Studies of B$_s$ Oscillations at LEP

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Abstract: A review of $B_s\bar{B}_s$ mixing results from LEP is given, putting emphasis on recent measurements presented for the first time at this conference. Combined results from the *B Oscillations Working Group* are also presented. The LEP experiments exclude $\Delta m_s < 14.3$ ps^{-1} @ 95% CL with a sensitivity of 15.4 ps^{-1}. Combination of all available data on B_s oscillations gives $\Delta m_s > 14.6$ ps^{-1} @ 95% CL with a sensitivity of 18.3 ps^{-1}.

1. Introduction

In the Standard Model, oscillations of neutral B mesons are described by second order weak interaction box diagrams with dominating contributions from top exchange. The mass difference of the mass eigenstates of B_d and B_s mesons is given by $\Delta m_{d,s} = \frac{G_F^2}{6\pi^2} \cdot m_{B^0_{d,s}} \cdot m_t^2 \cdot F(\frac{m_t^2}{m_w^2}) \cdot |V_{tb}^* V_{td,ts}|^2 \cdot \eta_b \cdot f^2_{B_{d,s}} \cdot B_{B_{d,s}}$, thus allowing in principle the extraction of V_{td} from existing precise measurements of Δm_d. However, the non-perturbative parameters f_B and B_B have large theoretical uncertainties. The ratio $\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \cdot \xi^2 \cdot |\frac{V_{ts}}{V_{td}}|^2$ is much better under control because many hadronic uncertainties cancel: $\xi^2 = 1.14 \pm 0.06$ [1].

$|V_{td}| = A\lambda^3\sqrt{(1-\rho)^2+\eta^2}$ and $|V_{ts}| = A\lambda^2 \approx |V_{cb}|$ in the Wolfenstein parametrisation [2]. Since $|V_{ts}|$ does not depend on ρ or η, $\Delta m_s/\Delta m_d$ and Δm_d give the same kind of measurement or constraint on the unitarity triangle (especially on the angle γ) in the $\rho-\eta$ plane (Figure 1). This is the main motivation to measure B_s oscillations. One can deduce a probability density function for Δm_s in the framework of the Standard Model from the other quantities constraining the unitarity triangle, giving expectation intervals $\Delta m_s = (16.3 \pm 3.4)$ ps^{-1} or $\Delta m_s < 23.2$ ps^{-1} @ 95% CL [1].

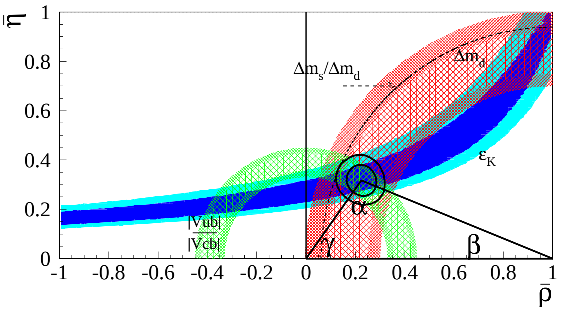

Figure 1: The various constraints on the unitarity triangle (from [1]).

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The time dependence of the mixing, neglecting CP violation and the width difference ($\Delta\Gamma \ll \Delta m$), is for an initial B^0 state given by $P_{B^0/\bar{B}^0}(t) = \frac{\Gamma}{2} \cdot e^{-\Gamma t} \cdot [1 \pm \cos \Delta m \cdot t]$. Since $\Delta m_s/\Delta m_d \propto 1/\lambda^2 \approx 20$, very fast oscillations are expected for B_s mesons. Typically B_s mesons undergo many oscillations before they decay, making time integrated measurements impossible. Excellent time resolutions are thus essential to successfully measure B_s oscillations. Another reason why B_s oscillation analyses are so difficult, is the low fraction of B_s mesons produced in Z decays: $f_{B_s} = (9.9 \pm 1.1)\%$ [3].

The significance of an oscillation signal is given by $\frac{1}{\sigma_A} \approx \sqrt{\frac{N}{2}} \cdot P_s \cdot (1-2\eta) \cdot e^{-(\Delta m_s \cdot \sigma_t)^2/2}$, with P_s being the fraction of B_s mesons in the sample, η the probability to incorrectly tag whether the B_s has mixed or not, and σ_t the proper time resolution. From this formula it becomes obvious what the main ingredients of a Δm_s analysis are:

For the **mixing tag**, the b-flavour has to be tagged at production and decay time. For the production tag, modern analyses combine information both from the opposite hemisphere (e.g. jet-charge, vertex-charge, leptons) and the same hemisphere (e.g. fragmentation charge, leading fragmentation particle). The decay tag and its performance are heavily depending on the channel under investigation (e.g. flavour of a reconstructed D_s meson, charge of the lepton in semileptonic decays).

