ candidates. The distribution of $\delta m$ for events passing the selection criteria in the muon sample is shown in Figure 1.
Figure 1: $\delta m$ distribution for events passing all selection criteria for $B^0 \rightarrow D^{*-}\ell^+\nu_\ell$ decays with a muon candidate. The points correspond to the data. The curve is the result of a fit. The shaded distributions correspond to the four types of background (BG) described in the text.

There are two types of background with respect to the $\delta m$ distribution: combinatoric background and peaking background. Combinatoric background is due to events with a mis-reconstructed $D^{*-}$ and does not peak in the $\delta m$ distribution. Peaking background is due to $\bar{B}B$ events with mis-identified leptons or uncorrelated true leptons, and continuum events. The $\delta m$ distribution of the peaking background is the same as the distribution of the signal. Several control samples are selected to characterize the various backgrounds in both the fraction and the time distribution.

All the charged tracks in the event, except the reconstructed tracks from the $D^{*-}\ell^+$ pair, are used to identify the flavor of the other $B$ (referred to as $B_{tag}$). There are five types of tagging categories. The first two tagging categories rely on the presence of a prompt lepton or charged kaons in the event, whose charge is correlated with the $b$-flavor of the decaying $B$. The other three categories exploit a variety of inputs (e.g. slow pions, momentum of the track with the maximum center-of-mass momentum) with a neural network technique.

The difference $\Delta t$ between the two $B$ decay times is determined from the measured separation $\Delta z = z_{D_{sl}} - z_{tag}$ along the beam axis between the $D^{*-}\ell^+$ vertex and the $B_{tag}$ vertex. The measured $\Delta z$ is converted into $\Delta t$ with the known $\Upsilon(4S)$ boost according to the relation $\Delta z = c\beta\gamma\Delta t$ which neglects the small $B$ momentum in the $\Upsilon(4S)$ frame. The resolution on the $D^{*-}\ell^+$ vertex is about 70 $\mu$m while the resolution on the $B_{tag}$ vertex is about 160 $\mu$m.

Each tagging category $i$ has a probability $w_i$ of incorrectly assigning the flavor of the $B_{tag}$ and there is a limited precision on the $\Delta t$ measurement. These two experimental complications affect the $\Delta t$ distribution of Equation 1 which becomes:

$$Prob(B^0\bar{B}^0 \rightarrow B^0\bar{B}^0, B^0\bar{B}^0 or \bar{B}^0\bar{B}^0) \propto R(\delta t; \hat{a}) \otimes e^{-\frac{\Delta t}{\sigma_{\Delta t}}}(1 \pm (1 - 2w_i)\cos\Delta m_\ell\Delta t).$$

The function $R(\delta t; \hat{a})$ is the resolution function which parametrizes the response to $\Delta t$ of the detector, $\delta t = \Delta t_{\text{meas}} - \Delta t_{\text{true}}$ and $\hat{a}$ is a set of parameters. The final $\Delta t$ distribution also includes terms for each relevant background source.
The oscillation frequency $\Delta m_d$ and the lifetime $\tau_{B^0}$ are determined simultaneously with an unbinned maximum likelihood fit to the measured $\Delta t$ distribution. Note that other mixing measurements fix $\tau_{B^0}$ to the world average and this is the source of the dominant systematic error. Also the resolution, the fraction of charged $B$, the mistag and the background parameters are floated in the fit. The results are: $\Delta m_d = 0.492 \pm 0.018 \text{(stat)} \pm 0.013 \text{(syst)}$ ps$^{-1}$ and $\tau_{B^0} = 1.523^{+0.024}_{-0.023} \text{(stat)} \pm 0.022 \text{(syst)}$ ps. The correlation between $\Delta m_d$ and $\tau_{B^0}$ is -0.22. A correction is applied to both $\Delta m_d$ and $\tau_{B^0}$ which takes into account selection and fit biases. The uncertainty on such a correction is the dominant systematic error. Other BABAR measurements for $\tau_{B^0}$ can be found in [8] and [9]. Figure 2 shows the mixing asymmetry defined as the difference between the number of unmixed and mixed events over their sum as a function of $\Delta t$.

