
New Results on B_s^0 Mixing from LEP

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1 Introduction

A prime goal of contemporary heavy flavour physics is the observation of B_s^0 - \bar{B}_s^0 oscillations and determination of the mass difference Δm_s to which the oscillation frequency is proportional. With the already well-measured quantity Δm_d from studies of B_d^0 - \bar{B}_d^0 oscillations [1], this would permit the extraction of the ratio of the CKM V_{ts} and V_{td} matrix elements

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \frac{|V_{ts}|^2}{|V_{td}|^2} \xi^2, \quad \xi^2 = \frac{F_{B_s}^2 B_{B_s}}{F_{B_d}^2 B_{B_d}}. \quad (1)$$

The theoretical uncertainties of roughly 10% are embedded in the ξ^2 parameter, the ratio of the decay constants and bag parameters of the B_s^0 and B_d^0 mesons. The phenomenological implication of B_s^0 - \bar{B}_s^0 oscillations is a proper time-dependent asymmetry in the probability to observe a *mixed* decay (*i.e.*, $B_s^0 \rightarrow \bar{B}_s^0 \rightarrow X$) compared to an *unmixed* decay (*i.e.*, $B_s^0 \rightarrow B_s^0 \rightarrow X'$). These probabilities are given as

$$\mathcal{P}_{\text{mixed}}(t) = \Gamma_s \frac{e^{-\Gamma_s t}}{2} [1 - \cos(\Delta m_s t)], \quad \mathcal{P}_{\text{unmixed}}(t) = \Gamma_s \frac{e^{-\Gamma_s t}}{2} [1 + \cos(\Delta m_s t)], \quad (2)$$

assuming CP conservation and small lifetime differences. The challenge to experiments in measuring a value for Δm_s is to determine if the B_s^0 meson decay is a mixed or unmixed one, and to measure the proper time associated to it.

The LEP experiments ALEPH [2], DELPHI [3, 4], and OPAL [5] have investigated B_s^0 - \bar{B}_s^0 oscillations as have SLD [6] and CDF [7]. This paper focuses on new (*i.e.*, released in early 2002) results from ALEPH [2] which motivate new LEP results on B_s^0 - \bar{B}_s^0 oscillations and briefly reviews the results from DELPHI and OPAL.

2 Experimental Strategy

At LEP, B_s^0 mesons are produced from hadronic decays of the Z boson ($e^+e^- \rightarrow Z \rightarrow b\bar{b}$). The boosted b hadrons result in a characteristic displaced vertex topology relative to the interaction point, forming the basis of most heavy flavour physics analyses.

The experimental strategy common to all analyses studying $B_s^0-\bar{B}_s^0$ oscillations can be grouped into four categories discussed below. Figure 1 illustrates components of this strategy.

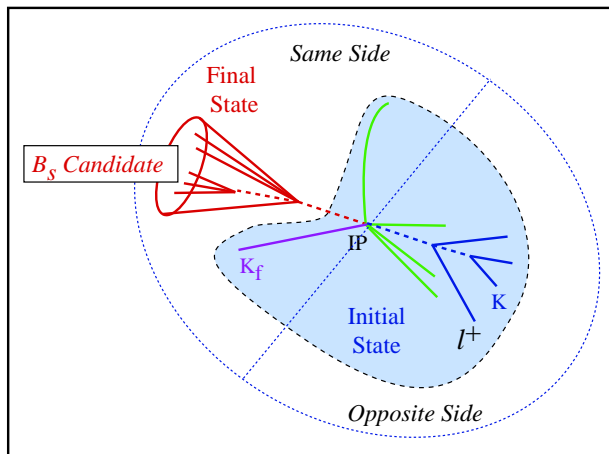


Figure 1: A diagram illustrating components of the experimental strategy. The event is divided into two hemispheres with respect to the thrust axis; the hemisphere containing the B_s^0 candidate is referred to as the *Same Side* while the other is the *Opposite Side*.

