B_s PHYSICS AT LEP, SLD, AND CDF: Δm_s AND $\Delta\Gamma_s$

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The current status of the experimental knowledge of B_s meson physics is reviewed. Results from LEP and CDF on the width difference $\Delta\Gamma_s$ are presented, the corresponding average is found to be in good agreement with the present theoretical estimation. The B_s oscillations have not yet been resolved, despite the progress recently achieved by SLD and ALEPH. The world combination, including results from the LEP experiments, SLD and CDF, is presented, together with the expected and observed lower limit on the B_s oscillation frequency. A tantalizing hint of an oscillation is observed around $\Delta m_s \sim 17\,\mathrm{ps}^{-1}$, near future results could increase the significance of this hint.

1 Introduction

While B^0/B^+ physics will soon become a monopoly of the new asymmetric B factories, interesting results are still coming from the existing data samples containing B_s mesons. The LEP experiments have collected around 160K B_s decays each (equivalent to ~ 300 $D_s\ell$ candidates reconstructed), while SLD collected a factor 10 less statistics. In a different environment, CDF recorded around 150K $B_s \to \ell$ decays with roughly 600 $D_s\ell$ candidates reconstructed. All these data, collected up to 1998, are diluted with nine times more other b-hadrons and are still partially under analysis due to the experimental difficulties involved.

The B_s mesons are particularly interesting because of their particle-antiparticle oscillations. The oscillation frequency, proportional to the mass difference between the mass eigenstates, Δm_s, is related to the CKM matrix through $\Delta m_s \sim |V_{tb}V_{ts}|$, and combined with the B_d mass difference, is related to the CP violation description in the Standard Model: $\Delta m_d/\Delta m_s \sim \sqrt{(1-\rho)^2+\eta^2}$. Physics beyond the Standard Model could be revealed by a measured value of Δm_s significantly larger than predicted.

The mass difference Δm_s is experimentally accessible through two complementary methods: *i*) direct searches for B_s oscillations and *ii*) measurement of $\Delta\Gamma_s$, the width difference between the two mass eigenstates, as the ratio $\Delta\Gamma_s/\Delta m_s$ is computable on the lattice. The B_s mass eigenstates have a defined CP parity, if CP is conserved in mixing.

2 The $\Delta\Gamma_s$ Measurement

The width difference, defined as $\Delta\Gamma_s \equiv \Gamma_s^{\mathrm{short}} - \Gamma_s^{\mathrm{long}}$, ($\Gamma_s^{\mathrm{short}} = \Gamma_s^{\mathrm{light}} = \Gamma_s^{\mathrm{even}}$), has been studied by the four LEP experiments and CDF. Experimental information on $\Delta\Gamma_s$ can be extracted by studying the proper time distribution of data samples enriched in B_s mesons. An alternative method based on the measurement of the branching ratio $B_s \to D_s^{(*)+}D_s^{(*)-}$ proposed in Ref. [1] has also been used by ALEPH. [2]

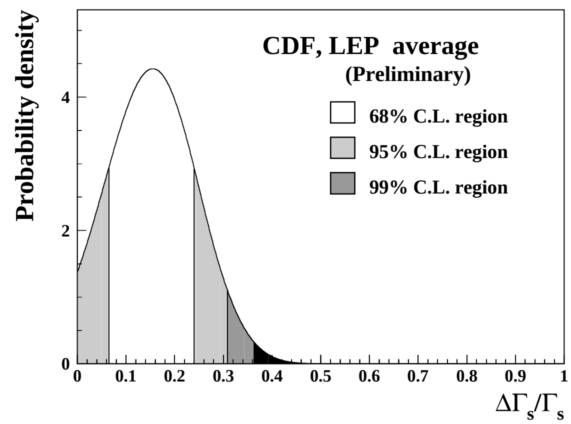

Figure 1: Probability density function for $\Delta\Gamma_s/\Gamma_s$ with the $1/\Gamma_s \equiv \tau_{B_d}$ constraint. The three shaded regions show the limits at 68%, 95%, and 99% C.L. respectively.

