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Search for $B_s^0 - \bar{B}_s^0$ Oscillations at SLD

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We present preliminary results on the time dependence of $B_s^0 - \bar{B}_s^0$ and $B_d^0 - \bar{B}_d^0$ mixing using a sample of 400,000 hadronic Z^0 decays collected by the SLD experiment at the SLC. The analyses take advantage of the excellent decay length resolution of the CCD vertex detector. The B or $\bar{B}$ production flavor is determined by exploiting the large forward-backward asymmetry of polarized $Z^0 \to b\bar{b}$ decays. This flavor tag is enhanced by incorporating additional information from the hemisphere opposite that of the reconstructed B decay. The $B_d^0 - \bar{B}_d^0$ mixing analysis uses the charge of high momentum kaons to identify the B or $\bar{B}$ decay flavor. The result is $\Delta m_d = 0.503 \pm 0.028(\mathrm{stat}) \pm 0.020(\mathrm{syst})\,\mathrm{ps}^{-1}$. The results of three separate $B_s^0 - \bar{B}_s^0$ mixing analyses are presented. These analyses determine the B decay flavor using the lepton charge in B semileptonic decays, the charge of fully reconstructed D_s decays, and the charge difference between topologically reconstructed B and D decays. The three analyses are combined to set a lower limit on the $B_s^0 - \bar{B}_s^0$ oscillation frequency of 12.0 ps^{-1} at 95% CL.

1. INTRODUCTION

In the neutral B meson system, second order weak interactions allow oscillations between the flavor eigenstates B^0 and $\bar{B}^0$ where B^0 refers to either B_d^0 or B_s^0. The oscillation frequency is determined by the mass difference, Δm_d or Δm_s, between the two mass eigenstates. In principle, a measurement of Δm_d allows the determination of the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{td}|$. Although Δm_d is now precisely measured, there exists a 15-20% uncertainty in the determination of $|V_{td}|$ due to uncertainties in the decay constant and "B" parameter from lattice QCD calculations[1]. If Δm_s can be measured, however, we may extract the ratio $|V_{td}|/|V_{ts}|$ from the measured $\Delta m_d/\Delta m_s$ with a reduced theoretical uncertainty of about 5-10% and thus provide a stronger constraint on the CKM parameters ρ and η.

Here we present results from one $B_d^0 - \bar{B}_d^0$ mixing analysis and three $B_s^0 - \bar{B}_s^0$ mixing analyses. These time-dependent mixing measurements require three main ingredients:

- The b quark flavor at production must be identified.
- The b quark flavor at decay must be identified.
- The proper time of the B decay must be determined.

All SLD analyses use the same initial state flavor tagging technique which exploits the polarization of the electron beam. The final state flavor tag and proper time reconstruction are analysis dependent. The B_d^0 analysis uses a novel technique employing a charged kaon as the final state tag. The three B_s^0 analyses will be denoted the D_s+Tracks, Charge Dipole, and Lepton+D. They determine the final state b quark flavor using the charge of a reconstructed D_s, charge dipole and high p_T lepton respectively. In all cases, the B decay length and boost ($\beta\gamma$) are reconstructed separately and the decay proper time is calculated as $t = L/\beta\gamma c$.

The results presented here were obtained using a sample of 400,000 hadronic Z^0 decays collected by the SLD experiment at the SLC between 1996 and 1998. SLD is particularly well suited for B physics due to the high-resolution CCD pixel vertex detector[2] which allows the precise location of B decay vertices in three dimensions. The track impact parameter resolution at high momentum is measured to be 7.8 μm in the xy projection and

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9.7 μm in the z projection. In addition, the luminous region produced by SLC is quite small and stable over many beam crossings. We are able to determine the interaction point with a resolution of about 3.5 μm in xy and 17 μm in z for $b\bar{b}$ events. Further details on the SLD detector may be found elsewhere [3].

