NEW MEASUREMENTS OF TIME-DEPENDENT B_d^0–$\overline{B_d^0}$ MIXING FROM THE SLD EXPERIMENT AT SLC

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The time dependence of B_d^0–$\overline{B_d^0}$ mixing has been measured using a sample of 150,000 hadronic Z^0 decays collected by the SLD experiment at the SLC between 1993 and 1995. Four different analyses have been performed. All analyses tag the B candidate at production with a combined tag that exploits the large polarized b forward-backward asymmetry together with the opposite hemisphere b jet charge. Two of the analyses exploit 3D topological vertexing to determine the B meson decay length, in conjunction with either a charged kaon or charge dipole final state tag. The other two analyses use identified high (p, p_t) leptons intersected with either a partially reconstructed D meson, or the weighted average of tracks in the b jet. Taking into account correlated statistical and systematic errors, the preliminary SLD average for the mass difference between the two B_d^0 mass eigenstates is: $\Delta m_d = 0.525 \pm 0.043(stat) \pm 0.037(syst)$ ps^{-1}.

1 Introduction

This paper presents four measurements of time dependent B_d^0 mixing using a sample of 150,000 hadronic Z^0 decays collected between 1993 and 1995 by the SLD experiment at the SLAC Linear Collider (SLC). The electron beam was longitudinally polarized at the interaction point (IP) with average polarization $\langle P_e \rangle = (63.0 \pm 1.0)\%$ in 1993 and $(77.2 \pm 0.5)\%$ in 1994/95. A detailed description of the experimental procedure can be found elsewhere [1]. In order to measure time dependent B_d^0 mixing all analyses must determine, for each decay, the B decay length (or proper time) and the particle-antiparticle nature of the B at production (the initial state at t=0) and at decay (final state).

2 Initial State Tagging

The large forward-backward asymmetry for $Z^0 \to b\bar{b}$ decays is used as a nearly 100% efficient tag of the initial state flavor for all analyses. The polarized forward-backward asymmetry $\tilde{A}_{FB}$ can be described by $\tilde{A}_{FB} = [2A_b(A_e + P_e)/(1 + A_e P_e)]\ [\cos\theta_T/(1 + \cos^2\theta_T)]$, where $A_b = 0.94$ and $A_e = 0.155$ (Standard Model values), and θ_T is the angle between the thrust axis and the positron beam direction (the thrust axis is signed such that it points in the same hemisphere as the reconstructed vertex). Thus, left- (right-)polarized electrons tag b ($\bar{b}$) quarks in the negative hemisphere, and $\bar{b}$ (b) quarks in the positive hemisphere (see Fig. 1a). This yields an average correct tag probability of 76% (62%) for $P_e = 77\%$ (63%). The probability for correctly tagging a b quark at production is expressed as $P_A(b) = 0.5(1 + \tilde{A}_{FB})$.

A jet charge technique is used in addition to the polarized forward-backward asymmetry. For this tag, tracks in the hemisphere opposite that of the reconstructed vertex are selected [2]. With these tracks, an opposite hemisphere momentum-weighted track charge is defined as $Q_{opp} = \sum_i q_i |\vec{p}_i \cdot \hat{T}|^\kappa$, where q_i is the electric charge of track i, $\vec{p}_i$ its momentum vector, $\hat{T}$ is the thrust axis direction, and κ is a coefficient chosen to be 0.5 to maximize the separation between b and $\bar{b}$ quarks. A clear separation can be observed as shown in Fig. 1b. The probability for correctly tagging a b quark in the initial state of the vertex hemisphere can be parameterized as $P_Q(b) = 1/(1 + e^{\alpha Q_{opp}})$, where the coefficient $\alpha \simeq -0.27$, as determined using the Monte Carlo simulation. This technique yields an average correct tag probability of 67% and is independent of the polarized forward-backward asymmetry tag. The

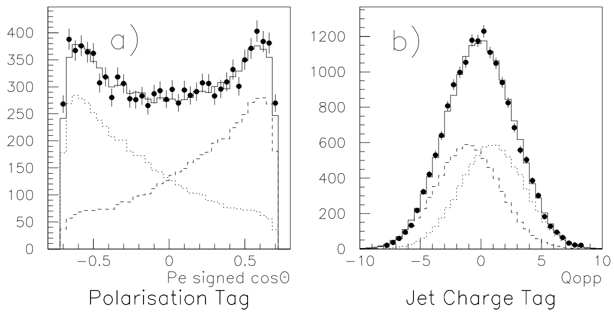

Figure 1: Initial state tag variables, polarization-signed $\cos\theta$ of the thrust axis and opposite hemisphere jet charge, for data (points) and MC (solid line) with MC b and $\bar{b}$ quark components (dashed and dotted lines respectively).