- **B_s^0 Selection and Event Purity Determination**

Candidate B_s^0 events are selected from LEP data collected between 1991 and 1995 (roughly 4 million hadronic Z decays per experiment).¹ Table 1 summarizes different selections used by the LEP experiments. Figures 2 and 3 show invariant mass distributions obtained from the ALEPH fully exclusive and semi-exclusive analyses. A selection-dependent event-by-event purity improves the statistical power of the event sample [2]. A probability for each candidate to originate from signal and background components is used in the oscillation fit described below.

- **Tagging the Initial and Final States**

A determination of the anti-particle/particle state of the B_s^0 candidate at its production (initial) and decay (final) is the key component of the analyses. The Final State tagging depends upon the selection. For fully exclusive decays, no ambiguity exists as all decay products are known. For the inclusive analyses with semileptonic B_s^0 decays, the charge of the lepton is used accounting for the non-zero mistag associated with cascade decays $b \rightarrow c \rightarrow \ell$. Initial State tagging is more complicated: information from both the Same and Opposite Sides may

¹In one case, the ALEPH fully exclusive B_s^0 selection, Z peak calibration data from LEP2 are included boosting the sample by about 400 000 hadronic events.

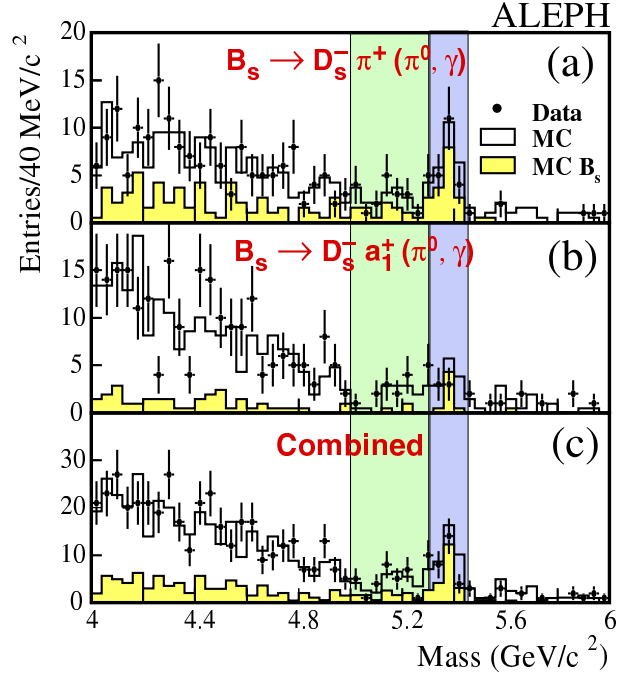


Figure 2: Invariant mass distributions for the reconstructed B_s^0 candidates in the ALEPH fully-exclusive selection [2]. Data (dots with error bars) and the simulation (histograms) are shown: a) the $D_s^- \pi^+ (\pi^0, \gamma)$ channel (a total of 44 events); b) the $D_s^- a_1^+ (\pi^0, \gamma)$ channel (a total of 36 events); and c) the sum of the two. The lightly and darkly shaded vertical bands show the satellite regions and the main peak area defining the mass selection windows.

be used as the flavour of the b hadron in the Opposite Side is anti-correlated with that of the B_s^0 at production. In each case, a variety of discriminants are used. The Opposite Side tag may rely upon jet charges, primary and secondary vertex charges, and lepton and kaon particle identification techniques. The Same Side information must necessarily exclude B_s^0 decay products, attempting to build discriminants based upon fragmentation tracks; identified kaons from fragmentation (produced in conjunction with the B_s^0) provide powerful tagging information. Again, a variety of kinematic and particle-identification-based discriminants are used. The Same and Opposite Side tags are then combined to yield an overall Initial State tag. The new ALEPH analyses [2] use series of neural networks (NN) to combine information, the final NN output is shown in Figure 4.

