B_s Oscillation at LEP and SLC

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1. INTRODUCTION

Seeing the time dependence and measuring the oscillation frequency, Δm_s, of $B_s^0 - \bar{B}_s^0$ mixing will allow the CKM element V_{td} to be determined with four times the accuracy of the current determination, which derives from the measurement of Δm_d. The resulting change in accuracy could be decisive in demonstrating that the Wolfenstein parameter which describes CP violation, η, is non-zero. In the longer term, a precise determination of V_{td}, together with a measurement of $\sin 2\beta$, will provide the most accurate determination of the Wolfenstein parameters ρ and η, and so complete the determination of the CKM matrix or point to fundamental inconsistencies in this description of quark mixing.

$B_q^0 - \overline{B_q^0}$ ($q = d$ or s) flavour oscillations are a typical quantum mechanical effect. The mass eigenstates are a linear superposition of the flavour eigenstates. Neglecting CP violation and width differences of the two mass eigenstates, the time evolution of initially produced B_q^0 mesons violates flavour conservation and the probability to decay as a $\overline{B_q^0}$ at proper time t is given by

$$P_{B_q^0 \to \overline{B_q^0}}(t) = \frac{\Gamma_q e^{-\Gamma_q t}}{2}\left[1 - \cos(\Delta m_q t)\right], \qquad (1)$$

where Γ_q is the decay width of the B_q^0 meson and Δm_q is the mass difference between the two mass eigenstates, which gives the oscillation frequency.

Theory links the measured oscillation frequency of B_d^0 (B_s^0) mesons to the CKM element V_{td} (V_{ts}), but with proportionality factors that are imperfectly known. However, in the ratio of the frequencies,

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s} f_{B_s}^2 B_{B_s} |V_{ts}|^2}{m_{B_d} f_{B_d}^2 B_{B_d} |V_{td}|^2} \qquad (2)$$

much of the uncertainty drops out [1]. Since $|V_{ts}|$ is constrained by unitarity of the CKM matrix to equal $|V_{bc}|$, and $|V_{bc}|$ is well-measured, the relation above allows a precise determination of $|V_{td}|$.

Expectations for Δm_s place it near the sensitivity limit of today's experiments. We know that B_s^0 mesons do mix, since the measurement of the time integrated mixing probability at LEP, $\bar{\chi} = 0.118 \pm 0.005$, is much greater than would be expected from B_d^0 mixing alone ($\bar{\chi} \approx 0.070$). These measurements imply B_s^0 mixing is maximal, but only weakly constrain $\Delta m_s (> 0.9\, ps^{-1}$ 95%CL) [2]. An estimate of Δm_s can be extracted from the formula above by taking V_{td} from the measured value of Δm_d, using theoretical estimates for the decay constant and bag factor. We are led to expect Δm_s in the range 11–23 ps^{-1}. More sophisticated analyses lead to essentially this same range [3]. The lifetime difference of the two B_s^0 mass eigenstates is proportional to Δm_s; present measurements imply $\Delta m_s = 16 \pm 9\, ps^{-1}$, with an additional 30% theoretical uncertainty [4]. In sum, the Standard Model expectation for Δm_s is roughly in the range 10–20 ps^{-1}. Since ICHEP 98 the world combined B_s^0 oscillation data has been suggestive of a signal at $\Delta m_s \sim 15\, ps^{-1}$, compatible with this range of values. This has led us all to hope that a definitive observation is just around the corner. It has also emphasized the need for enhanced sensitivity in these measurements.

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2. Methods of investigation

At LEP, $b\bar{b}$ pairs are produced in about 22% of hadronic decays of the Z. The relative proportion of B^+, B_d^0, B_s^0 and b-baryons is about $4:4:1:1$.

From an experimental point of view, the strategy to resolve the time evolution of the oscillations is the following: enrich the sample in B_s, tag the B_s or $\overline{B_s}$ nature at production and decay time, measure the B_s proper time at decay and finally extract Δm_s from a maximum likelihood fit to mixed an unmixed events