4 Measurement of $\Delta m_d$ with fully reconstructed $B^0$ hadronic decays

The analysis is based on $\sim$6300 $B^0$ selected from 32 million $B\bar{B}$ pairs. The $B^0$ are reconstructed in the flavor eigenstates $D^-\pi^+$, $D^-\rho^+$, $D^-a_1^+$, $J/\psi K^{*0}$ and the purity of the selected sample is about 86%. $B^0$ candidates are selected using the difference between the energy of the candidate and the beam energy $\sqrt{s}/2$ in the center of mass frame, and the beam energy substituted mass, calculated from $\sqrt{s}/2$ and the reconstructed momentum of the $B$.

The tagging algorithm and the tagging vertex reconstruction technique are described in the previous section. $\Delta m_d$ is extracted with an unbinned maximum likelihood fit to the $\Delta t$ distribution (obtained from $\Delta z$ as described in the previous section) where also all the mistag probabilities and the resolution parameters are floated. The result is $\Delta m_d = 0.516 \pm 0.016 \text{(stat)} \pm 0.010 \text{(syst)}$ ps$^{-1}$, the dominant systematic error being the uncertainty on $\tau_{B^0}$ which is fixed in the fit.
5 Measurement of $\Delta m_d$ with inclusive dilepton events

The analysis is based on 23 million $B\bar{B}$ pairs. The measurement technique consists in the identification of events containing two high energy leptons from semileptonic decays of $B$ mesons. The flavor of the $B$ mesons at the time of their decay is determined by the charge of the leptons. About 99000 events are selected, $\sim 55\%$ of them being $B^+B^-$ events which are not removed by the event selection criteria. Another non negligible background is due to leptons from the $b \rightarrow c \rightarrow l$ decay chain ($\sim 13\%$) which are also the main source of wrongly tagged events. The difference of the $z$ coordinates of the two $B$ decay vertices $\Delta z$ is determined using the two lepton tracks and a beam spot constraint. $\Delta t$ is then obtained from $\Delta z$ as described in section 3. A binned maximum likelihood fit is used to extract $\Delta m_d$ together with the resolution parameters, the fraction of charged $B$ and some of the background fractions and parameters. The result is $\Delta m_d = 0.493 \pm 0.012(stat) \pm 0.009(syst) \text{ps}^{-1}$. The dominant systematic error is due to the uncertainty on $B^0$ and $B^+$ lifetimes which are fixed in the fit.

6 Conclusions

The oscillation frequency $\Delta m_d$ of the $B^0\bar{B}^0$ system has been measured by the BABAR experiment with different experimental techniques. The combined BABAR result is $\Delta m_d = 0.500 \pm 0.008 \pm 0.006 \text{ps}^{-1}$. The corresponding precision is 2% to be compared with the world average precision which is 1.2%.

References

[1] UA1 Collaboration, C.Albajar et al., Phys.Lett. B186, 247 (1987); ARGUS Collaboration, H. Albrecht et al., Phys. Lett. B192, 245 (1987).

[2] N.Cabibbo, Phys.Rev.Lett. 10, 531 (1963); M.Kobayashi and T.Maskawa, Prog. Th. Phys. 49, 652 (1973).

[3] D.E. Groom et al., Eur. Phys. Jour. C15, 1 (2000);

[4] The BABAR Collaboration, B. Aubert et al., Nucl. Instrum. Meth. A479, 1 (2002).

[5] The BABAR Collaboration, B. Aubert et al., hep-ex/0207071, 2002.

[6] The BABAR Collaboration, B. Aubert et al., Phys. Rev. Lett. 88, 221802 (2002).

[7] The BABAR Collaboration, B. Aubert et al., Phys. Rev. Lett. 88, 221803 (2002).

[8] The BABAR Collaboration, B. Aubert et al., Phys. Rev. Lett. 89, 011802 (2002).

[9] The BABAR Collaboration, B. Aubert et al., Phys. Rev. Lett. 87, 201803 (2001).