two initial state tags can be combined to form an overall initial state tag: $P_i(b) = P_A(b)P_Q(b)/(P_A(b)P_Q(b) + [1 - P_A(b)][1 - P_Q(b)])$, which yields an overall average correct tag probability of 84%.

3 Inclusive Analyses, Kaon and Dipole

3.1 Topological Vertex Reconstruction

In both the Kaon and Dipole final state tag analyses, a novel topological vertexing technique for reconstructing the secondary vertices is employed [3]. Strict quality cuts are imposed on the tracks [2]. Secondary vertices are identified as regions of high track overlap probability, where tracks are represented as gaussian 3D probability functions, their transverse size reflecting impact parameter errors. The inclusive efficiency for reconstructing at least one secondary vertex in a b hemisphere is $\sim 50\%$. The secondary vertex farthest from the IP is selected in hemispheres containing more than one vertex. Additional tracks are associated with this "seed" vertex if they pass within 1 mm of the vertex axis (the line joining the IP to the seed) and if the distance between the IP and their point of closest approach to the vertex axis is at least 30% of the distance to the seed. The "P_T added" invariant mass of all the tracks associated with the secondary must exceed 2 GeV/c^2 in order to remove most of the light-quark and charm contamination [2]. Applying the mass cut yields a sample of 16803 decays with b hemisphere purity of 93% and efficiency of 36% (including the vertex reconstruction efficiency).

3.2 Final State Kaon Tag

The Kaon final state tagging technique uses the charge of identified kaons attached to the secondary vertex and exploits the fact that most B decays occur via the dominant quark transition $b \rightarrow c \rightarrow s$. The rate of right-sign kaon production is large and has been measured to be $(82 \pm 5)\%$ in B_d^0 decays [4]. Kaon identification is performed with the Cherenkov Ring Imaging Detector using information from both liquid and gas radiators. Separation between pion, kaon and proton hypotheses is carried out on the basis of differences in logarithms of likelihood ($\mathcal{L}_i$ with $i = \pi, K, p$) between these hypotheses. The particle identification performance is calibrated with a pure sample of pion tracks from $K_s^0 \rightarrow \pi^+\pi^-$ decays. The final state tag uses the sum of identified kaon charges in the vertex. The requirement $\sum Q_K < 0$ (> 0) tags $\overline{B_d^0}$ (B_d^0) decays. This K^-/K^+ tag is available for some 1/3 of the selected secondary vertices. MC shows that the probability for correctly tagging the final state is $P_K(b) = 77\%$ (81%) for $\overline{B_d^0}$ (B_u^-) decays. The number of decays passing the above selection criteria and used for the kaon tag measurement is 5694.

3.3 Final State Charge Dipole Tag

The $B \rightarrow D$ cascade charge structure is exploited to separate the final state $B^0/\overline{B^0}$ decay flavor. A sample enriched in B_d^0 decays is selected by requiring that the total charge of the tracks associated with the vertex is equal to zero. The direction of the vertex axis is adjusted in order to minimize the summed impact parameters of the tracks in the secondary vertex. The mean of the track impact parameters is required to be less than 50μm at this minimum. The charge dipole δq of the vertex is defined as the relative displacement between the weighted mean location L_i of the positive tracks and of the negative tracks along the vertex axis taking each track at its point of closest approach to the vertex axis: $\delta q = (\sum^+ w_i L_i)/(\sum^+ w_i) - (\sum^- w_i L_i)/(\sum^- w_i)$ where the first (second) term sums over all positive (negative) tracks in the vertex and the weight for track i is $w_i = \sin^2\theta_i/\sigma_{T_i}$ where θ_i is the angle between track i and the vertex axis and σ_{T_i} is the uncertainty in the impact parameter of track i to the vertex axis. Fig. 2 shows the charge dipole distribution for data compared with the Monte Carlo, including the MC distributions for $B_d^0(\bar{b})$ and $\overline{B_d^0}(b)$ separately. The correct tag probability for this final state tag increases