In order to gauge the power of an analysis it is customary to use the following quality factor :

$$S \approx \sqrt{N} f_q(1-2\eta)\exp\left[-0.5(\Delta m_q \sigma_t)^2\right] \quad (3)$$

where N is the total number of selected events, f_q is the purity of the B_q^0 mesons, η is the total mistag defined as the probability of tagging incorrectly the B nature, either at production or decay time, and σ_t is the average proper time error, which is given by the combination of decay length resolution σ_l and momentum resolution σ_p

$$\sigma_t \approx \sigma_l \cdot m/p \oplus (\sigma_p/p)\cdot t. \quad (4)$$

Only a handful of events can be completely reconstructed in very specific decay modes, such as $B_s^0 \to D_s^- \pi^+$, but they offer a very good proper time resolution (of the order of 0.08 ps) and are useful for the B_s oscillation analyses. Semi-exclusive analyses use partially reconstructed decays such as $\overline{B_d^0} \to D^{\star +}\ell^-\overline{\nu}$ or $\overline{B_s^0} \to D_s^+\ell^-\overline{\nu}$ with fully reconstructed D mesons. The decay length resolution for such analyses is good, since all tracks are measured, while the momentum of the B meson has to be evaluated using missing energy techniques. The flavor at decay time is well identified by the lepton charge, but the total yield is not very large.

Leptons with high p_T with respect to the jet axis, coming mainly from b decays, offer a valid alternative yielding the largest samples available for oscillation measurements, at the expense of a reduced purity and slightly worse proper time resolution. The b decay vertex is reconstructed using the lepton together with tracks from the charm decay, giving good decay length resolutions, but the momentum reconstruction is more problematic due to the need to distinguish tracks coming from the decay from the ones from fragmentation. Also in this case the lepton charge is used for tagging the flavor at decay time. In general, the flavor at production time is determined combining the available information from both sides of the event. A variety of information is conveyed into discriminating variables, mainly from vertex and jet-charges as well as opposite side lepton information, to give an initial mistag rate of about 24% to 30%.

3. LEP B_s^0 oscillation studies

The study of B_s^0 oscillation at LEP has been performed by ALEPH, DELPHI and OPAL. No individual experiment has been able so far to directly observe B_s^0 oscillations, so the present analyses give only lower limits on Δm_s. This is done using the amplitude method described in Ref. [5], which consists of multiplying the oscillating term in Equation 1 by an amplitude A. For each value of the testing frequency ω, the amplitude $A(\omega)$ is measured in each analysis, from a likelihood fit to the time distribution of events tagged as mixed and unmixed. The value of ω for which the amplitude is consistent with being unity, within errors, gives the estimated Δm_s. Vice versa, A is expected to be compatible with zero below the true oscillation frequency. At a given frequency ω, the measured amplitude follows a Gaussian distribution and its error does not depend on the value of the true frequency. Therefore, if at a given frequency ω the measured amplitude is $A(\omega)$, with an error $\sigma_A(\omega)$, this value of frequency can be excluded at 95% CL if

$$A(\omega) < 1 - 1.645\sigma(\omega). \quad (5)$$

The largest frequency for which $1.645\sigma(\omega) < 1$ is called sensitivity.

The very fast oscillations need careful tuning of all ingredients. Each analysis uses different decay length resolution classes and B_s^0 purity classes to optimally enhance the power of a sets of data. Since the proper time resolution increases with proper time proportionally to the momentum resolution, in order not to decrease the impact of events with large proper times, which have also less background, particular care has to be taken minimizing the momentum resolution.

The most powerful individual analysis is the one from ALEPH[6] which uses inclusive leptons, and has recently been updated profiting from a reprocessing of the data which improves tracking as well as particle identification.

Events with at least one candidate lepton are selected within the silicon vertex detector acceptance. The b decay vertex is determined by vertexing the lepton with a set of tracks kinematically compatible with coming from a charmed hadron, detached from the primary vertex. The addition of a b track in the vertex fit, having the jet direction and passing through the primary event vertex, significantly improves the decay length resolution, achieving a core resolution of about 200μm. Resolution classes are defined, with the purpose to enhance the power of the analysis. The momentum of the b hadron is computed using the lepton and charm tracks momenta together with an estimate of the neutrino energy coming from a missing energy technique with an average resolution of about 10%.

The b hadron purity of the sample is increased by means of a discriminating variable, combining lifetime and lepton information, leading to an average purity of 98% using about 74000 events. The $b \rightarrow \ell$ fraction is estimated from a different neural network designed to discriminate $b \rightarrow \ell$ from $b \rightarrow c \rightarrow \ell$.

The fraction of B_s^0 meson is evaluated on an event-by-event basis, by using a neural network which uses several estimators. Neutral B mesons can be distinguished from $B^{\pm}$ using variables related to the charge and track multiplicity of the vertex, while the presence of fragmentation kaons helps in distinguishing B_d^0 from B_s^0. The sign correlation between the charged kaons among the charm tracks and the lepton from the b decay is also used.

