TIME-DEPENDENT B_d^0–$\overline{B_d^0}$ MIXING MEASUREMENTS FROM SLD

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Four measurements of the time dependence of B_d^0–$\overline{B_d^0}$ mixing have been made using a sample of 150,000 hadronic Z^0 decays collected by the SLD experiment at the SLC. All analyses tag the B candidate at production using the large polarized forward-backward asymmetry together with the opposite hemisphere jet charge. Two of the analyses use 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 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 the current status of four measurements of time dependent B_d^0 mixing. Each uses a sample of 150,000 hadronic Z^0 decays collected between 1993 and 1995 by the SLD experiment at the SLAC Linear Collider (SLC). In all four analyses, the initial state is tagged as having originated from a b or a $\bar{b}$ quark using the polarized forward-backward b asymmetry in combination with the opposite side jet charge. The polarization tag is unique to the SLD experiment. Two of the analyses exploit 3D topological vertexing to determine the B meson decay length, but differ in the choice of final state tag. The first analysis ("Kaon") uses the charge of final state kaons identified in the CRID (Cherenkov Ring Imaging Detector) to tag the final state while the second analysis ("Dipole") takes advantage of the charge dipole observed using positive and negative tracks along the vertex line-of-flight. The remaining two analyses determine the B decay length by intersecting identified high (p, p_t) leptons with either a partially reconstructed D meson ("Lepton + D"), or the tracks in the b jet ("Lepton + Tracks"), with the final state being tagged by the sign of the high (p, p_t) lepton. Vertex charge is also used to enrich the neutral B mesons in the Dipole and Lepton + D analyses.

2 Initial State Tagging

The polarized forward-backward asymmetry, $\tilde{A}_{FB}$, is 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), P_e is the electron beam longitudinal polarization, and θ_T is the angle between the thrust axis and the electron beam direction. The thrust axis is signed such that it points in the same hemisphere as the reconstructed vertex. This asymmetry yields a useful separation of jets from initial b and $\bar{b}$ quarks, as illustrated in Figure 1. The probability for correctly tagging a b quark at production using this technique, expressed as $P_A(b) = 0.5(1 + \tilde{A}_{FB})$, is 76% (62%) for an average electron polarization $P_e = 77\%$ (63%). A jet charge initial state tag is also used in these analyses. For this tag, tracks in the hemisphere opposite that of the reconstructed vertex are selected.[1] These are used to construct 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 Figure 1. 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 $\alpha \sim -0.27$, 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 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 av-

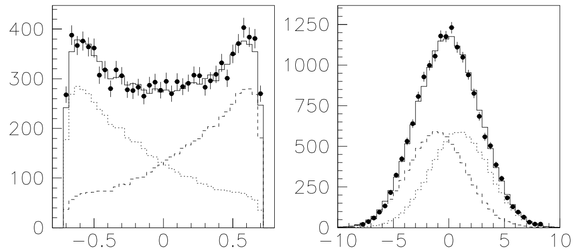

Figure 1: Initial state tag variables, polarization-signed $\cos\theta$ of the thrust axis (on left) and opposite hemisphere jet charge (on right), for data (points) and MC (solid line) with MC b and $\bar{b}$ quark components (dotted and dashed lines, respectively).

erage correct tag probability of 84%.

3 Inclusive Analyses, Kaon and Dipole

3.1 Topological Vertex Reconstruction

A novel topological vertexing technique for reconstructing the secondary vertices produced by weakly decaying hadrons in charged particle jets is employed in the Kaon and Dipole analyses.[2] Strict quality cuts are imposed on the tracks. Secondary vertices are identified as regions of high track overlap probability, where tracks are represented as gaussian 3D probability functions, their transverse size reflecting the relevant errors. The inclusive efficiency for reconstructing at least one secondary vertex in a b hemisphere is $\sim 50\%$. The vertex reconstruction efficiency is 80% for B hadron decays at lengths greater than 3 mm from the IP. The efficiency falls for shorter decay lengths. The secondary vertex farthest from the IP is selected in hemispheres having more than one vertex. Additional tracks are associated with the secondary if they pass cuts on their distance of closest approach to the line joining the IP to the secondary vertex (the vertex axis) and on the location of this distance of closest approach along the vertex axis. The "P_T added" invariant mass of all the tracks associated with the secondary is required to exceed 2 GeV/c^2 in order to remove charm contamination. This is the minimum mass the decaying hadron could have in order to produce a vertex with the measured invariant mass and track momentum transverse to the vertex line-of-flight. This mass cut yields a sample of 16803 decays with $Z^0 \to b\,\bar{b}$ purity of 93% and efficiency of 36% (including the vertex reconstruction efficiency).

