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B_s^0 Oscillation Results

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Abstract

We review new studies of the time dependence of B_s^0–$\overline{B_s^0}$ mixing by the ALEPH, DELPHI and SLD Collaborations, with an emphasis on the different analysis methods used. Combining all available results yields a preliminary lower limit on the oscillation frequency of $\Delta m_s > 14.4$ ps^{-1} at the 95% C.L.

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B_s^0 Oscillation Results

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We review new studies of the time dependence of B_s^0–$\overline{B_s^0}$ mixing by the ALEPH, DELPHI and SLD Collaborations, with an emphasis on the different analysis methods used. Combining all available results yields a preliminary lower limit on the oscillation frequency of $\Delta m_s > 14.4$ ps^{-1} at the 95% C.L.

1. INTRODUCTION

Studies of the time dependence of B_d^0–$\overline{B_d^0}$ and B_s^0–$\overline{B_s^0}$ mixing continue to play an important role in the exploration of both the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix and the phenomenon of CP violation. The B_d^0 oscillation frequency is related to the poorly known CKM element V_{td} according to [1]

$$\begin{aligned}\Delta m_d &= \frac{G_F^2}{6\pi^2} m_{B_d} m_t^2 F(m_t^2/m_W^2) f_{B_d}^2 B_{B_d} \\ &\quad \times \eta_{QCD} \left|V_{tb}^* V_{td}\right|^2 \qquad (1)\end{aligned}$$

and has recently been precisely measured by the BaBar and Belle collaborations—the current world average is $\Delta m_d = 0.503 \pm 0.006$ ps^{-1} [2]. However, this measurement cannot be translated into a precise determination of $|V_{td}|$ due the 15-20% theoretical uncertainty in $f_{B_d}\sqrt{B_{B_d}}$ (see Ref. [3] for a review of Lattice QCD estimates). Uncertainties are reduced for the ratio

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \left|\frac{V_{ts}}{V_{td}}\right|^2 , \qquad (2)$$

where the quantity $\xi \equiv (f_{B_s}\sqrt{B_{B_s}})/(f_{B_d}\sqrt{B_{B_d}})$ is estimated to be $1.18 \pm 0.04^{+0.12}_{-0.00}$ from Lattice QCD [3]. This implies that the ratio $|V_{ts}/V_{td}|$ can be determined with an uncertainty smaller than that for $|V_{td}|$ [4]. In the Wolfenstein parameterization of the CKM matrix, we have $\Delta m_d \propto |V_{td}|^2 \simeq A^2\lambda^6[(1-\rho)^2+\eta^2]$ and $\Delta m_s \propto |V_{ts}|^2 \simeq A^2\lambda^4$, where $\lambda = 0.2237 \pm 0.0033$ and $A = 0.819 \pm 0.040$ [5], but ρ and η are not well known. Studies of B_d^0 and B_s^0 oscillations thus provide some of the strongest constraints on the CKM unitarity triangle parameters ρ and η.

Experimental studies of B_s^0 oscillations require two main ingredients: (i) reconstruction of the B_s^0 decay and its proper time, (ii) determination of the B_s^0 or $\overline{B_s^0}$ flavor at both production and decay to classify the decay as either 'mixed' (if the tags disagree) or 'unmixed' (otherwise). The significance for a B_s^0 oscillation signal can be approximated by [6]

$$S = \sqrt{\frac{N}{2}}\, f(B_s^0)\ [1 - 2\,w]\ e^{-\frac{1}{2}(\Delta m_s \sigma_t)^2}, \qquad (3)$$

where N is the total number of decays selected, $f(B_s^0)$ is the fraction of B_s^0 mesons in the selected sample, w is the probability to incorrectly tag a decay as mixed or unmixed (i.e. the mistag rate) and σ_t is the proper time resolution. The proper time resolution depends on both the decay length resolution σ_L and the momentum resolution σ_p according to $\sigma_t^2 = (\sigma_L m_B/p)^2 + (t\,\sigma_p/p)^2$. Based on the Wolfenstein parameterization, we see that $\Delta m_s/\Delta m_d \simeq 1/\lambda^2$, which is of order of 20 (the other Wolfenstein parameters are of order 1). Therefore, B_s^0 oscillations are expected to be much more rapid than B_d^0 oscillations. The ability to resolve such rapid oscillations thus requires excellent decay length and momentum resolution, and benefits from having a low mistag rate and a high B_s^0 purity.