Precise **reconstruction of the proper time $t = m_B l/p$** is the most crucial point. Since $\sigma_t \approx \frac{m_B}{p}\sigma_l \oplus t\frac{\sigma_p}{p}$, sensitivity is given mainly to the first oscillations and the decay length resolution σ_l – and thus precise reconstruction of the secondary decay vertex – becomes very important. The sample can be subdivided into resolution classes to profit from events with very good resolution being essential to gain sensitivity at high Δm_s.

Enrichment in B_s mesons can be achieved by using e.g. vertex charge, charge of an inclusively reconstructed charm system or the fragmentation kaon expected to accompany a B_s meson. For some analyses (e.g. exclusive B_s or $D_s - X$ channels), this is given intrinsically.

B_s oscillation results are presented in the framework of the 'Amplitude Method' [4] simplifying the setting of limits and combination of analyses.

2. Measurements at LEP

Each LEP experiment collected about 4 million hadronic Z decays during the LEP I phase. Five basic analysis methods have been carried out by the LEP collaborations. Their specific strengths and weaknesses are summarised in Table 1.

ALEPH, L3 and OPAL didn't release new results for this conference. ALEPH performed analyses using exclusively reconstructed B_s mesons, D_s-hadron and D_s-lepton correlations and samples with inclusive high p_t leptons [5]. With a sensitivity of 11.7 ps^{-1}, the high p_t lepton analysis is the most sensitive single measurement currently available[1]. OPAL analysed D_s-lepton and inclusive hight p_t lepton events, giving sensitivities of 4.2 ps^{-1} and 7.2 ps^{-1}, respectively [6].

[1]Some numbers quoted in this article might differ from the numbers in the original publication, because the *B Oscillations Working Group* uses a common set of input variables which might differ from the one originally used by the collaboration in the publication.

Method	Collab.	N	σ_t	$1-2\eta$	P_s	sensitivity	σ_A at high Δm_s
excl. B_s	AD	*	*****	*****	*****	*	**
D_s-lepton	ADO	**	****	****	****	****	****
D_s-hadron	AD	***	**	***	***	**	*
incl. leptons	ADO	****	***	****	*	*****	*****
incl. vertices	D	*****	*	*	*	***	**

Table 1: Performances of the basic analysis methods performed by the LEP collaborations (A=ALEPH, D=DELPHI, O=OPAL), sorted in increasing order of the statistics of the samples. Marks are from one to five stars on a 'LEP scale', with a typical uncertainty of one star (depending on the specific methods and capabilities of the experiments etc.).

2.1 New results from DELPHI

Apart from the analysis using exclusively reconstructed B_s mesons and D_s-hadron correlations [7], DELPHI updated all B_s oscillation analyses for this conference.

2.1.1 Inclusive vertices and soft leptons [8]

This analysis is based both on total inclusive vertex reconstruction and 'soft' leptons having a momentum $p > 2$ GeV and not overlapping with the lepton selection of the analysis using 'high p_t' leptons ($p_t > 1.2$ GeV). A B decay vertex is fitted in a fully inclusive way based on probabilities P_i that a track stems from the secondary B decay vertex, defined by quantities like e.g. impact parameters and rapidity. The momentum estimate is also based on these probabilities and gives a momentum resolution of about 5 GeV. The sample is subdivided in eight resolution classes. The huge numbers of 130k and 500k events are available in the soft lepton and inclusive vertex sample, respectively. The production tag with a purity of about 71% is based on jet-charges for B decay and fragmentation particles as well as information from identified particles in the opposite hemisphere. In the same hemisphere, the fragmentation charge and identified particles (especially kaons) are used. For the soft leptons, the lepton-charge is used as decay tag. Additional variables like the momentum of the lepton in the B rest frame and its impact parameter with respect to the secondary vertex are exploited to separate between direct $b \to l$ and background $b \to c \to l$ decays, resulting in a purity of about 69%. For the inclusive vertices, the decay tag is based on the reconstruction of the dipole charges (typically $W^+ - D_s^-$ in a B_s decay) in the B rest frame, giving a purity of about 58%.

This analysis excludes $\Delta m_s < 1.1$ ps^{-1} and $\Delta m_s \in [1.5, 5.3]$ ps^{-1} @ 95% CL and has a sensitivity of 6.1 ps^{-1}. The strength of this analysis is the large statistics of the samples leading to a competitive limit and sensitivity. However, due to the limited proper time resolution and the relatively poor decay tag (especially for the inclusive vertices), the error of the amplitude rapidly increases for high values of Δm_s.

