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The Search for B_s^0 Oscillations at SLD *

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Abstract

The SLD experiment at the SLAC Linear Collider has updated three searches for the time dependence of B_s^0 oscillations. One search uses events with a reconstructed D_s meson; a second search uses events with a lepton and a topologically identified charmed meson; and the third uses events in which both a secondary and tertiary vertex are distinguished. The combined analyses are sensitive to values of Δm_s, the oscillation frequency, up to 13.0 ps^{-1}. A preliminary maximum likelihood analysis excludes $\Delta m_s < 7.6\,ps^{-1}$ and $11.8 < \Delta m_s < 14.8\,ps^{-1}$ at 95% CL. Including this data, the combined world data now imply $\Delta m_s > 15.0\,ps^{-1}$ at 95% CL, and are not incompatible with a signal near the expected value, $\Delta m_s \sim 15\,ps^{-1}$.

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1 Introduction

Why search for B_s^0 oscillations? Seeing the time dependence and measuring the oscillation frequency, Δm_s, of $B_s^0 - \overline{B_s^0}$ 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. See Ref. [1] for a more detailed discussion of B_s^0 mixing phenomenology.

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. In the ratio of the frequencies,

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s} f_{B_s}^2 B_{B_s} |V_{ts}|^2}{m_{B_d} f_{B_d}^2 B_{B_d} |V_{td}|^2} = (1.11 \pm 0.06)^2 \frac{|V_{ts}|^2}{|V_{td}|^2} \ , \tag{1}$$

much of the uncertainty drops out [2]. 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, $\overline{\chi} = 0.118 \pm 0.005$, is much greater than would be expected from B_d^0 mixing alone ($\overline{\chi} \approx 0.070$). These measurements imply B_s^0 mixing is maximal, but only weakly constrain $\Delta m_s (> 0.9\, ps^{-1}$ 95%CL) [3]. 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 [4]. 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 [5]. In sum, the Standard Model expectation for Δm_s is roughly in the range 10–20 ps^{-1}. Since ICHEP 98 the world average 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 underscored the need for enhanced sensitivity in these measurements.

2 Measurement Tools

The SLD experiment [6] complements the extensive experimental work done at LEP and CDF 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 with its upgraded vertex detector during 1996–1998, 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 [7] achieves better than 4 μm space point resolution. Consisting of three overlapping layers of large area CCDs, the first of which is only 2.5 cm from the IP, the vertex detector achieves impressive impact parameter resolution: $\sigma_{xy} = 7.8 \oplus 33/p(GeV/c)\sin^{3/2}\theta\,[\mu m]; \sigma_{rz} = 9.7 \oplus 33/p(GeV/c)\sin^{3/2}\theta\,[\mu m]$. 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%, and the polarization is flipped randomly beam crossing to beam crossing. Polarization is monitored to high accuracy with a Compton Polarimeter [8].

3 Measuring Time Dependent Mixing

The excellent detector performance pays off handsomely for B_s^0 mixing measurements. Time-dependent oscillation studies require three quantities be measured: (1) flavor at production; (2) flavor at decay; (3) proper decay time.

The proper decay time is determined by measuring the decay length and the B meson momentum (or boost). The excellent impact parameter resolution leads to decay length resolution in the 50 to 75 μm range, several times better than that of competing experiments. Linkage of central drift chamber tracks to the vertex detector is essentially error free and highly efficient thanks to the pattern recognition capability of the CCDs. The tracking efficiency is enhanced by using tracks found exclusively in the vertex detector. By requiring hits in each of the three layers, track reconstruction is essentially noise-free. Remarkably, given just a few centimeters of path length, the vertex detector determines track charge reasonably well for transverse momenta up to about 4 GeV/c. The resulting increase in net tracking efficiency improves the charge resolution for detached vertices, which in turn improves initial state tagging (by selecting $Q = \pm 1$) and increases the B_s^0 fraction in the sample (by selecting $Q = 0$).

Good proper time resolution is required to see high frequency oscillations since the experimental sensitivity reduces exponentially when $\Delta m_s > \sigma_t^{-1}$. Given SLD's excellent decay length resolution, it is the boost resolution which limits the proper time resolution. The low statistics sample precludes the use of exclusive state reconstructions which could determine the B meson momentum accurately. In our inclusive analyses, the boost resolution is modest, at best around 7%. The proper time resolution is consequently best at short proper times, and degrades almost linearly as proper time increases: $\sigma_t = (\sigma_L/\gamma\beta c) \oplus (\sigma_p/p)t$. At best, $\sigma_t < .05\, ps^{-1}$, giving SLD a considerable advantage in exploring high Δm_s.

