Update on the $\mathrm{B_d^0}$ Meson Oscillation Frequency Measurement Using Dilepton Events

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Abstract

The time-dependent $\mathrm{B^0}$-$\mathrm{\bar{B}^0}$ mixing has been studied using about two million hadronic Z decays registered by L3 in 1994 and 1995. Tagging of b quark production is performed by identifying leptons from semileptonic B decays and using the charge correlation between leptons in opposite hemispheres as a signature for mixing. The proper time of the B-particle decay is measured by reconstructing the production and decay vertices. The frequency for a $\mathrm{B_d^0}$ meson oscillation corresponds to the mass difference Δm_d between the two $\mathrm{B_d^0}$ mass eigenstates:

$$\Delta m_d = 0.458 \pm 0.046(\mathrm{stat}) \pm 0.032(\mathrm{syst})\ \mathrm{ps}^{-1}$$

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Introduction

As in the case of K-mesons, oscillations between particle-antiparticle states are expected in the system of neutral B-mesons. In the Standard Model, the mechanism causing mixing is a second order weak interaction through box diagrams. The flavour eigenstates $\mathrm{B_d^0}$ ($\mathrm{\bar{b}d}$) and $\mathrm{\bar{B}_d^0}$($\mathrm{b\bar{d}}$) are linear combinations of the mass eigenstates $\mathrm{B_1}$ and $\mathrm{B_2}$. Neglecting effects from CP violation (expected to be small), the probability to find a $\mathrm{B_d^0}$ decaying at proper time t, provided it was produced as $\mathrm{\bar{B}_d^0}$ at $t = 0$, is given by

$$P(\mathrm{\bar{B}_d^0} \to \mathrm{B_d^0}) = \frac{1}{\tau} e^{-\frac{t}{\tau}} \left(\frac{1 - \cos \Delta m_d t}{2} \right)$$

where τ is the lifetime of the B-meson. A measurement of the oscillation frequency thus gives a direct measurement of the mass difference Δm_d between two physical states.

The phenomenon of $\mathrm{B^0}$-$\mathrm{\bar{B}^0}$ mixing is well established by experiment. Time integrated probabilities for mixing in the $\mathrm{B^0}$-$\mathrm{\bar{B}^0}$ system were first observed by the UA1 Collaboration [1], as a result of the combined $\mathrm{B_d^0}$ and $\mathrm{B_s^0}$ contribution. Mixing of $\mathrm{B_d^0}$-$\mathrm{\bar{B}_d^0}$ alone was measured at the Υ(4S) by ARGUS and CLEO [2]. Comparing these results with precise measurements of $\mathrm{B^0}$-$\mathrm{\bar{B}^0}$ mixing at LEP [3] leads one to expect a large oscillation frequency for the $\mathrm{B_s^0}$ meson, which makes it difficult to measure. The time dependence of mixing for $\mathrm{B_d^0}$ mesons has been recently measured at LEP using different techniques [4–6, 8].

Here we present a measurement of the $\mathrm{B_d^0}$ oscillation frequency with the L3 detector. For this study we use dileptons in opposite hemispheres to tag the flavour of the B particles at production and decay time. The signature for mixing is the presence of same sign lepton pairs. Proper time is measured by reconstructing secondary vertexes. The dilepton sample corresponds to about two million hadronic Z decays recorded in 1994 and 1995. The measurement of $\mathrm{B_d^0}$ oscillation frequency using 1994 data was published in [7].

Fit Results and Systematic Errors for Δm_d

For the fit of the $\mathrm{B_d^0}$-$\mathrm{\bar{B}_d^0}$ oscillation frequency dilepton events with at least one proper time measured are selected. Additional quality cuts for the decay length measurement are then applied. We require that the error estimate for the decay length reconstruction is less than 1 mm. Negative values of the decay length, due to resolution, should be no further that 3 sigma away from the primary vertex. With these requirements, 1490 dilepton events with 1928 secondary vertices remain. There are 630 reconstructed vertices in the like-sign events and 1298 in the unlike-sign ones.

To find Δm_d an eight parameter fit was performed. Fitted parameters are Δm_d itself and f_Λ, f_s, f_{bcl}, where f_Λ and f_s are the fractions of B baryons and $\mathrm{B_s^0}$ mesons in the sample and f_{bcl} is the fraction of leptons coming from cascade decays ($\mathrm{b \to c \to l}$, $\mathrm{b \to \bar{c} \to l}$, $\mathrm{b \to J \to l^+l^-}$) in $\mathrm{b\bar{b}}$ events. Other four parameters are the life times of b-hadrons, $\mathrm{B_d^0}$ (τ_d), $\mathrm{B^\pm}$ (τ_u), $\mathrm{B_s^0}$ (τ_s) and $\mathrm{B_\Lambda^0}$ (τ_Λ). The oscillation frequency Δm_d is a free parameter; for the last seven parameters Gaussian constraints are applied with the following central values and ranges