2. RECONSTRUCTION METHODS

The study of the time dependence of B_s^0–$\overline{B_s^0}$ mixing has been performed with different analysis techniques, ranging from fully inclusive to fully exclusive reconstruction of B_s^0 decay candidates. The study of B_s^0 oscillations is more chalenging than that of B_d^0 oscillations due to two main differences. First, only about 10% of b quarks fragment into B_s^0 mesons, as compared to about 40% into B_d^0 mesons. Second, the B_s^0 oscillation frequency is expected to be at least a factor of 20 larger than that for B_d^0 oscillations. To address this, sophisticated analyses have been developed with an emphasis on lowering the mistag rate, increasing the B_s^0 purity and, especially, improving the proper time resolution, all of which affect the sensitivity to B_s^0 oscillations.

The production flavor tag combines a number of different individual tags. The single most powerful tag exploits the large polarized forward-backward asymmetry in $Z^0 \to b\,\overline{b}$ decays. This tag is available at SLD thanks to the large electron beam polarization ($P_e = 73\%$). A left- (right-) handed incident electron tags the quark produced in the forward hemisphere as a b ($\overline{b}$) quark. This method yields a mistag rate of 28% with nearly 100% efficiency. Tags used in all analyses rely on charge information from the event hemisphere opposite that of the B_s^0 candidate: (i) charge of lepton from the direct transition $b \to \ell^-$, (ii) momentum-weighted jet charge, (iii) secondary vertex charge, (iv) charge of secondary vertex kaon from the dominant transition $b \to c \to s$, (v) charge dipole of secondary vertex (SLD only). Other tags from the same hemisphere as the B_s^0 candidate are also used: (i) unweighted (or weighted) jet charge, and (ii) charge of fragmentation kaon accompanying the B_s^0. These various tags are combined on an event-by-event basis to yield an average mistag rate of approximately 22% at SLD and 27-29% at LEP.

The analyses differ in the way the B_s^0 decay is reconstructed and thus in the way the decay flavor is determined. Three general classes can be identified: inclusive, semi-exclusive and fully exclusive. Inclusive analyses benefit from the large available statistics but suffer from low B_s^0 purity, whereas more exclusive analyses benefit from higher purity and resolution but suffer from the lack of statistics (this is particularly true for the fully exclusive analyses). Several analyses are discussed below to highlight these differences.

Inclusive analyses have been performed by ALEPH, DELPHI, OPAL and SLD. The SLD charge dipole analysis is the most sensitive fully inclusive method [7]. It aims to reconstruct the b-hadron decay chain topology. This method takes full advantage of the superb decay length resolution of the SLD CCD pixel vertex detector to separate secondary tracks (from the B decay point) from tertiary tracks (from the D decay point). The decay length resolution is parametrized by the sum of two Gaussians with $\sigma_L = 78\,\mu$m (60% fraction) and $304\,\mu$m (40%), whereas the momentum resolution is parametrized with $\sigma_p/p = 0.07$ (60%) and 0.21 (40%). A "charge dipole" δQ is defined as the distance between secondary and tertiary vertices signed by the charge difference between them such that $\delta Q > 0$ ($\delta Q < 0$) tags $\overline{B^0}$ (B^0) decays. The average decay flavor mistag rate is estimated to be 22% and is mostly due to decays producing two charmed hadrons. A sample of 11,462 decays is selected with a B_s^0 purity estimated to be 16% (higher than the production rate of 10% due to the fact that only neutral decays are selected).