- **Measurement of Proper Time of the B_s^0 Decay**

Proper time t is given as $t = lm/p$ where m is the B_s^0 mass; the B_s^0 momentum p and the measured decay length l must be measured. For the fully exclusive mode, the B_s^0 momentum is determined with excellent precision from knowledge

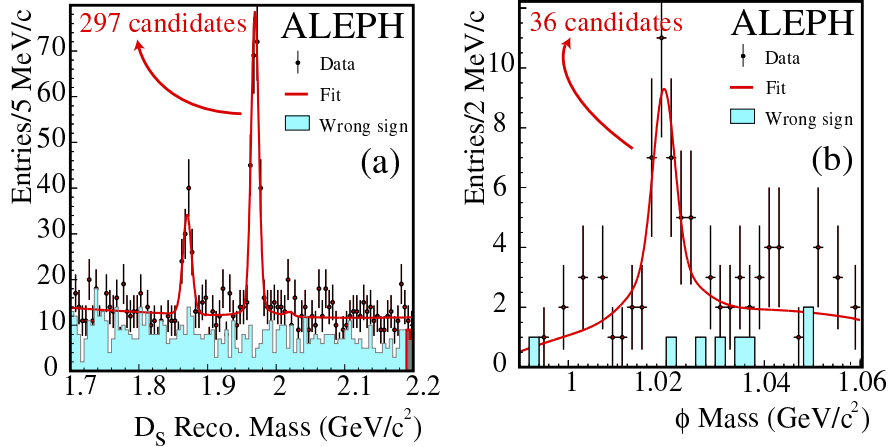


Figure 3: Invariant mass distributions for the ALEPH semi-exclusive selection [2] showing a) the selected D_s^- candidates with $D_s^- \ell^+$ combinations for hadronic D_s^- decays, and b) the selected ϕ candidates for semileptonic D_s^- decays in data (dots with error bars).

of the momenta of all of the decay products. In more inclusive selections with semileptonic B_s^0 decays, a correction is done to account for missing neutrino momentum based upon event energy-momentum conservation; uncertainties associated with this correction procedure dominate the momentum resolution. The decay length is determined by the distance between the primary vertex and the B_s^0 decay vertex. At LEP, the primary vertex may be determined on an event-by-event basis. The secondary vertex determination is again selection-dependent, and the best precision (*e.g.*, $180 \mu\text{m}$ for the ALEPH fully exclusive selection [2]) is obtained from the fully exclusive modes. More inclusive measurements suffer from a less precise knowledge of the B_s^0 flight direction (*e.g.*, missing neutrinos from semileptonic B decay) onto which the primary-secondary vertex distance is projected.

- **Determination of Δm_s**

A signal likelihood function can be constructed from the probability density function for mixed and unmixed events given in Equation 2. A procedure referred to as the Amplitude Method [10] replaces Δm_s in the probabilities by a hypothesized oscillation frequency ω and an *amplitude* \mathcal{A} in front of the oscillation term. This permits combination of analyses including the systematic uncertainties. The likelihood is maximized with respect to the amplitude for each ω . An amplitude consistent with zero is expected for values of ω far below the true value of Δm_s ; an amplitude consistent with unity is expected for values of ω very close to the true value of Δm_s . A range of ω may be excluded at 95% C.L. if $\mathcal{A} + 1.645\sigma_{\mathcal{A}} < 1$.