$$\begin{aligned}
f_\Lambda &= 0.087 \pm 0.029 \\
f_s &= 0.102 \pm 0.016 \\
f_{bcl} &= f_{bcl}^{MC}(1. \pm 0.15) \\
\tau_d &= 1.56 \pm 0.06\mathrm{ps}
\end{aligned}$$

$$\begin{aligned}\tau_u &= 1.62 \pm 0.06\text{ps} \\ \tau_s &= 1.61 \pm 0.10\text{ps} \\ \tau_\Lambda &= 1.14 \pm 0.08\text{ps}\end{aligned}$$

where f_{bcl}^{MC} is the relative fraction of cascade decays as derived from Monte Carlo. The value for the $\mathrm{B_s^0}$ fraction in $\mathrm{b\bar{b}}$ events f_s is fixed to the world average derived from time integrated mixing measurements (using χ_d from measurements at Υ(4S)) and from D_sl correlations [9]. The value for the fraction of B baryons in $\mathrm{b\bar{b}}$ events is derived from Λ_c-lepton and Λ-lepton correlations [10]. The fractions of $\mathrm{B_d^0}$ and $\mathrm{B^\pm}$ are then derived through

$$f_d = f_u = 0.5 \times (1 - f_\Lambda - f_s)$$

The central values and uncertainties of the b-hadron life times are taken from [11]. We also impose a Gaussian constraint on the sum of the b-hadron life times weighted by their fractions, $\tau_B = f_d\tau_d + f_u\tau_u + f_s\tau_s + f_\Lambda\tau_\Lambda$, requiring it to be compatible with the world average value $\tau_B = 1.549 \pm 0.02$ ps [11]. The result of the fit is:

$$\begin{aligned}\Delta m_d &= 0.458 \pm 0.054\ \text{ps}^{-1} \\ f_\Lambda &= 0.086 \pm 0.027 \\ f_s &= 0.104 \pm 0.015 \\ f_{bcl} &= f_{bcl}^{MC} * (1.04 \pm 0.13) \\ \tau_d &= 1.57 \pm 0.05\text{ps} \\ \tau_u &= 1.64 \pm 0.05\text{ps} \\ \tau_s &= 1.61 \pm 0.10\text{ps} \\ \tau_\Lambda &= 1.12 \pm 0.08\text{ps}\end{aligned}$$

The error on Δm_d includes the statistical error as well as a contribution from systematic errors of the fitted parameters. To separate out the statistical error we fix all the fitted parameters to their fitted values and perform one parameter fit. This gives

$$\Delta m_d = 0.458 \pm 0.046\ (\text{stat})\ \text{ps}^{-1}$$

where the error is purely statistical. The systematic error on Δm_d is then obtained by subtracting in quadrature from the eight parameter fit error the statistical error. This gives ± 0.028 ps^{-1} for the systematic error estimate. The individual systematic errors on Δm_d from fitted parameters are estimated by varying the central value of each constrained parameter by $\pm 1\sigma$ and refitting. The change in Δm_d is taken as systematic error and is listed in Table 1. Due to correlations, the sum in quadrature of the contributions obtained this way is not equal to the total systematic error above (labelled "subtotal" in the Table 1).

The values of other parameters are the same as in the 1994 data analysis [7].

The contributions to the systematic error on Δm_d are summarised in the Table 1.

Except for the cascade decay fraction, the variation of the fractions was taken to be $\pm 30\%$ for fake leptons and $c\bar{c}$ events and $\pm 50\%$ for light quarks events other than $c\bar{c}$.

Contributions to the systematic error from the resolution were estimated by changing the widths of the resolution function by $\pm 25\%$.

The boost term contribution to the systematic error was estimated by changing the average fraction of beam energy carried by the B mesons within 0.85 ± 0.015.

Source of uncertainty	Variation of Δm_d [ps^{-1}]
B_Λ^0 fraction	± 0.006
B_s^0 fraction	∓ 0.013
cascade decay fraction	∓ 0.019
τ_d	∓ 0.003
τ_u	± 0.005
τ_s	± 0.001
τ_Λ	± 0.001
τ_B	∓ 0.002
subtotal	0.028
fakes fraction	∓ 0.007
$c\bar{c}$ fraction	± 0.001
uds fraction	∓ 0.001
B life time	∓ 0.001
resolution	± 0.007
boost term	± 0.006
w_{bl}	∓ 0.003
w_{bcl}	∓ 0.007
w_{bfk}	∓ 0.006
w_{udsc}	∓ 0.001
Δm_s	∓ 0.001
total	0.032

Table 1: Summary of contributions to the systematic error on Δm_d.

The charge confusion factor w_{bl} was varied within $\pm 30\%$. The other w factors were changed by a rough estimate of their relative uncertainty: ± 0.05 for w_{bcl}, ± 0.10 for w_{bfk} and ± 0.10 for w_{udsc}.