Polarized electrons, which are unique to the SLC/SLD, produce polarized Z^0 bosons, which decay to b quark pairs with nearly maximal forward-backward asymmetry [9]. 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. We use a variety of tags which are characterized by their efficiency and correct tag fractions: Jet Charge (100%,66%); Vertex Charge (43%,75%); Kaon Charge (16%,74%); Lepton Charge (9%,74%); and Dipole Charge (17%,70%). Initial state correct tag fractions are lower than those for final states because of the presence of B mixing. All the available tags are combined and correlations accounted for in deriving a net initial state tag, which is correct 78% of the time and has many events with high purity tags. See Fig. 1.

4 Three Analyses

We follow three different avenues to identify B_s^0 candidates and tag final state flavor. Details describing event selection and likelihood fits are in Refs. [10]

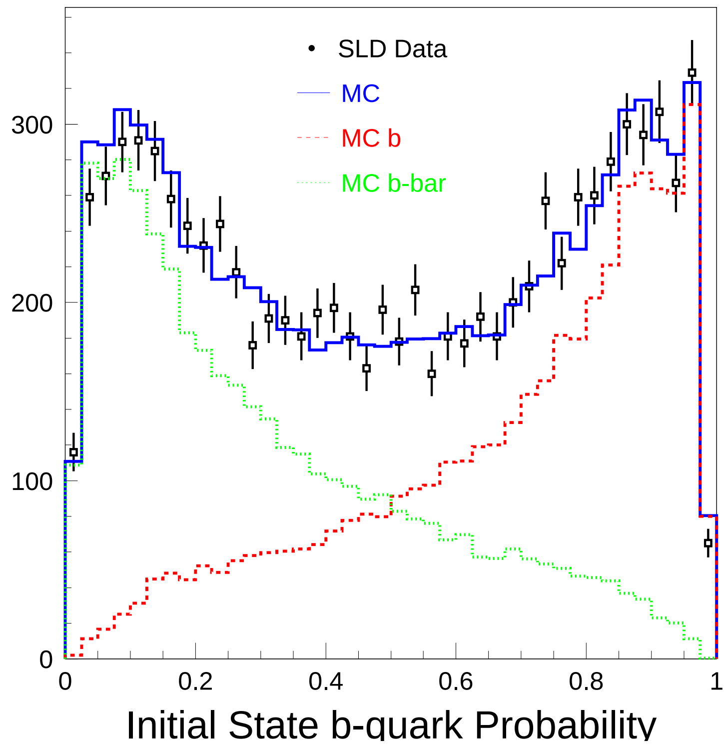

Figure 1: Distribution of the Combined Initial State b quark Probability. The b and $\overline{b}$ components are shown separately. The data (points with error bars) agree well with the sum of these components.

and [11].

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 [12] 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. Figure 2 shows that a clean signal is observed in the D_s channel, 361 decays in all. 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 event. 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.

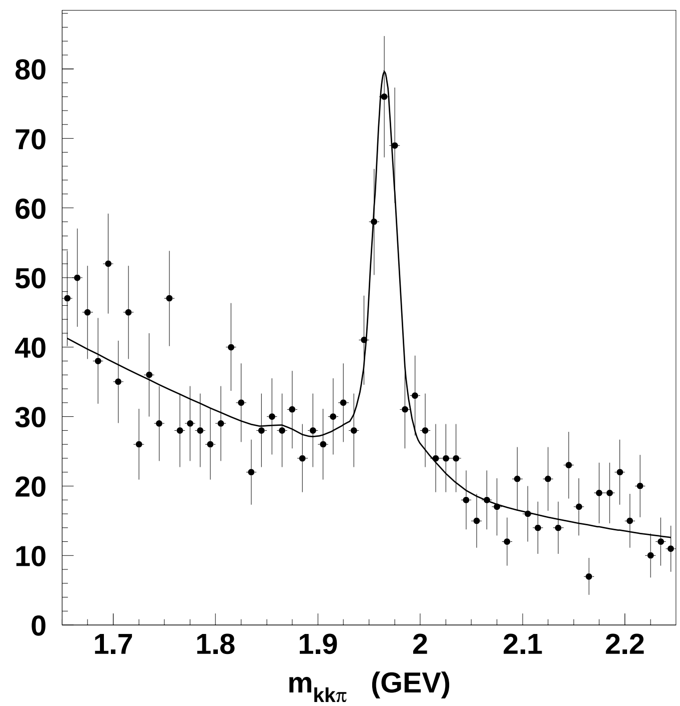

Figure 2: Invariant mass of $K^+K^-\pi^\pm$ combinations in $Z^0 \to b\bar{b}$ events. A clear peak corresponding to D_s production is evident.