| Selection | Decay Modes | Sample (events) | Purity % | LEP Experiment | Δm_s Limit obs. (exp.) ps^{-1} |
|-----------------|--|-----------------|----------|----------------|---|
| Fully Exclusive | $B_s^0 \rightarrow D_s^-(\pi^+ \text{ or } a_1^+)$ | 50 – 80 | 50 – 80 | ALEPH [2] | 2.5 (0.4) |
| | $B_s^0 \rightarrow \bar{D}^0 K^-(\pi^+ \text{ or } a_1^+)$ | | | DELPHI [4] | †4.0 (3.2)† |
| Semi-Exclusive | $B_s^0 \rightarrow D_s^{(*)-} \ell^+ \nu_\ell$ | $10^2 - 10^3$ | 40 – 60 | ALEPH [2] | 7.2 (7.5) |
| | † $B_s^0 \rightarrow D_s^{(*)-} h^+$ † | | | DELPHI [3, 4] | 7.4 (8.1) |
| | | | | OPAL [5] | 1.0 (4.1) |
| Semi-Inclusive | $B_s^0 \rightarrow \ell^+ \nu_\ell + X$ | $10^4 - 10^5$ | 10 – 20 | ALEPH [2] | 11.4 (14.0) |
| | | | | DELPHI [8] | 2.0 (7.8) |
| | | | | OPAL [9] | 5.2 (7.0) |
| Fully Inclusive | $B_s^0 \rightarrow X$ | 5×10^5 | 10 | DELPHI [8] | 1.2 (4.9) |

Table 1: A summary of the LEP experiments' B_s^0 - \bar{B}_s^0 oscillation selections, their characteristics, and the resulting 95% C.L. lower limit on Δm_s . DELPHI combine their Fully Exclusive and Semi-Exclusive $D_s^- h^+$ results providing only a combined exclusive result, denoted by the †.

3 Results

Results of all LEP studies of B_s^0 - \bar{B}_s^0 oscillations are summarized in Table 1. Results in terms of amplitude versus hypothesized Δm_s are shown in Figure 5 for the semi-exclusive analyses of DELPHI [3] and OPAL [5]. The corresponding plots for each of the new ALEPH analyses [2] are shown in Figure 6.

The combination of LEP results with those of CDF and SLD is shown in Figure 7 [11]. For this world combination, an observed 95% C.L. lower limit on Δm_s of 14.9 ps^{-1} is obtained with an expectation of 19.3 ps^{-1} . There is an apparent difference between the expected and observed limits which suggests that a signal may lie in this region. Furthermore, there is an enticing deviation away from consistency with a zero amplitude hypothesis between 16 and 18 ps^{-1} which may hint at a signal; however the statistical significance of this deviation is below 2σ .

4 Conclusions

To date, no experiment has been able to resolve oscillations. It is presumed that the oscillation frequency lies beyond the current experimental sensitivity to discover it at the level of 5σ ; however, there may be a hint of signal in the Δm_s region between 16 and 18 ps^{-1} . Further data from Run II of the Tevatron and results of future CDF and D0 studies may soon be available with the hope of discovering evidence for B_s^0 - \bar{B}_s^0 oscillations.

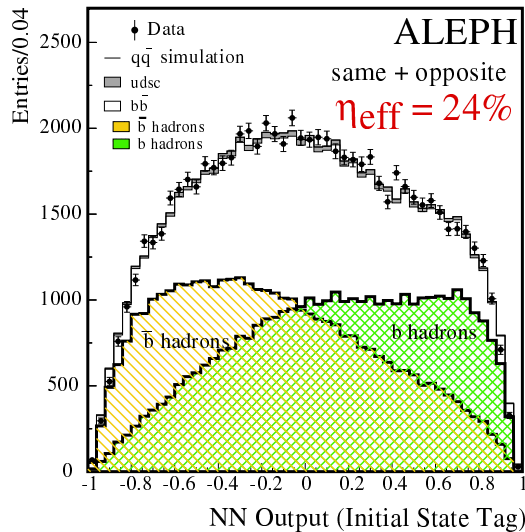


Figure 4: The ALEPH neural network-based Initial State tagging variable shown here for the semi-inclusive analysis in selected data (dots with error bars) and simulation (histograms) [2].