The B_s^0 flavor state at decay time is given by the lepton charge, while at production it is estimated on an event-by-event basis using sets of discriminating variables from both hemispheres of the event. The effective mistag is about 24%. The inclusive lepton analyses have been complemented using three different techniques: semi-exclusive reconstruction of $D_s - \ell$[7–9] and D_s−hadron events[10,11], fully inclusive reconstruction[12] and fully reconstructed events[7]. This gives decay length resolutions of the order of 200μm. The momentum resolution is of the order or better than 10%. In the $D_s - \ell$ channel the main background comes from combinatorics and amounts to about 40% while the physical background coming from $B \rightarrow \overline{D^{(*)}} D_s^{(*)}$, $D \rightarrow \ell$ is reduced to about 10% using its different topology with

The fully inclusive analysis by DELPHI benefits from the large statistics, and has to use neural networks to enhance the small intrinsic purity as well as initial and final state flavor tags, having neither leptons nor D_s in the final state. The momentum is reconstructed in a inclusive way and in different classes of charged tracks per hemisphere, varying from 4% to 15% resolution. Different classes in secondary vertex quality were built to parameterize the decay length resolution, which ranges from 250 to 350 μm. Including systematic uncertainties, the sensitivity of the analysis is 4.9 ps^{-1}.

Only about 50 events per experiment with an average purity of 50% have been used by ALEPH and DELPHI in the fully reconstructed hadronic decay channels of the B_s^0: $D_s^+ \pi^-, D_s^+ a_1^-$ and $D^0 K^+ \pi^-$. These events are particularly clean and are those where the final state tag has the lowest mistag, close to zero. The momentum is known to better than 1% and the decay length resolution is of the order of about 150μm, giving a proper time resolution of about 0.08 ps. The initial state tag is determined combining the information from both sides of the event. For small values of the oscillation frequency the contribution of these analyses is negligible, but they help for $\Delta m_s > 15$ ps^{-1}, thanks to the superior proper time resolution, which is almost completely dominated by the decay length resolution, therefore equally weighting events with large and small proper times.

The amplitude spectra measured by the different analyses are combined, after having rescaled their central values and systematic uncertainties. In particular, the B_s^0 fraction in an unbiased sample of weakly decaying b-hadrons has been set to

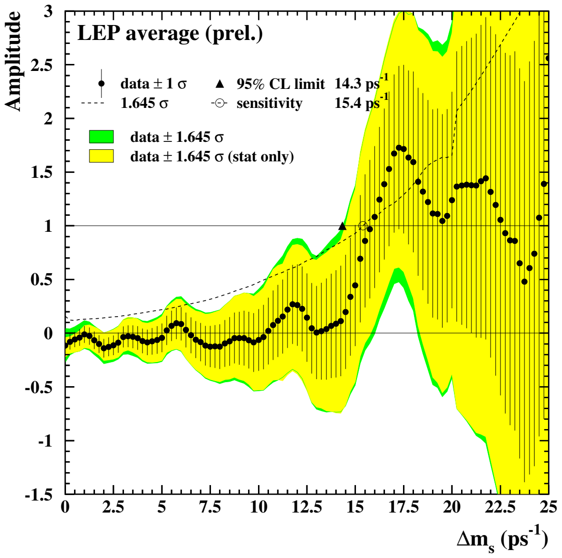

Figure 1. Amplitude as a function of Δm_s for the combined LEP data .

$9.8 \pm 1.2\%$. Figure 1 shows the LEP combined amplitude spectrum: all values below 14.3 ps^{-1} are excluded at 95% confidence level, with an expected limit of 15.4 ps^{-1}.

4. SLD B_s Oscillation studies

The SLD experiment [13] complements the extensive experimental work done at LEP on B_s^0 mixing by bringing two unique tools to bear on the measurement problems. SLD suffers a decided luminosity disadvantage vis a vis the LEP experiments. SLD accumulated about 400 K Z^0 decays compared to roughly 4 M Z^0 decays per LEP experiment. This statistical disadvantage is offset by the presence of electron beam polarization, which enhances initial state flavor tagging, and CCD vertex detection, which has demonstrated world record impact parameter resolution.

The vertex detector [14] achieves better than 4 μm space point resolution. The interaction point, which is micron-sized at the SLC, is known to $\sigma_{xy} = 4\,\mu m$ and $\sigma_z = 20\,\mu m$.