Methods based on double exponential lifetime fits to samples which contain a mixture of CP eigenstates have a quadratic sensitivity to $\Delta\Gamma_s$, whereas methods based on isolating a single CP eigenstate have a linear dependence on $\Delta\Gamma_s$. The branching ratio measurement mentioned above has also a linear dependence on $\Delta\Gamma_s$. The two last methods are therefore, in principle, more sensitive to $\Delta\Gamma_s$, and are the only ones sensitive to the $\Delta\Gamma_s$ sign. These methods, however, suffer from reduced statistics.

To obtain an improved limit on $\Delta\Gamma_s$, the results based on proper time distributions fits are obtained with an additional constraint on the allowed range for $1/\Gamma_s$. The world average B_s lifetime is not used, as its meaning is not clear if $\Delta\Gamma_s$ is non-zero. Instead, it is chosen to constrain $1/\Gamma_s$ to the world average τ_{B_d} lifetime: $1/\Gamma_s \equiv 1/\Gamma_d = (1.562 \pm 0.029)$ps (this assumption is motivated by theory).[3]

A description of all the analyses available, along with the results obtained with each of them is found in Ref. [3]

The world combined probability density function for $\Delta\Gamma_s/\Gamma_s$ is shown in Fig. 1. From this distribution an experimental limit and first measurement of $\Delta\Gamma_s$ is obtained:

$$\begin{aligned} \Delta\Gamma_s/\Gamma_s &= 0.16^{+0.08}_{-0.09} \\ \Delta\Gamma_s/\Gamma_s &< 0.31 \text{ at } 95\,\%\,\text{C.L.} \, , \end{aligned} \quad (1)$$

which is in good agreement with the theoretical prediction given in Ref. [4]:

$$\Delta\Gamma_s/\Gamma_s = 0.097\,^{+0.038}_{-0.050} \, . \quad (2)$$

The ratio $\Delta\Gamma_s/\Delta m_s$ is calculated on the lattice, the value obtained in Ref.[4] is $\Delta\Gamma_s/\Delta m_s = (3.5\,^{+0.94}_{-1.55}) \times 10^{-3}$, which combined with the above $\Delta\Gamma_s$ experimental results provides a mild constraint on the allowed range for Δm_s:

$$\Delta m_s = 29\,^{+16}_{-21}\,\text{ps}^{-1} \, .$$

3 The B_s Oscillations

3.1 The Amplitude Method

The B_s oscillation analyses performed so far are not able to resolve the fast oscillation frequency Δm_s and can only exclude a certain range of frequencies. The combination of such excluded ranges is not straightforward, and a specific method, the *Amplitude Method*, has been developed for this purpose.[5,6] An amplitude $\mathcal{A}$ is introduced in front of the oscillating term of the probability density function for unmixed and mixed B_s mesons:

$$p.d.f.^{u,m}(t) = \frac{\Gamma_s e^{-\Gamma_s t}}{2}\left[1 \pm \cos(\Delta m_s t)\right] \;\Rightarrow$$
$$p.d.f.^{u,m}(t) = \frac{\Gamma_s e^{-\Gamma_s t}}{2}\left[1 \pm \mathcal{A}\cos(\omega t)\right] \, . \quad (3)$$

The amplitude $\mathcal{A}$ is measured for any value of the test frequency ω, with its uncertainty $\sigma_{\mathcal{A}}$. The value $\mathcal{A} = 0$ is expected far below the true oscillation frequency, and $\mathcal{A} = 1$ at $\omega = \Delta m_s$. Frequencies for which $\mathcal{A} + 1.645\sigma_{\mathcal{A}} \leq 1$ are excluded at 95% C.L. The expected limit for a given analysis (also known as sensitivity) is defined as the frequency for which $1.645\sigma_{\mathcal{A}} = 1$.