Acknowledgements

This presentation summarizes the work of the ALEPH, DELPHI, and OPAL collaborations as well as the LEP B Oscillations Working Group. As a member of the ALEPH collaboration, I wish to thank my colleagues in the CERN accelerator divisions for the successful operation of LEP. I am grateful to Dr. Duccio Abbaneo for his help in preparing this presentation as well as members of the ALEPH Heavy Flavour Group and the LEP B Oscillations Working Group. Dr. Markus Elsing also provided valuable input and suggestions.

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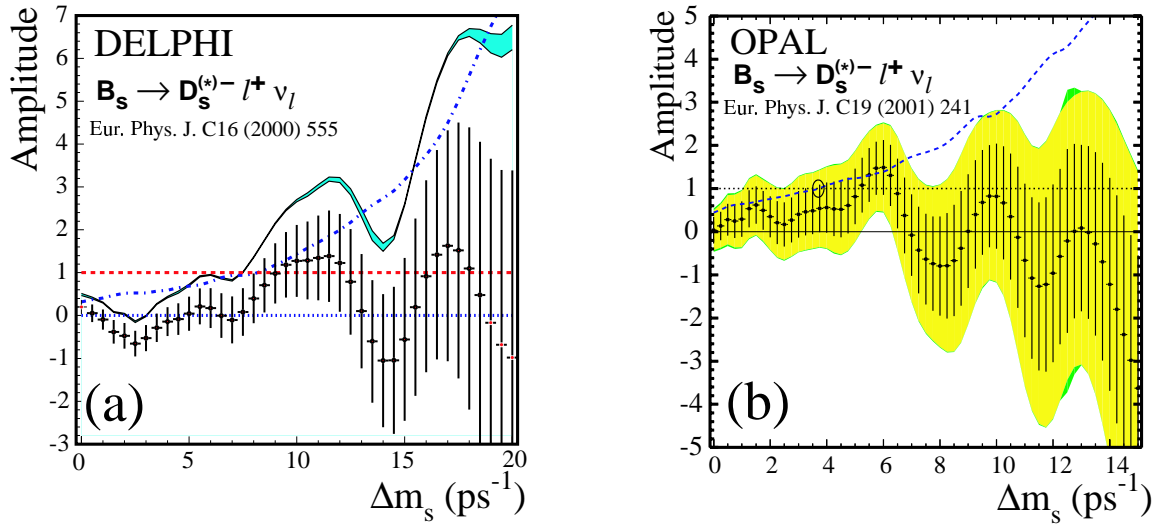


Figure 5: Plots showing Amplitude versus hypothesized Δm_s for a) the DELPHI semi-exclusive analysis [3], and b) the OPAL semi-exclusive analysis [5]. In the case of the a) DELPHI analysis, an observed (expected) 95% C.L. lower limit of 7.4 ps^{-1} (8.1 ps^{-1}) is obtained; b) OPAL analysis yields 1.0 ps^{-1} (4.1 ps^{-1}).