In the fit to the data the value for the oscillation frequency of B_s^0 mesons was fixed to 10 ps^{-1}, thus assuming a large mixing in the B_s^0 system. Variation of this parameter from 3 to 20 ps^{-1} gives a negligible contribution to the systematic error.

In total the systematic error for Δm_d from all listed sources is ± 0.032 ps^{-1}. The result for Δm_d measurement is consistent with previous one [7]; the statistical error is reduced due to larger sample have been used, and the systematic error is smaller due to the improved constraints on the parameters in the fit (mainly f_s) and also due to all systematic errors were estimated now from multi-parameter fit (then an uncertainty is attributed to the all correlated parameters of the fit, not only to the Δm_d).

The fraction of like-sign leptons is plotted in Figure 1 as a function of proper time.

Conclusion

Using data registered by L3 in 1994 and 1995 the time dependent B_d^0-$\bar{B}_d^0$ mixing has been measured from the decay length reconstruction in same sign and opposite sign dilepton events. The oscillation frequency is found to be

$$\Delta m_d = 0.458 \pm 0.046(\mathrm{stat}) \pm 0.032(\mathrm{syst})\ \mathrm{ps}^{-1}$$

The result for Δm_d measurement is consistent with previous one [7]; the statistical error is reduced due to larger sample have been used, and the systematic error is smaller due to the improved constraints on the parameters in the fit.

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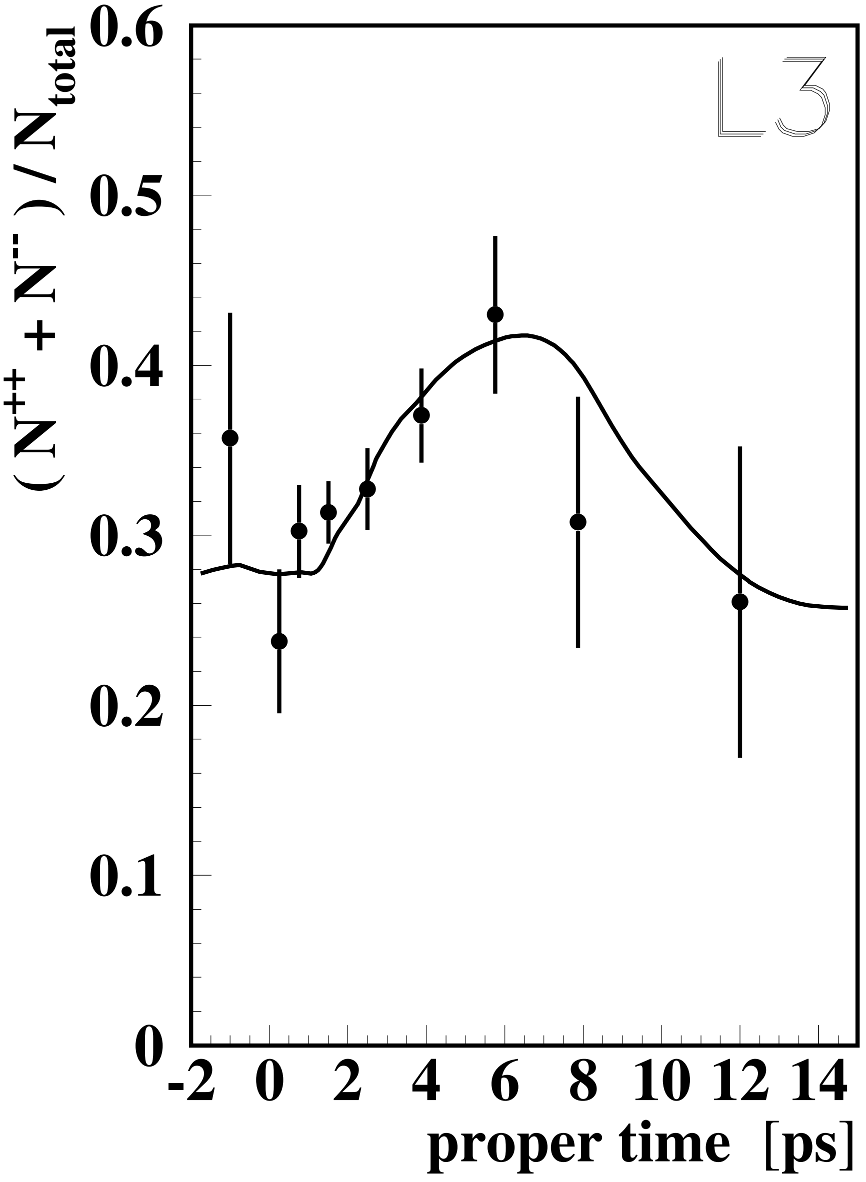

Figure 1: Ratio of same-sign dilepton events to the total number of dilepton events versus the measured proper time compared to the fit result. The solid line is the sum of individual contributions of different sources of such events.