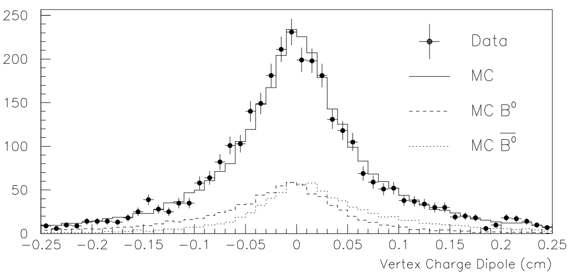

Figure 2: Distribution of the reconstructed charge dipole δq.

with the magnitude of δq, reaching a maximum of 84% in the tails. The purity of b quarks in vertices selected in Monte Carlo is used to parameterize the probability of a successful dipole tag as $P_D = 0.84\,e^{-|2.4\times|\delta q|-0.8|^3}$ where $P_D(b) = P_D$ or $1-P_D$ for $\delta q > 0$ or $\delta q < 0$ respectively. The final charge dipole selection cut requires $\delta q < 0.5$ cm, which yields a sample of 3291 decays [2].

4 Semileptonic Analyses

4.1 Lepton + D

In the first of the two semileptonic methods, the B decay vertex is taken to be the intersection of the trajectory of a decay lepton and a D meson candidate which is identified topologically. The lepton can be an electron or muon, with $p > 2$ GeV/c and momentum transverse to the nearest jet $p_t > 400$ MeV/c, where jets are found using the JADE algorithm with $y_{cut} = 0.005$. The D candidate is made up of tracks which miss the primary interaction point by at least 3.5σ. The D vertex momentum vector approximates the D trajectory. The point of closest approach between the D and lepton trajectories defines the B decay vertex, which is required to be at least 0.8 mm from the IP. Requirements to form acceptable B and D vertices, including cuts on the D to B pointing, are described elsewhere [5]. As a final step, other tracks in the hemisphere are attached to either the B or D decay vertices if the resulting vertices satisfy all cuts. In this analysis, a sample enriched in B_d^0 decays is obtained by selecting three neutral topologies: a single prong (the lepton) at the B vertex along with a three prong D; two prongs at the B vertex (the lepton and a transition pion from a D^*) along with either two or four prongs at the D vertex. The algorithm selects 582 neutral decays with a B_d^0 purity of 61% and less than 1% of residual udsc contamination [5].

4.2 Lepton + Tracks

The second semileptonic analysis exploits a high transverse momentum cut ($p_t > 0.8$ GeV/c) on identified leptons to enrich the sample in b hemispheres and to give a well measured line along which the B decay must have occurred. The B hadron decay position is estimated as the weighted average position along the lepton path of the points of closest approach of all the quality charged tracks in the jet containing the high-p_t lepton. The weights are adjusted to lessen the contribution to the weighted average from tracks emanating from the IP or long-lived cascade charm decays. By taking the average of many tracks (four on average) the resolution of the B decay position is improved and the vertex reconstruction efficiency is $\sim 98\%$. The core fraction of the Monte Carlo decay length residual is Gaussian with $\sigma \sim 170\mu$m. This analysis also makes an estimate of the relativistic boost of the B hadron by assuming energy and momentum conservation to determine the total energy of the jet containing the lepton (including any missing energy) [6]. The final sample consists of 2609 decays, with a B hadron purity estimated to be 93% using the Monte Carlo simulation. As is the case in both semileptonic analyses, the charge of the final state lepton is a simple and direct tag of the final state with a correct sign probability of $\sim 85\%$.

5 Results

The Kaon, Charge Dipole and Lepton + D analyses all use a χ^2 fit of the data fraction of decays tagged as mixed to the Monte Carlo in bins of reconstructed decay length. The lepton + Tracks analysis uses a likelihood fit to an analytic function for the mixing probability as a function of proper time. The results of the fits to the data are shown in Fig. 3. The fits yield measurements of $\Delta m_d = 0.580 \pm 0.066$ ps^{-1} with χ^2/dof $= 10.2/10$ for the kaon tag, $\Delta m_d =$