The most sensitive of all analyses is the ALEPH inclusive lepton analysis [8], which selects semileptonic B decays. In this analysis, a D meson is reconstructed inclusively based on topological and kinematical properties of the decay, and a resultant D track is vertexed with the lepton and the b-hadron direction (from the jet direction) to form a B decay vertex. The average decay length and momentum resolutions are $\sigma_L = 251\,\mu$m (75% fraction) and $718\,\mu$m (25%), $\sigma_p/p = 0.064$ (60%) and 0.20 (40%). Fairly loose selection criteria are used at the various stages of the analysis to obtain a high statistics sample of 74,026 events. The analysis relies on several neural network algorithms to perform the following tasks: production flavor tagging, $b\bar{b}$ event selection, direct ($b \to \ell$) lepton selection, and B_s^0 fraction enhancement. To maximize sensitivity to B_s^0 oscillations, the analysis incorporates all the information event by event, including estimates of the decay length and momentum resolution.

Semi-exclusive analyses have been performed by ALEPH, CDF, DELPHI, OPAL and SLD. B_s^0 decays are partially reconstructed in the modes $B_s^0 \rightarrow D_s^- \ell^+ \nu_\ell X$ and $B_s^0 \rightarrow D_s^- h^+ X$, where h represents any charged hadron (or system of several hadrons) and the D_s^- meson decay is either fully or partially reconstructed in the modes $D_s^- \rightarrow \phi\pi^-$, $K^{*0}K^-$, K^0K^-, $\phi\pi^-\pi^+\pi^-$, $\phi\ell^-\overline{\nu_\ell}$, etc.

The most sensitive semi-exclusive analysis performed by DELPHI selects 436 $D_s^-\ell^+$ events [9]. The small statistics is compensated by the high $B_s^0 \rightarrow D_s^-\ell^+\nu_\ell$ purity, estimated to be $\sim 53\%$, and the good decay length and momentum resolution, $\sigma_L = 200\,\mu$m (82% fraction) and 670 μm (16%), $\sigma_p/p = 0.07$ (82%) and 0.16 (16%). Analyses selecting $D_s^-h^+$ final states benefit from higher statistics but are less sensitive than those selecting $D_s^-\ell^+$ states because of lower B_s^0 purity and worse proper time resolution. The SLD D_s+Tracks analysis [10] combines fully reconstructed D_s mesons with either a lepton or one (or more) charged hadron(s). It contributes especially at large values of Δm_s thanks to a B_s^0 purity of 40% and the best available decay length resolution: $\sigma_L = 50\mu$m (60% fraction) and 151μm (40%).

Finally, fully exclusive analyses have been performed by ALEPH [8] and DELPHI [11] via the (all charged particles) modes $B_s^0 \rightarrow D_s^-\pi^+$, $D_s^-a_1^+$, $\overline{D^0}K^-\pi^+$, and $\overline{D^0}K^-a_1^+$ (last two for DELPHI only), where the D_s^- and $\overline{D^0}$ are fully reconstructed. The decays $B_s^0 \rightarrow D_s^{*-}\pi^+$, $D_s^{*-}a_1^+$ and $D_s^{(*)-}\rho^+$ are also reconstructed by adding one or more photons to the above final states (ALEPH only) or by including the "satellite" mass region below the B_s^0 mass peak. The number of decay candidates is 80 for ALEPH and 44 for DELPHI with signal purities of approximately 36% and 50%, respectively. The main advantage of the exclusive method is its excellent proper time resolution with a negligible contribution from momentum resolution ($\sim 0.5\%$). As a result, unlike all other methods, σ_t does not grow significantly with increasing proper time t and thus the oscillation amplitude is not damped as t increases. Due to limited statistics, this method is not competitive with respect to the inclusive and semi-exclusive methods. However, this is the method of choice for future studies of B_s^0 oscillations at hadron colliders.