The expected amplitude shape for $\Delta m_s = 17\,\text{ps}^{-1}$, $p_B = 32\,\text{GeV}$, and different resolution values are obtained from analytical calculations;[6] these curves are shown in Fig. 2. The typical resolutions achieved at LEP correspond to the curve marked with a star, while SLD is represented by the curve marked with a circle.

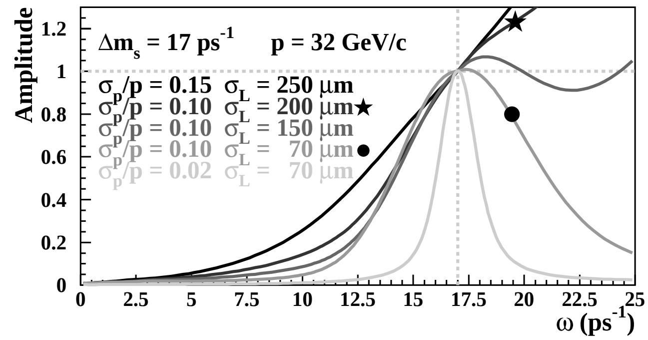

Figure 2: Expected amplitude shape for $\Delta m_s = 17\,\text{ps}^{-1}$, $p_B = 32\,\text{GeV}$ and different resolution values.

3.2 Analysis methods

The first step for a B_s meson oscillation analysis is the selection of final states suitable for the study. The choice of the selection criterion determines also the strategy for the tagging of the meson flavour at decay time. Then, the flavour at production time is estimated, to give the global mistag probability η. The production rate of B_s mesons in the fragmentation of high-energy b quarks is about 10%. In some analyses the selection of the final state chosen yeilds a higher B_s content. In inclusive analyses several techniques are used to effectively increase the B_s content of the sample selected.

Finally, the proper time is reconstructed for each meson candidate, and the oscillation is studied by means of a likelihood fit to the distributions of the decays tagged as mixed or unmixed.

The statistical power of a B_s analysis is described by the uncertainty on the measured amplitude as a function of the test frequency ω; it can be written as:

$$S = \sigma_{\mathcal{A}}^{-1} \propto \sqrt{N} f_s (1 - 2\eta)\mathcal{F}(\omega, \sigma_t) \, , \quad (4)$$

where N is the total number of events, f_s is the effective fraction of B_s, and $\mathcal{F}$ is a function increasing fast with ω. The proper time resolution σ_t is expressed as a function of the decay length and momentum resolutions, σ_l, σ_p/p, as:

$$\sigma_t = \frac{m}{p}\sigma_l \oplus \frac{\sigma_p}{p} t \, . \quad (5)$$

The statistical power of an analysis at high frequency (where the actual interest is) is mainly determined by the proper time resolution; while number of events, tagging and B_s enrichment contribute an overall factor to S, independent of frequency.

The analysis methods used so far are explained below. Up-to-date references for all the B_s oscillation analyses are available from: `http://lepbosc.web.cern.ch/LEPBOSC/`.

Fully reconstructed B_s candidates

Specific hadronic B_s decays to flavour eigenstates such as $B_s \to D_s\pi$ and $B_s \to D_s a_1$ can be fully reconstructed.

No more than a few dozen such events have been reconstructed but their proper time resolution is so good that such analyses, in spite of their low sensitivity individually, contribute at high frequency. Only DELPHI [7] and ALEPH [8] have released results with this method.