The electron beam is routinely polarized to 73%. This produces polarized Z^0 bosons, which decay to b quark pairs with nearly maximal forward-backward asymmetry [15]. Knowledge of the polarization and the polar angle of the B decay in question therefore allows an a priori assignment of the initial state flavor. This "polarization" tag is 100% efficient, and assigns flavor correctly 72% of the time. The polarization tag is augmented with other tags based on properties of the jet opposite the B_s^0 meson candidate.

SLD follows three different avenues to identify B_s^0 candidates and tag final state flavor. Details describing event selection and likelihood fits are in Refs. [16] and [17].

The first of these approaches uses the exclusive reconstruction of a D_s meson into the final states $\phi\pi$ and K^*K. SLD's Cerenkov Ring Imaging Detector [18] identifies kaons and pions. Selecting a D_s meson significantly enhances the B_s^0 fraction in these events; and of course the charge of the D_s meson tags the flavor of the B_s^0 at decay. The B_s^0 decay point is found by first vertexing the D_s decay products, reconstructing a D_s trajectory from the vertex position and net momentum direction, and then vertexing that trajectory with other secondary tracks in the jet. Excellent decay length resolution is obtained ($\sigma_l = 48\,\mu m$). Monte Carlo studies lead us to conclude that 38% of the observed D_s's are from B_s^0 decays. The correct tag fraction is 87%, diminished principally by the occurrence of B_s^0 decays to two charmed mesons. The sample statistic is obviously small, but the good sample purity and excellent decay length resolution lead to appreciable significance at high Δm_s.

The second approach uses events with well-identified leptons and topologically identified D mesons. In all, 2087 decays are chosen after excluding any events which overlap with the selection above. The D meson is identified as a separated vertex; again a D meson trajectory is reconstructed from the vertex information and the net momentum of the tracks included in the D vertex. The D trajectory is vertexed with the lepton and any other secondary tracks to find the B decay point. Demanding the net vertex charge be zero boosts the B_s^0 fraction of these candidates to 16%. A neural net is used in candidates selection. The B to D decay distance, lepton impact parameter with respect to the D vertex, the lepton p_t, and other variables discriminate against cascade decays (*i.e.* $B \to D \to l$). The charge of the lepton signs the b flavor, yielding an excellent 96% correct tag fraction.

The third approach is the most inclusive, and makes use of the fact that the decay of a neutral B_s^0 meson into a single, charged D_s meson gives rise to B and D vertices of opposite charge. The sign of the resulting "charge dipole" tags the B_s^0 flavor. The analysis begins by identifying events which have distinguishable secondary (B) and tertiary (D) vertices, and have net vertex charge zero. This selects 8556 events, of which 15% are expected to be B_s^0 decays. Events which have been selected in either of the previous two analyses are excluded. The charge dipole, defined as $D = \mathrm{sign}(Q_D - Q_B) \cdot L_{BD}$, where L_{BD} is the distance between the secondary and tertiary vertices, effectively tags b and $\bar{b}$ quarks. The average correct sign fraction is 76%. The B decay point is reconstructed by vertexing B tracks with a virtual D track as above, and is known to 72 μm precision. Figure 2 shows the combined result of the three analyses. With sensitivity as high as 13 ps^{-1}, SLD proves to be an equal competitor to LEP.

5. Summary

The individual results of LEP and SLD were combined using the Amplitude method as shown in figure 3. The present limit on the oscillation frequency is set to 14.6 ps^{-1} while the sensitivity is as high as 18.3 ps^{-1}. Further examination of the figure revels a hint of a signal around 17 ps^{-1}. This departure from zero, at a level of 2.6 σ, and the fact that it is above the combined sensitivity, require extra caution when interpreting. However, a closer examination of the individual experiment results, shown in figure 4, suggests that most of the upward pull around 17 ps^{-1} is a result of the ALEPH measurements. Furthermore, the figure also demonstrates the need to include less successful experiment whose limit is far inferior to others but yet can balance and shed light on the overall picture.