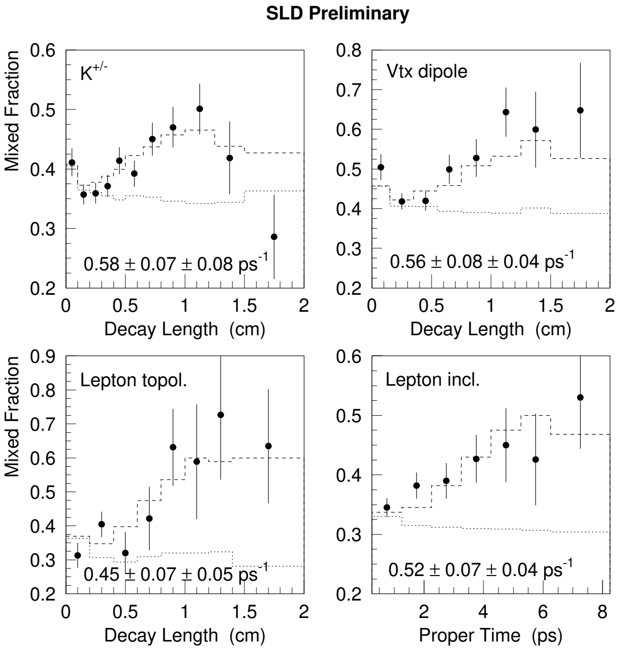

Figure 3: Fraction of mixed decays as a function of decay length for the kaon tag, dipole charge tag, and lepton+D analyses. For the Lepton+Tracks analysis, the fraction of of mixed decays is shown as a function of proper time. Shown are data (points), best fit MC (dashed histograms) and MC without B_d^0 mixing (dotted histograms).

0.561 ± 0.078 ps^{-1} with $\chi^2/\text{dof} = 8.8/7$ for the charge dipole tag, and $\Delta m_d = 0.452 \pm 0.074$ ps^{-1} with $\chi^2/\text{dof} = 7.8/7$ for the Lepton + D method. The maximum likelihood fit in the case of the Lepton + Tracks method yields a value of $\Delta m_d = 0.520 \pm 0.072$ ps^{-1}. A preliminary examination of the systematic errors has been made for all four analyses and is summarized in Table 1. Upon averaging the results of the four analyses, taking into account correlated statistical and systematic errors, we find the following SLD average for the mass difference between the two B_d^0 mass eigenstates: $\Delta m_d = 0.525 \pm 0.043(stat) \pm 0.037(syst)$ ps^{-1}.

References

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Systematic error	Uncertainty in Δm_d (ps^{-1})			
	Kaon Tag	Dipole Tag	Lepton + D	Lepton + Tracks
	Detector Modeling			
Tracking efficiency	0.006	0.010	0.017	< 0.001
Detector resolution	0.003	0.003	0.010	0.013
Kaon ID efficiency	0.035	—	0.003	< 0.001
	Physics Modeling			
b fragmentation	0.015	0.011	0.009	—
Boost	—	—	—	0.008
K^-, K^+ production	0.030	—	—	—
B.R.($B \to D^0X, D^+X$)	—	0.010	—	—
B.R.($B \to DDX$)	—	0.006	—	—
$b \to c \to l$	—	—	0.003	0.013
B.R.($B_d \to c \to l / b \to c \to l$)	—	—	0.003	0.006
B.R.($B \to D^{**}l\nu / B \to l\nu X$)	—	—	0.007	—
B.R.($B \to DDX$)	—	—	0.002	—
B multiplicity	0.005	0.008	—	—
B_u lifetime	0.010	0.001	< 0.001	< 0.001
B_d lifetime	0.004	0.008	0.004	0.009
B_s lifetime	0.010	0.002	0.009	0.001
B baryon lifetime	0.002	0.001	0.003	0.004
B_s fraction in $b\bar{b}$	0.016	0.007	0.004	0.014
B baryon fraction in $b\bar{b}$	0.021	0.003	0.002	0.015
B_s mixing	0.005	0.009	0.009	0.006
Charm decay multiplicity	—	0.002	—	—
Charm decay K^0 production	—	0.009	—	—
Charm lifetime	0.008	0.003	0.004	0.005
Tagging parameters	0.010	0.010	0.011	0.014
	Monte Carlo and Fitting			
Fit Systematics	0.042	0.016	0.032	—
MC Statistics	0.017	0.021	0.021	—
Total	0.075	0.039	0.049	0.035

Table 1: Summary of contributions to the systematic uncertainty in Δm_d for the four B_d^0–$\overline{B_d^0}$ mixing analyses.