Semi-exclusive samples: $D_s\ell$, D_s-hadron, $\phi\ell$

Specific D_s decay channels are reconstructed and vertexed with a lepton (or hadron) to form the B_s candidates. Statistics are relatively limited, typically a few hundred events for a LEP experiment, to be compared to several ten thousand events in the inclusive lepton analyses explained below. On the other hand, the full reconstruction of the D_s improves significantly the decay length resolution, and the B_s purity can be as high as 40%. The lepton sign is used for final state tagging. Results from ALEPH, DELPHI, and OPAL are available. [8,9,10] At SLD, due to their overall lower statistics (with respect to a LEP experiment), a $D_s\ell$ analysis is not competitive, instead a D_s-hadron analysis, where the D_s candidates are vertex with a charged hadron, is performed.[11] Finally, CDF and DELPHI have analyses [9,12] where ϕ-lepton correlations are exploited.

Inclusive semileptonic samples

High-p_T leptons are searched for and vertexed together with an inclusively reconstructed charmed particle. This method profits from high statistics, reasonable resolution (depending on the charm selection) but low B_s purity, at the level of $f_s \approx 10\%$. The final state tag is given by the lepton sign. Results from ALEPH, DELPHI, OPAL, and SLD are available with this method. [13,14,15,16]

Inclusive lepton and D_s-lepton are the most sensitive analysis methods at LEP.

Fully inclusive samples

The b hadron is reconstructed inclusively. The final state tag is computed with inclusive charge estimators from the decay hemisphere. In particular, in SLD, thanks to their excellent resolution, the secondary and the tertiary vertices are reconstructed and the charge flow between the two is used to separate B^0 from $\overline{B^0}$. This method benefits from the highest statistics. Only SLD and DELPHI have released results with such a method. [16,14]

Inclusive lepton and fully inclusive analyses are the most sensitive at SLD.

3.3 Analysis comparison

The most competitive results to date on B_s oscillations are obtained by the LEP experiments and SLD. The differences between the two environments are illustrated in Fig. 3. The statistical error on the measured amplitude is plotted as a function of the test frequency ω. The best inclusive lepton analysis from LEP is equivalent to the corresponding SLD one at high frequency. However, in the case of a fully inclusive analysis, the SLD experiment has no rival.

The inclusive lepton analyses from ALEPH, DELPHI and OPAL are compared in Fig. 4. The statistical power

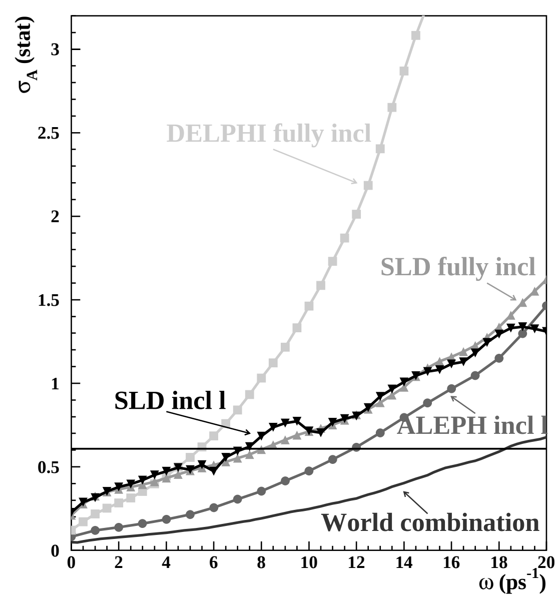

Figure 3: Comparison of the statistical power of the best inclusive lepton and fully inclusive analyses at LEP and SLD.

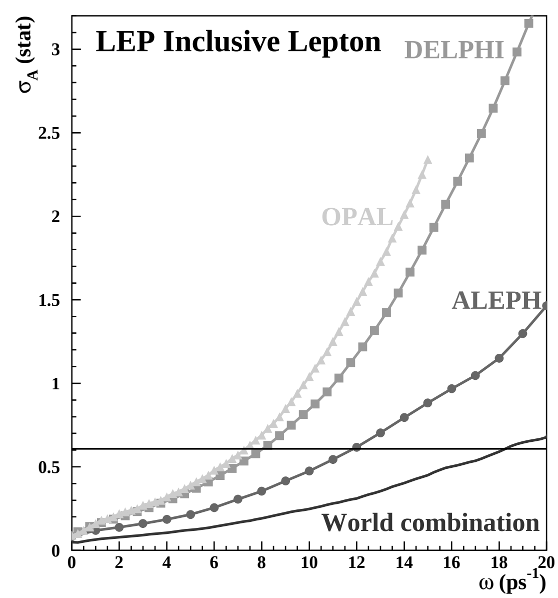

Figure 4: Inclusive lepton analyses comparison between LEP experiments.