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 in these events to 16%. A neural net is used in event 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 expected polarized forward-backward asymmetry gives a good check that the analyzing power is correctly simulated. Figure 3 demonstrates good agreement between the data and the Monte Carlo.

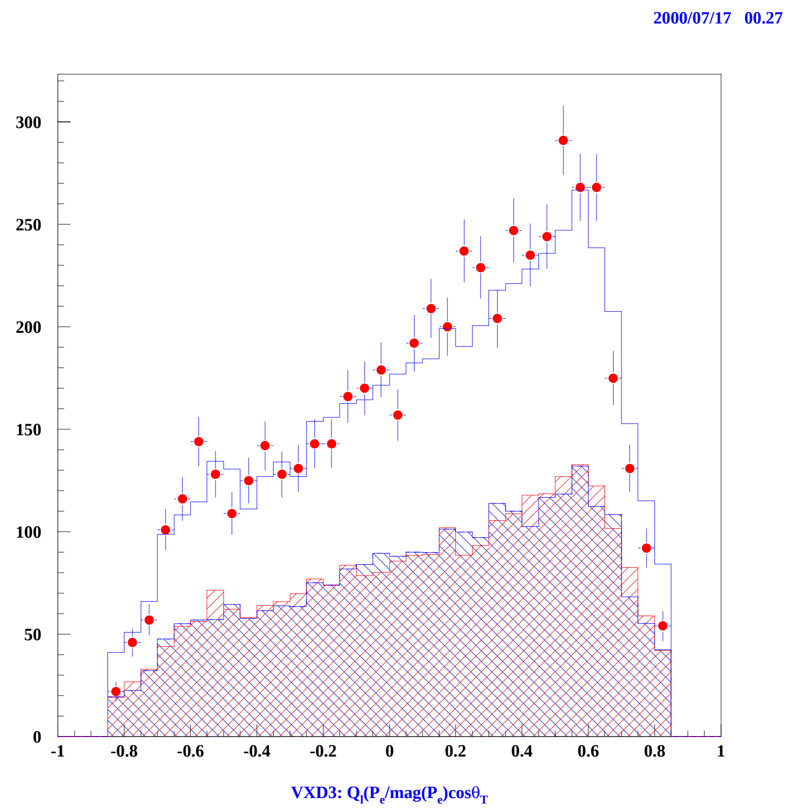

Figure 3: Asymmetric Angular Distribution of B jets in Polarized Z^0 Decays. The polar angle is signed with the product of the lepton charge and sign of the electron polarization. The agreement of data and Monte Carlo confirms our estimate of the tag's analyzing power.

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 $D = \text{sign}(Q_D - Q_B) \cdot L_{BD}$, where L_{BD} is the distance between the secondary and tertiary vertices, is displayed in Fig. 4. As the figure shows, the dipole effectively tags b and $\overline{b}$ quarks, and the data are well-described by the Monte Carlo. 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. Checks