2. TOPOLOGICAL VERTEXING

All SLD mixing analyses employ an inclusive topological vertexing technique[4] to locate secondary vertices. This technique locates *seed* vertices from regions of high track overlap probability and uses a neural network to attach other secondary tracks. At least one secondary vertex is located in 73% of b hemispheres and 28% of charm hemispheres. To enhance the fraction of $Z^0 \rightarrow b\bar{b}$ events we calculate the invariant mass of the secondary vertex making a correction for missing transverse momentum. Typically, events are required to have at least one secondary vertex with a p_T-corrected mass greater than 2 GeV in either hemisphere. The B selection efficiency is 57% and yields a B sample purity of 98%.

3. INITIAL STATE TAG

At SLD the highly polarized electron beam ($\langle P_e \rangle \approx 73\%$ in the 96-98 data) allows us to tag the initial state b quark flavor by exploiting the strong polarized forward-backward asymmetry of the b quark in $Z^0 \rightarrow b\bar{b}$ decays. The asymmetry, and thus the tag purity, depends on the initial $b\bar{b}$ quark directions which are approximated by the event thrust axis. The initial state tag also includes information from a standard jet charge technique using charged tracks in the hemisphere opposite the tagged B vertex. Finally, information from topological vertexing in the opposite hemisphere is included when available. The sensitive variables include the charges of high p_T leptons and high momentum kaons, as well as the vertex charge and charge dipole of secondary vertices. Information from the opposite hemisphere tags is combined with a neural network to determine the b quark probability. Finally, the result is analytically combined with the independent b quark probability determined from the polarization tag.

The initial state tag efficiency is 100% and has an average correct tag probability of 78%. However, the information is used on an event-by-event basis so a significant fraction of the events benefit from a very high tag purity. The initial state b quark probability distribution is plotted for the data and MC in figure 1. It indicates clear separation between b and $\bar{b}$ quarks and good agreement between data and MC.

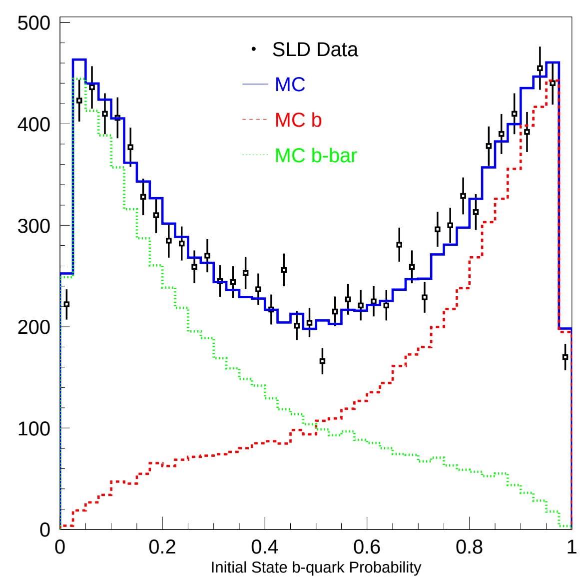

Figure 1. Distribution of the computed b-quark probability at production for data(points) and Monte Carlo (histograms) showing the b and $\bar{b}$ components.

4. $B_d^0 - \bar{B}_d^0$ MIXING WITH KAON TAG

The B_d^0 mixing analysis[5] tags the final state b quark flavor using the charge of high momentum kaons. This novel technique relies on the dominant quark decay sequence $b \rightarrow c \rightarrow s$ such that B_d^0 is tagged by a K^+ ($B_d^0 \rightarrow D^-/\bar{D}^0 \rightarrow K^+$)

and $\bar{B}_d^0$ is tagged by a K^-. The kaon right sign fraction in this decay was measured by the Argus Collaboration to be 82±5%[6].