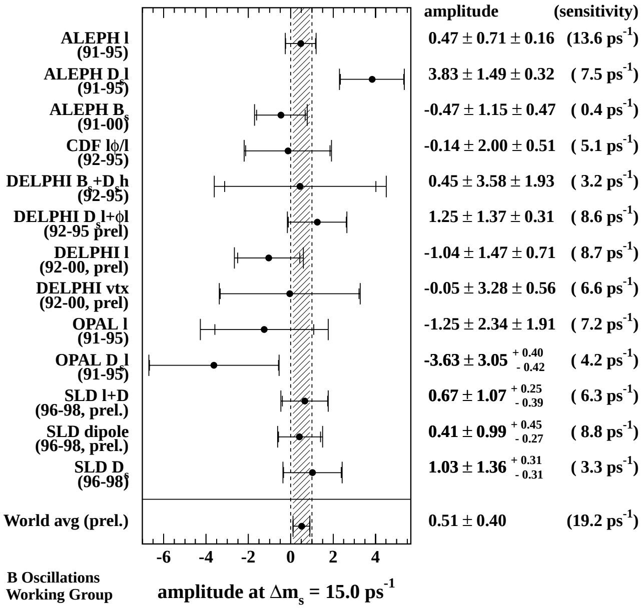

Figure 1. Measurements of the B_s^0 oscillation amplitude for $\Delta m_s = 15$ ps^{-1}.

3. RESULTS

Studies of the time dependence of B_s^0–$\overline{B_s^0}$ mixing are carried out with the amplitude method, which is equivalent to a normalized Fourier transform [6]. The oscillation amplitude A is expected to be $A = 0$ ($A = 1$) for oscillation frequencies sufficiently far from (close to) the true value of Δm_s. All available measurements of the oscillation amplitude at $\Delta m_s = 15$ ps^{-1} are summarized in Figure 1. Also shown are the sensitivities for each analysis to set a 95% C.L. lower limit on Δm_s (Δm_s value at which $1.645\,\sigma_A = 1$).

The measured oscillation amplitudes are combined [2], taking statistical and systematic correlations into account, to obtain the world aver-

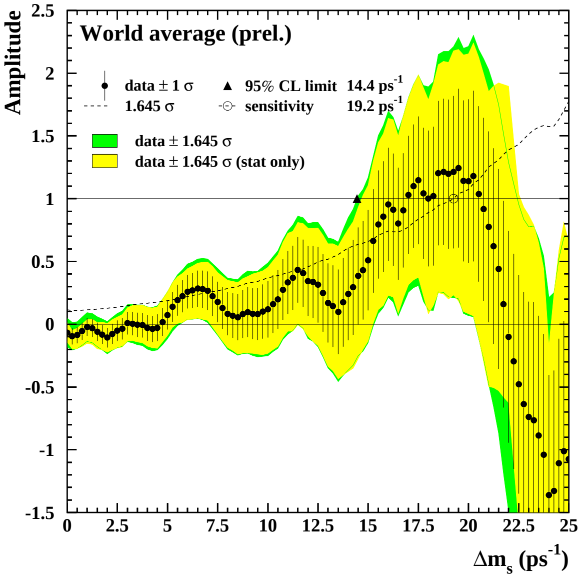

Figure 2. World average B_s^0 oscillation amplitude as a function of Δm_s. Values of the frequency for which $A + 1.645\,\sigma_A < 1$ are excluded at the 95% C.L.

age amplitude spectrum shown in Figure 2. The combination also corrects for the different input parameters used (Δm_d, b-hadron lifetimes and production rates). Furthermore, the amplitude statistical uncertainties measured by the inclusive analyses are adjusted to take into account the B_s^0 production rate of $(9.3 \pm 1.1)\%$. The rise in statistical error as Δm_s increases comes from the fact that an increasingly smaller fraction of the data sample has sufficient proper time resolution to resolve more rapid oscillations; the better the resolution, the smaller the rise. The preliminary combined amplitude spectrum excludes mixing ($A = 1$) for $\Delta m_s < 14.4$ ps^{-1} at the 95% C.L., whereas the sensitivity is 19.2 ps^{-1}. The significance of the deviation from $A = 0$ near $\Delta m_s = 17.5$ ps^{-1} is $2.3\,\sigma$. It is interesting to note that, while the sensitivity has been increasing steadily over the past 8 years, the limit has remained near 15 ps^{-1} for the past 3 years. In August 1999, the limit was $\Delta m_s > 14.3$ ps^{-1} but the sensitivity was only 14.7 ps^{-1}.

Many of the LEP and SLD analyses have been or are being finalized. One will thus have to wait for the next generation of experiments to measure the B_s^0 oscillation frequency. Prospects for such a measurement during Run 2 of the Fermilab Tevatron are excellent.

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