2.1.2 Inclusive leptons [9]

Two algorithms are used for the reconstruction of the secondary decay vertex: the 'Mini-Jets Algorithm' finding the 'charm jet' from the B decay with a small p_t based cluster parameter and the 'Grid Algorithm' testing candidate charm vertices around the 'B track'. The secondary B decay vertex is then obtained by intersecting the trajectories of a high p_t lepton ($p_t > 1.2$ GeV) and the charm candidate. A set of discriminant variables is used to choose the best solution among the algorithms and to define five decay length resolution classes, the best one having a resolution of about 180 μm. For the momentum estimate two algorithms are used as well and three resolution classes are defined, resulting in 15 proper time resolution classes. The production tag uses a multivariate neural-network based flavour-tag in the opposite hemisphere (using e.g. jet- and vertex charges and identified particles as input) and the fragmentation charge and possibly identified fragmentation kaon from the same hemisphere. To improve the decay tag, given by the charge of the lepton, two discriminant variables are used to enhance the fraction of $b\bar{b}$ events and the fraction of direct $b \to l$ decays. To enrich the sample in B_s mesons, two discriminant variables are used (based on secondary vertex charge, number of tracks at the secondary vertex and charged kaons associated to primary and secondary vertex) to separate B_s mesons from other neutral and charged b hadrons. All these informations are used on event-by-event basis.

70k events are finally used. With a limit $\Delta m_s > 11.7$ ps^{-1} @ 95% CL and a sensitivity of 9.9 ps^{-1}, this is the most sensitive analysis from DELPHI.

2.1.3 D_s-lepton correlations [9]

The published D_s-lepton analysis [10] already provided a good sensitivity of 8.1 ps^{-1} (with a limit $\Delta m_s > 7.4$ ps^{-1}), but suffered from a rapid increase of the amplitude error at high Δm_s because of the global parametrisation of σ_t. In the improved analysis presented here, σ_t is used on event-by-event basis, isolating decays with excellent decay length resolution (based on variables like errors and χ^2 of secondary and tertiary vertex fit) and momentum resolution (based on the reconstructed B momentum and D_s mass). For the best events, resolutions of better than 200 μm for σ_l and 5% for σ_p/p are achieved. So far, the channels $D_s^- \to \phi\pi^-$ and $D_s^- \to K^{*0}K^-$ have been reanalysed with this technique in the 94/95 data set (corresponding to about 30% of the total statistics), the other channels and years remaining unchanged.

This gives an increased sensitivity and limit of 8.7 ps^{-1} and 7.9 ps^{-1}, respectively. However, the main improvement is the strongly decreased error of the amplitude at large Δm_s, e.g. at $\Delta m_s = 20$ ps^{-1}, σ_A could be reduced by a factor of 1.3.

2.1.4 Combined DELPHI results

Combination of all DELPHI B_s oscillation results gives a limit of $\Delta m_s > 14.5$ ps^{-1} @ 95% CL and a sensitivity of 12.0 ps^{-1}. Figures 2 and 3 show the combined amplitude spectrum and the amplitude errors versus Δm_s for all DELPHI analyses.

3. Combined Results [3]

The compilation of oscillation results is performed by the *B Oscillations Working Group*. Combination of the LEP results on B_s oscillation gives $\Delta m_s > 14.3$ ps^{-1} @ 95% CL with a

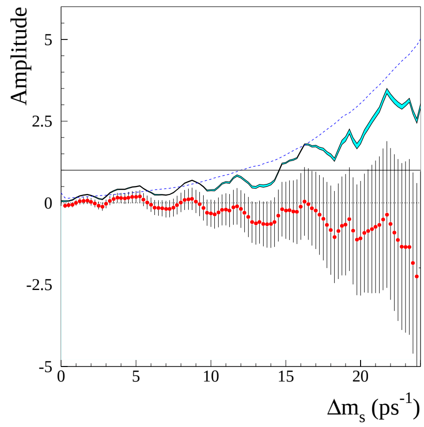

Figure 2: Combined amplitude distribution from DELPHI.