3.2 Final State Kaon Tag

For the Kaon analysis, the final state tagging technique makes use of the correlation between the charge of kaons emanating from the secondary vertex and the flavor of the decaying b quark. The rate of right-sign kaon production has been measured to be $(82 \pm 5)\%$ in B_d^0 decays.[3] Kaon identification is performed with the CRID. Cuts are applied to guarantee acceptably low misidentification rates while keeping 65% of all secondary vertex tracks. Information from the gas and liquid radiators is combined to enhance the identification performance in the momentum range 2.5 to 4.0 GeV/c where the kaon spectrum from B decays peaks. The particle identification performance is calibrated with a pure sample of pion tracks from $K_s^0 \to \pi^+\pi^-$ 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

In the Dipole analysis, the $B \to D$ cascade charge structure is exploited to separate the final state $B^0/\overline{B}^0$ decay flavor.[1] An enhanced sample of 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 charge dipole δq of the vertex is defined as the relative displacement between the weighted mean location 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 w_i is the weight for track i, $w_i = \sin^2\theta_i/\sigma_{T_i}$ where θ_i is the angle between track i and the vertex axis and σ_{T_i} is an estimate of the uncertainty of the impact parameter of track i to the vertex axis. Figure 2 shows the charge dipole distribution for data compared

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

Systematic error	Uncertainty in Δm_d (ps^{-1})			
	Kaon	Dipole	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

with the Monte Carlo. Also shown are the MC distributions for $B_d^0(\bar{b})$ and $\overline{B_d^0}(b)$ separately. The

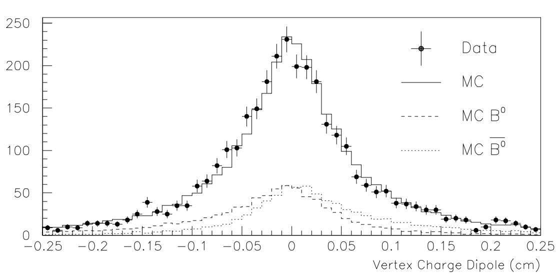

Figure 2: Distribution of the reconstructed charge dipole δq.

correct tag probability for this final state tag increases with the magnitude of δq, reaching a maximum of 84% in the tails. Using a selection cut of $\delta q < 0.5$ cm yields a sample of 3291 decays for the Dipole analysis.

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.[4] The lepton can be an electron or muon, with at least 2 GeV/c momentum and 400 MeV/c momentum transverse to the nearest jet. Two, three or four prong D candidates are allowed. A number of cuts on track and vertex characteristics are used to isolate a pure sample of D and B decays. Only neutral B meson candidates are used for the mixing analysis. Three topologies are allowed: 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. This algorithm selects 582 neutral decays from the 150K hadronic Z^0 sample. MC studies give the B composition of the neutral sample as 60.8% B_d, 19.6% B_u, 14.0% B_s, and 4.7% B baryon. The sample is estimated to have less than 1% residual udsc contamination.

4.2 Lepton + Tracks

The second semileptonic analysis exploits a high transverse momentum cut ($P_t > 0.8$ GeV/c) on identified leptons in hemispheres containing candidate b events to enrich the B sample and to give a well measured line along which the B decay must have occurred.[5] 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 hemisphere containing the high-P_t lepton. The weights are adjusted to lessen the contribution to the weighted average from tracks emanating from the interaction point 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. The core decay length residual (58% fraction) for this method is 170 μm. The technique is 98% efficient. This analysis also makes an estimate of the relativistic boost of the B hadron. The core width of the relative boost residual (50% fraction) is 8%. In the case of both semileptonic analyses, the charge of the final state lepton is a simple and direct tag of the final state b quark decay flavor with a correct sign probability of 85%.

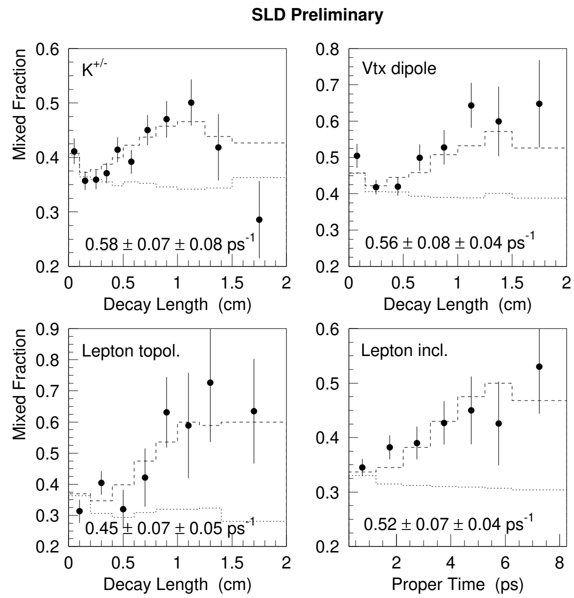

Figure 3: Fraction of mixed decays as a function of decay length for the Kaon (a), Dipole (b) and Lepton+D (c) analyses. In (d) is shown the fraction of mixed decays as a function of proper time for the Lepton+Tracks analysis. Shown are data (points), best fit MC (dashed histograms) and MC without B_d^0 mixing (dotted histograms).

5 Systematic Errors, Results and Conclusions

The Kaon, Dipole and Lepton + D analyses all use a χ^2 fit of the data mixed fraction 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 for Δm_d are shown in Figure 3. A preliminary examination of the systematic errors has been made for all four analyses (see Table 1). Combining the results, taking into account correlated statistical and systematic errors, the 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}.

References

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