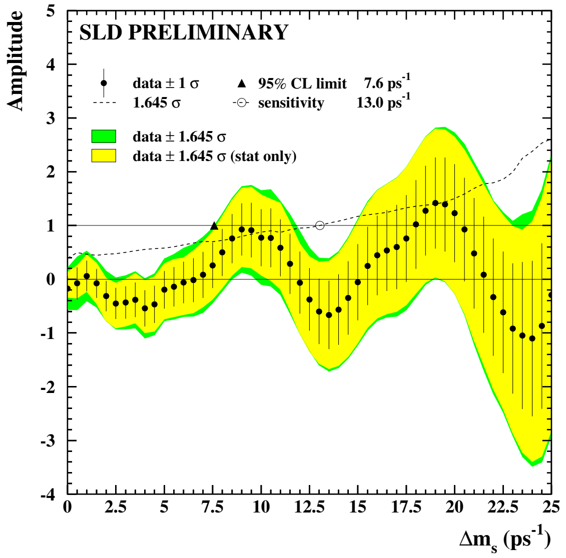

Figure 2. Amplitude as a function of Δm_s for the combined SLD analyses .

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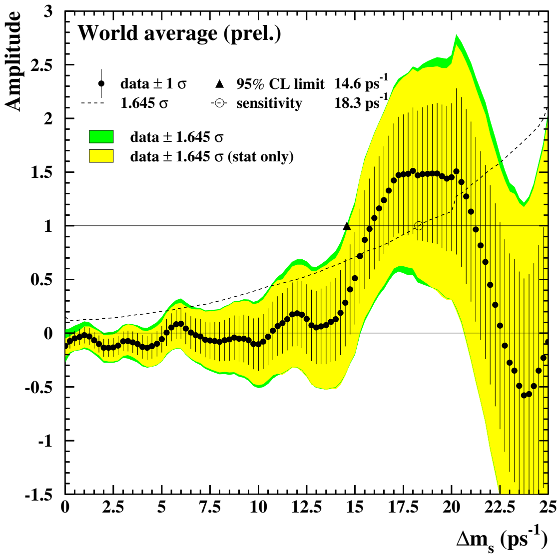

Figure 3. Amplitude as a function of Δm_s for the combined LEP and SLD analyses .

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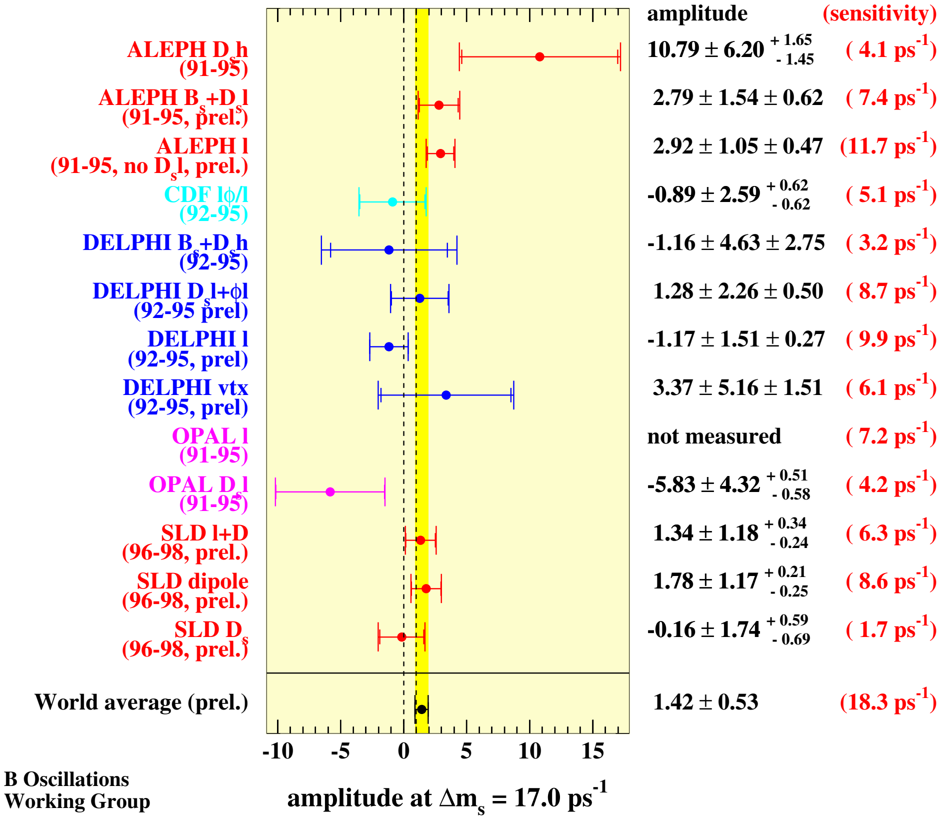

Figure 4. Amplitude values for $\Delta m_s = 17 ps^{-1}$ for all reported analyses.