Kaon tracks with momentum greater than 0.8 GeV/c are identified with the Cherenkov Ring Imaging Detector (CRID) and required to be included in a secondary topological vertex. If more than one track satisfies the selection criteria, the sum of their charges is used as the tag. A maximum likelihood fit is performed to determine the oscillation frequency and the kaon correct tag fraction simultaneously. The result is $\Delta m_d = 0.503 \pm 0.028(\text{stat}) \pm 0.020(\text{syst})\,\text{ps}^{-1}$ with a correct tag fraction of 0.797±0.022 for B_d^0 decays.

5. $B_s^0 - \bar{B}_s^0$ MIXING

5.1. D_s+Tracks

The D_s+Tracks analysis[7] attempts to reconstruct the decay $B_s^0 \to D_s^- X$ with full reconstruction of the D_s^- in two modes: $\phi\pi^-$ and $K^{*0}K^-$. In each case the decay products consist of a charged pion and two charged kaons which are identified with the CRID. Candidate D_s^- decays are selected using a neural network which considers the invariant mass of the ϕ and K^{*0} candidates, the D_s^- vertex probability and normalized decay length, the D_s^- momentum, and two helicity angles defined by the D_s^- daughters.

A pseudo-D_s^- track is constructed by combining the helix parameters and errors of the three daughter tracks. The B_s^0 decay position is located by intersecting the pseudo-D_s^- track with remaining tracks in the hemisphere that are inconsistent with production at the interaction point. To enhance the neutral B fraction, the total charge of all associated tracks is required to be 0 or ±1 (0) for the $\phi\pi^-$ ($K^{*0}K^-$) mode. The average decay length resolution for the B_s^0 signal can be described as the sum of two Gaussians with widths of 50 μm for the core (60%) and 151 μm for the tail.

The final sample includes 361 events consisting of 280 $D_s^- \to \phi\pi^-$ and 81 $D_s^- \to K^{*0}K^-$ decays with an average B_s^0 purity of 40%. The final state b quark flavor is tagged by the charge of the D_s^-. The mistag probability is roughly 10% for hadronic B_s^0 decays and 5% for semileptonic decays (39 events).

5.2. Charge Dipole

The charge dipole technique[8] aims to reconstruct both B and D decay vertices and tags the B_s^0 or $\bar{B}_s^0$ decay flavor based on the charge difference between these vertices. The method relies on the fact that the B and D flight directions are very nearly collinear and the decay points are separated along the flight direction due to the finite D lifetime.

Secondary decay tracks, identified through topological vertexing, are used to locate a *ghost* axis which approximates the original B decay line of flight. B and D decay vertices are then located along the ghost axis. The advantage of this technique is that it allows for the reconstruction of 1-prong vertices. Hemispheres with exactly two secondary vertices are selected and the distance between these vertices is required to satisfy 250 $\mu\text{m} < L_{BD} < 1$ cm. To enrich the sample in neutral B decays, the vertex charge is required to be 0.

A sample of 11,462 decays is selected with a B_s^0 purity of 16%. The decay flavor is tagged by the sign of the *charge dipole* defined as $\delta Q = L_{BD} \times SIGN(Q_D - Q_B)$, where $Q_B(Q_D)$ is the charge of the B (D) vertex. The average mistag probability for B_s^0 decays is estimated to be 22%. Much of the mistag is due to decays of the type $B_s^0 \to D\bar{D}X$ which accounts for 24% of the selected B_s^0 decays where the mistag rate is 46%. The average decay length resolution for correctly tagged $B_s^0 \to D_{(s)}X$ decays containing three or more tracks can be described as the sum of two Gaussians with a 60% core width of 78 μm and tail width of 304 μm.