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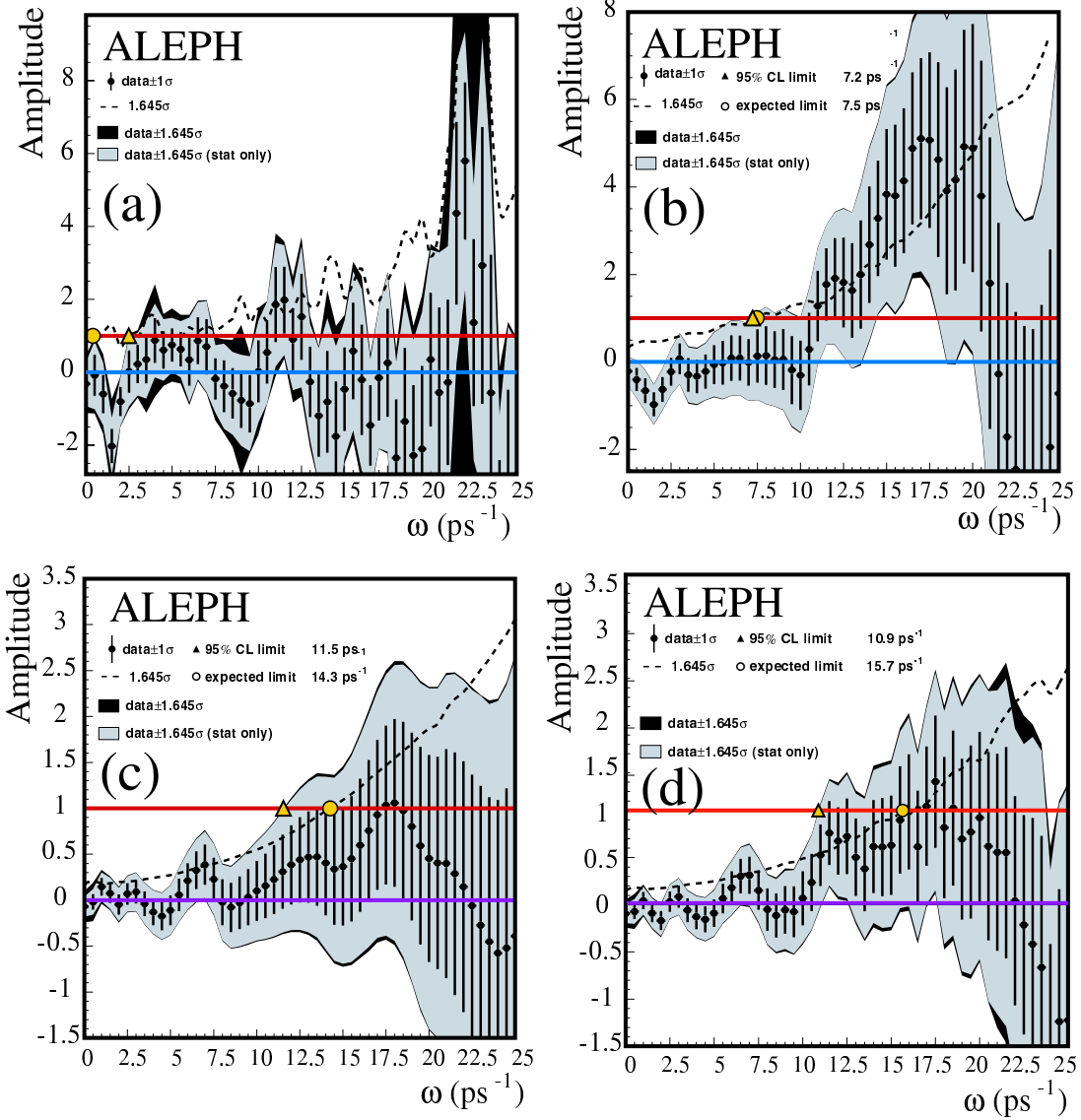


Figure 6: The new ALEPH results [2] shown here in terms of Amplitude versus hypothesized $\Delta m_s(\omega)$ for a) the fully exclusive analysis, b) the semi-exclusive $D_s\ell$ analysis, c) the semi-inclusive lepton analysis, and d) the combination of the three. In each case an observed (expected) 95% C.L. lower limit is set on Δm_s : a) 2.4 ps^{-1} (0.3 ps^{-1}), b) 7.2 ps^{-1} (7.4 ps^{-1}), c) 11.4 ps^{-1} (14.0 ps^{-1}), and d) 10.9 ps^{-1} (15.7 ps^{-1}).