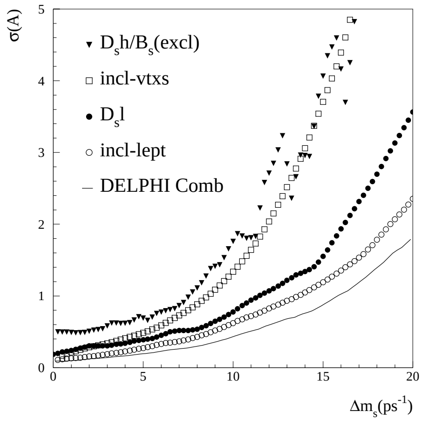

Figure 3: The error of the amplitude vs. Δm_s for the DELPHI analyses.

sensitivity of 15.4 ps^{-1}. At last years summer conferences [11], the limit and sensitivity were 11.9 ps^{-1} and 14.6 ps^{-1}, respectively. The gain is mainly due to the improved DELPHI analyses presented in this article.

Besides the LEP results, analyses on B_s oscillations are available from SLD [12] and CDF [13]. The world combined amplitude spectrum including also these results is shown in Figure 4. The resulting limit is $\Delta m_s > 14.6$ ps^{-1} @ 95% CL with a sensitivity of 18.3 ps^{-1} (last year [11]: 15.0 ps^{-1} and 18.1 ps^{-1}, respectively). The amplitude and its error at $\Delta m_s = 17$ ps^{-1} are shown for all analyses in figure 5. At this value close to the current sensitivity, LEP and SLD roughly have equal weight.

The amplitude spectrum can be converted into a likelihood curve with respect to $\Delta m_s = \infty$ [4] to investigate the 'bump' at around 17 ps^{-1}. The minimum at $\Delta m_s \approx 17$ ps^{-1} has a significance of about 2.6 standard deviations.

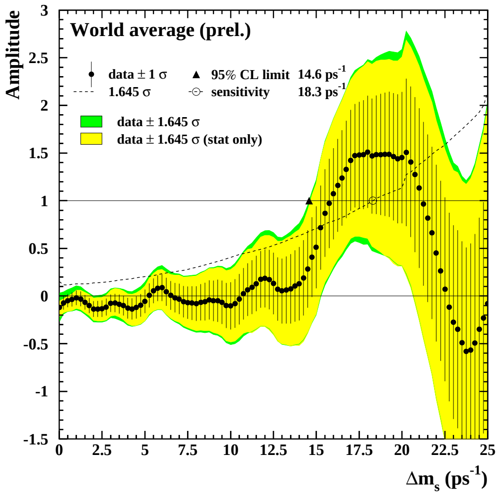

Figure 4: The combined B$_s$ oscillation amplitude.

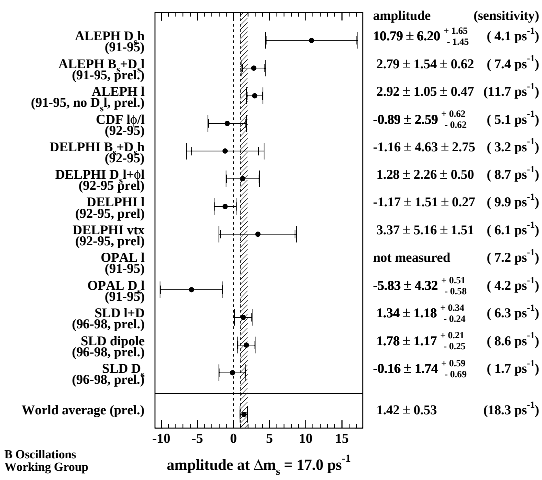

Figure 5: The amplitude and its error for all Δm_s measurements at $\Delta m_s = 17$ ps^{-1}.

4. Conclusions and Outlook

Impressive progress has been made in the field of B_s oscillations in the last decade. The evolution of the sensitivity on Δm_s with time is shown in Figure 6. Even six years after end of data-taking, there are still efforts to improve the analyses on B_s oscillations at LEP and also SLD. However, it seems that these experiments are approaching their limits.

The current combined limits (and sensitivities) are 14.3 ps^{-1} (15.4 ps^{-1}) for LEP and 14.6 ps^{-1} (18.3 ps^{-1}) for all existing results.

These limits will be either improved significantly or B_s mixing will be measured in the near future at the Tevatron in Run II (see e.g. [14]).

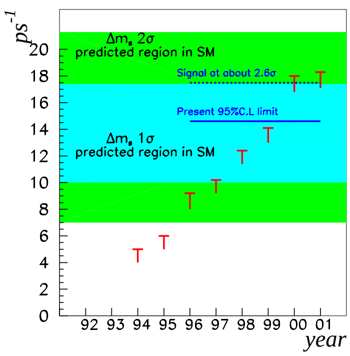

Figure 6: The evolution of the Δm_s sensitivity in the last years.

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