5.3. Lepton+D

The Lepton+D analysis attempts to reconstruct semileptonic B decays $B_s^0 \to D_s^- \ell^+ \nu$ where the lepton is either an electron or muon. The b quark decay flavor is tagged by the charge of the lepton. The analysis performs an inclusive reconstruction of the D decay via topological vertexing. This vertex is then intersected with the lepton track to locate the B decay point. A neural network is employed to separate the direct $b \to \ell$ decays from the cascade $b \to c \to \ell$ decays which produce wrong-sign leptons. The resulting final state mistag rate is roughly 4% for the signal B_s^0 decays. By requiring the B vertex charge to be 0, the B_s^0 sample purity is increased to 16%. In those events where a kaon with charge opposite that of the lepton is associated with the B decay, the B_s^0 fraction is increased to 34%.

A total of 2087 events are selected in the data. The decay length resolution is described by the sum of two Gaussians where the core Gaussian (60%) has a width of 54 μm and the tail Gaussian has a width of 213 μm.

5.4. $B_s^0 - \bar{B}_s^0$ Mixing Results

The study of the time dependence of B_s^0 mixing is carried out using the amplitude method[9]. The analysis is performed at fixed values of Δm_s and a likelihood fit for the amplitude $\mathcal{A}$ of the oscillation is performed. We expect $\mathcal{A} \approx 1$ for Δm_s near the true value and $\mathcal{A} \approx 0$ far from the true value. If a measurement of Δm_s cannot be made, we may exclude at 95% CL any value of Δm_s for which $\mathcal{A} + 1.645\sigma_{\mathcal{A}} < 1$ where $\sigma_{\mathcal{A}}$ is the combined statistical and systematic error on $\mathcal{A}$.

The amplitude fit has been performed on the three analyses presented here and the combined results are shown in figure 2. To avoid statistical overlap, the event sample is divided among the three analyses with the D_s+Tracks receiving highest priority followed by the Charge Dipole and finally the Lepton+D. Combining the three analyses we see no evidence of a significant signal and determine $\Delta m_s > 12.0$ ps^{-1} at 95% CL. The sensitivity of the experiment is 13.5 ps^{-1}. Systematic uncertainties have been evaluated for the sample composition, initial and final state flavor tagging, B lifetimes, Δm_d, and detector resolution modeling.

6. CONCLUSIONS

We have presented preliminary results on $B^0 - \bar{B}^0$ mixing using 400,000 hadronic Z^0 decays at SLD. Using a charged kaon final state tag, the $B_d^0 - \bar{B}_d^0$ oscillation frequency has been measured to be $\Delta m_d = 0.503 \pm 0.028(\text{stat}) \pm 0.020(\text{syst})\,\text{ps}^{-1}$. Combining three separate $B_s^0 - \bar{B}_s^0$ mixing analyses we see no evidence for a significant signal and, therefore, set a lower limit on the oscillation frequency. We determine $\Delta m_s > 12.0$ ps^{-1} at 95% CL.

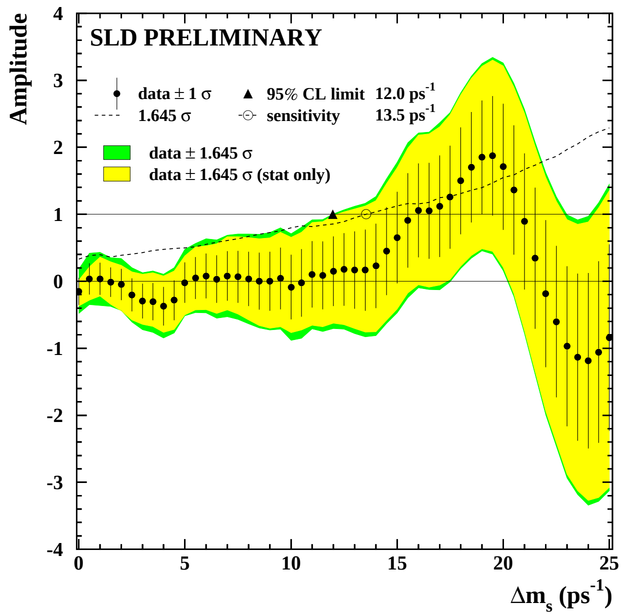

Figure 2. SLD combined amplitude fit.

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