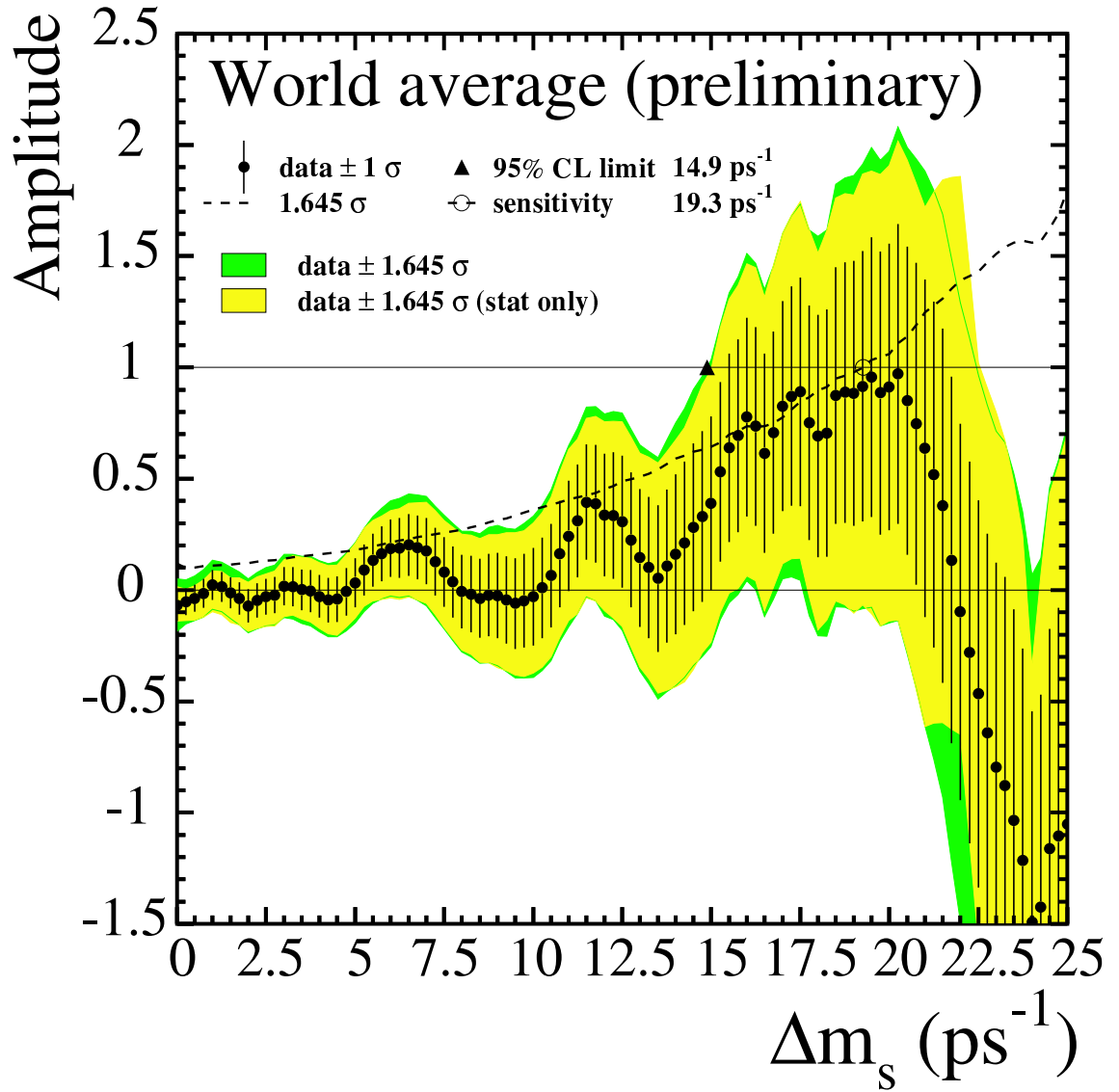


Figure 7: The combined B_s^0 oscillation results from ALEPH, CDF, DELPHI, OPAL, and SLD shown as amplitude versus hypothesized Δm_s [11]. The dots with error bars show the fitted amplitude values and uncertainties. An observed (expected) 95% C.L. lower limit on Δm_s of 14.9 ps^{-1} (19.3 ps^{-1}) is obtained.