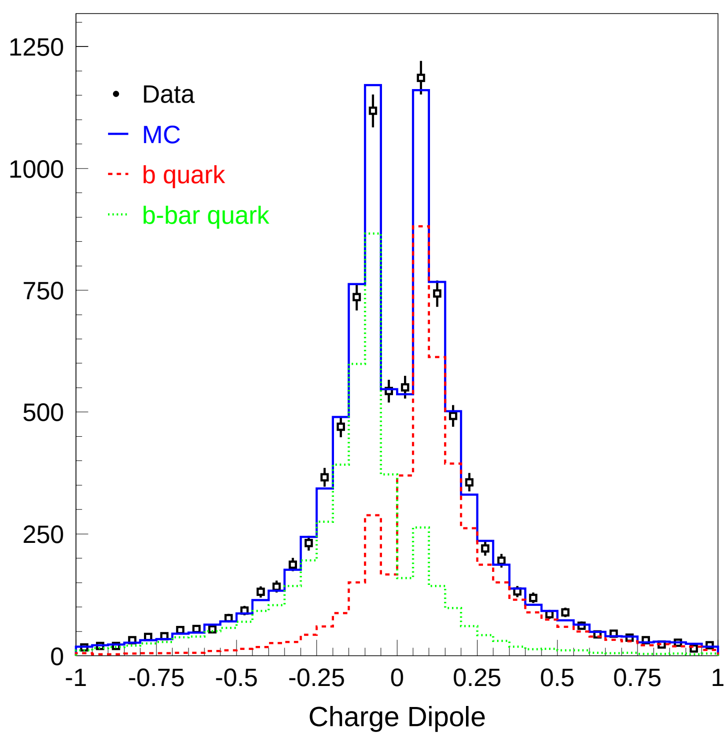

Figure 4: Distribution of the charge dipole reconstructed in B decays. The separate contributions from b and $\overline{b}$ quarks are shown, demonstrating good final state analyzing power.

of the polarized forward-backward asymmetry confirm the analyzing power of this tag.

5 Amplitude Fits

The data from each of the above analyses are fit with a maximum likelihood fit, which determines the amplitude A as a function of Δm. The amplitude, which is implicitly defined by the expressions, $P(B_s^0 \to B_s^0) = \frac{\Gamma}{2} e^{-\Gamma t}(1 + A\cos\Delta mt)$ and $P(B_s^0 \to \overline{B}_s^0) = \frac{\Gamma}{2} e^{-\Gamma t}(1 - A\cos\Delta mt)$, has the properties that $A = 1$ when $\Delta m = \Delta m_s$ and $A = 0$ when $\Delta m \ll \Delta m_s$ [13].

As Abbaneo and Boix [14] point out, the signature for a mixing signal in a graph of amplitude vs Δm depends on the decay length and boost resolution, and varies from a Lorentzian peak with value $A = 1$ at $\Delta m = \Delta m_s$ in the case of good resolution ($\sigma_t < \Delta m_s^{-1}$) to a monotonically increasing function which passes through $A = 1$ at $\Delta m = \Delta m_s$ when the resolution is poor ($\sigma_t > \Delta m_s^{-1}$). This average behavior in an amplitude plot is subject to large, correlated statistical fluctuations. The significance of a bump in such a plot is *not* simply the number of standard deviations by which the amplitude at the peak exceeds zero. One must also take into account the fact that a statistical fluctuation could occur in any of several regions in the plot. Abbaneo and Boix show how to evaluate the significance with Monte Carlo methods, by considering a large ensemble of experiments.

We test our fitting procedures on large Monte Carlo samples to confirm that we can see amplitude bumps for $\Delta m_s = 10\,ps^{-1}$ and $\Delta m_s = 20\,ps^{-1}$, and that we don't see significant structure when Δm_s is very high (1000 ps^{-1}). The same tests confirm our evaluation of the amplitude errors. We also fit the data for B_d^0 mixing, using the same likelihood apparatus, and find values of Δm_d consistent with the present world average.

6 Results and Conclusions

The results of the individual analyses can be found in Refs. [10] and [11]. Systematic errors have been included according to the prescription in Ref. [13]. The SLD preliminary combined result is shown in Fig 5. The sensitivity of the analysis, which is the average value at which a 95% CL limit could be set in the absence of signal, is 13.0 ps^{-1}. Our data shows two minor bumps in amplitude, one at $\Delta m_s = 9\,ps^{-1}$ and the other at $\Delta m_s = 18\,ps^{-1}$. Neither one is statistically significant. By itself, our data excludes $\Delta m_s < 7.6\,ps^{-1}$ and $11.8 < \Delta m_s < 14.8\,ps^{-1}$ at 95% CL. The combined SLD data have sensitivity equal to or greater than all other experiments individually, and because of the excellent decay length resolution, dominate the world average beyond $\Delta m = 15\,ps^{-1}$.