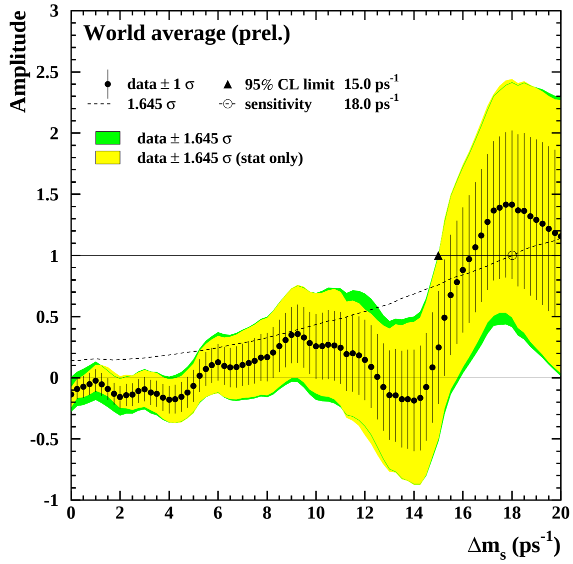

Figure 5: World average amplitude spectrum as for summer 2000.

of the three analyses is similar at low frequency, but at high frequency the ALEPH analysis has a significantly better performance. The bulk of the difference is not related with the detector performance, but is rather due to the analysis technique: specifically, ALEPH achieves a higher statistical power also thanks to a more detailed event-by-event estimation of the uncertainty on the reconstructed B_s decay length and momentum.

3.4 Present Results

All available B_s oscillations analyses are combined to obtain the amplitude spectrum shown in Fig. 5. In one year, from summer 1999 to summer 2000, an overall sizable improvement is observed: the expected limit has gone up by 3.5ps^{-1}, or in other words, the statistical error on the amplitude at high frequency has been reduced by a factor of 2. Most of this improvement is given by the new results from ALEPH and SLD.[13,16,11] The limit set at 95% C.L., however, has not followed this increase due to the presence of a 2.3σ deviation from $\mathcal{A} = 0$ around $\Delta m_s = 17\text{ps}^{-1}$. The probability that this deviation be due to a statistical fluctuation is estimated to be at the 3% level with gedanken experiments.

3.5 Perspectives for the near future

By next summer final results from present analyses at LEP (ALEPH and DELPHI) and SLD are expected. The combined sensitivity could increase by few inverse picoseconds and therefore the significance of the signal hint observed could also increase.

Table 1: Summary of B_s experimental knowledge.

m_{B_s}	$=\ 5369.6 \pm 2.4\,\text{MeV}$
τ_{B_s}	$=\ 1.464 \pm 0.057\,\text{ps}$
$\Delta\Gamma_s/\Gamma_s$	$=\ 0.16\,^{+0.08}_{-0.09}$
Δm_s	$>\ 15\,\text{ps}^{-1}$ at 95% C.L.

In principle more B_s oscillations studies could be performed with the LEP data, but might remain undone.

3.6 Conclusions

The LEP, SLD and CDF collaborations have greatly contributed to B_s physics. A summary of our present knowledge is shown in Table 1, the value of the measured B_s meson mass and lifetime are included for completeness.

Efforts to resolve B_s oscillations are still ongoing at LEP and SLD. Soon CDF and D0 will take over and Δm_s will probably be measured (if not before) from the data collected in the Tevatron RunII

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