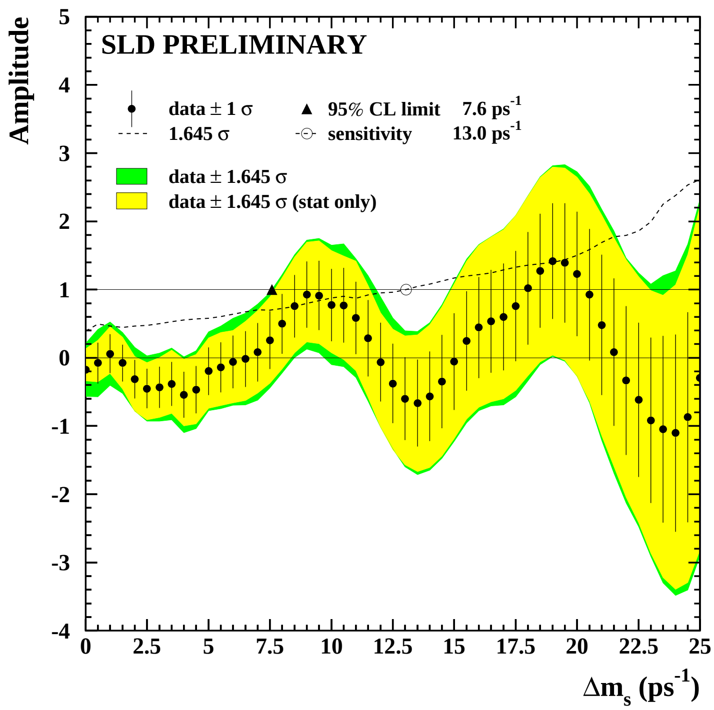

Figure 5: Amplitude versus Δm_s for the Preliminary Combined SLD Result.

The world's combined data, as prepared by the LEP Oscillations Working Group [5] is shown in Fig. 6. The sensitivity of the combined data is 18.0 ps^{-1}, which represents a minor improvement since the time of the Osaka Conference, but quite a substantial improvement from Lepton Photon 1999 (14.7 ps^{-1}). Experimental sensitivity continues to improve. The combined data set a rather interesting lower limit on the oscillation frequency: $\Delta m_s > 15.0\,ps^{-1}$ at 95% CL. The "bump" in the amplitude at high Δm_s has

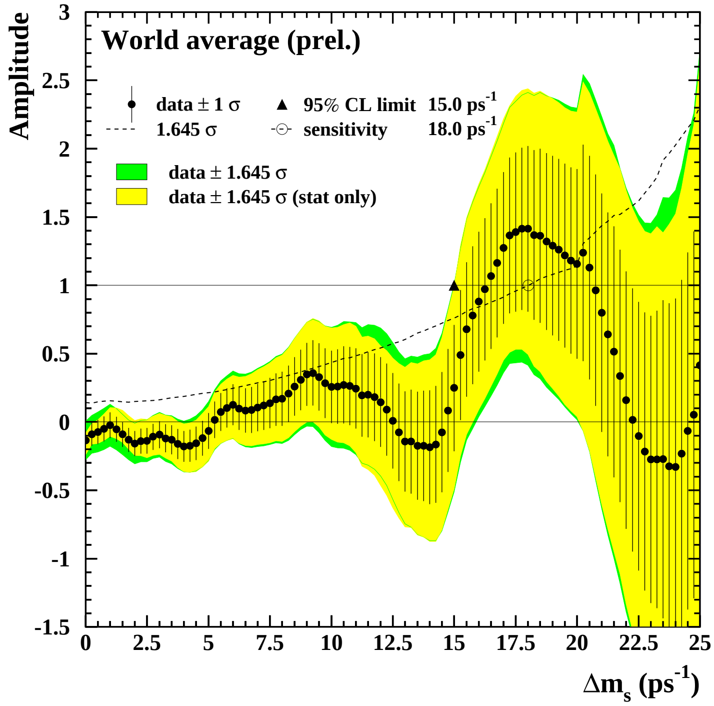

Figure 6: Amplitude versus Δm_s for the Combined World Data.

remained, although its significance hasn't changed appreciably in the past year. Lacking a formal treatment of its significance, I have guesstimated the probability that the bump is a statistical fluctuation using the results of Abbaneo and Boix. I find the probability to be $\sim 2\%$. This means that the "significance of the effect" is about 2 σ. That is enough to be interesting, especially given our theoretical predisposition to an answer in this range. But it is not an observation. We wait on continued refinements in experimental sensitivity from the present analyses, and the results from Run 2 at the Tevatron. SLD is continuing to improve the sensitivity of its analyses.

We have yet to measure the oscillation frequency of B_s^0 oscillations, but the limits set already result in the strongest constraints on V_{td} to date. In fact, the improved limits on Δm_s and the reduction of theoretical errors in some of the quantities needed to extract V_{td}, have reduced the size of the error ellipse on the Wolfenstein parameters ρ and η roughly four-fold in the past decade [4]. The next few years, which promise first measurements of both $\sin 2\beta$ and Δm_s, will sharpen the present picture considerably.

7 Acknowledgments

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