Vol. 31 (2000) *ACTA PHYSICA POLONICA B* No 10–11

A REVIEW OF Δm_s*

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(Received July 13, 2000)

The present status of the knowledge of the B_s^0 meson oscillations is presented. An overview of the different methods to detect B_s^0 oscillations and possibly measure the value of the Δm_s parameter is shown, and the most recent results from different experiments are combined. The overall preliminary lower limit on Δm_s is 14.6 ps^{-1} for a 95% C.L.

PACS numbers: 12.15.Hh, 14.40.Nd

1. Introduction

Mixing between particle and antiparticle in neutral mesons is a well known consequence of the flavour non-conservation in charged weak-current interactions.

Although the oscillation frequency is known precisely in the case of K^0 and B^0 mesons, a measurement for the B_s^0 is still lacking, because of the much faster oscillations. On the other hand, the knowledge of the B_s^0 oscillation frequency would give an important constraint to the CKM matrix element values.

This paper is organized as follows. In Sec. 2 the fundamentals of the oscillation theory are briefly explained. In Sec. 3 the statistical techniques used in the interpretation of the analyses results are described. In Sec. 4 the existing analysis methods are classified and their performances are evaluated. Finally, in Sec. 5 the results of the most recent preliminary world combination are shown.

* Presented at the Meson 2000, Sixth International Workshop on Production, Properties and Interaction of Mesons, Cracow, Poland, May 19–23, 2000.

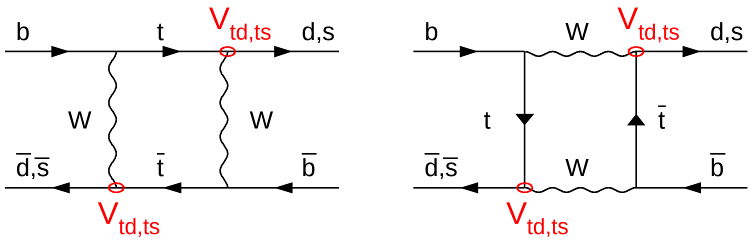

Fig. 1. Feynman diagrams contributing to the B_s^0 and B^0 mixing.

2. Theoretical framework

The time evolution of a B_s^0 ($\overline{B}_s^0$) meson can be described in a perturbation theory approximation by means of an effective lagrangian $\mathcal{H}_{\text{eff}}$ expressed as

$$\mathcal{H}_{\text{eff}} \equiv \begin{pmatrix} M_{B_s} & M_{12} \\ M_{12}^* & M_{B_s} \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma_s & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_s \end{pmatrix}, \tag{1}$$

while the B_s state is written as $|\Psi(t)\rangle = a(t)|B_s^0\rangle + b(t)|\overline{B}_s^0\rangle$ [1]. The physical states and their masses and widths are found by diagonalizing $\mathcal{H}_{\text{eff}}$, and the probability for a meson produced at $t = 0$ in a definite flavour eigenstate to be found at a time t in the opposite (or same) flavour state is[1]

$$P(t)_{B_s^0 \to \overline{B}_s^0 (B_s^0)} = \frac{1}{2\tau_s} e^{-\frac{t}{\tau_s}} \left[1 \mp A \cos(\Delta m_s t)\right] , \tag{2}$$

where $A \equiv 1$, τ_s is the average B_s^0 lifetime and Δm_s is the mass difference between the mass eigenstates, often referred to as the "B_s^0 oscillation frequency".

The main interest of the oscillation phenomenon lies in the possibility to extract information on the Cabibbo–Kobayashi–Maskawa (CKM) matrix. The evaluation of the Feynman diagrams (Fig. 1) allows to write the following equation:

$$\Delta m_q = \frac{G_F^2}{6\pi^2} |V_{tq} V_{tb}^*|^2 m_t^2 M_{B_q} \eta_B F\left(\frac{m_t^2}{M_{\text{W}}^2}\right) B_{B_q} f_{B_q}^2 ; \tag{3}$$

$q = d, s$ is the light quark flavour, $V_{qq'}$ are CKM matrix elements, M_{B_q} is the B_q meson mass, $\eta_B = 0.55 \pm 0.01$ is the contribution of perturbative

[1] In the hypothesis that CP violation is negligible and $\Delta\Gamma_s/\Gamma_s \ll 1$, where $\Delta\Gamma_s$ is the width difference of the mass eigenstates. The effect of these assumptions is estimated as a systematic uncertainty by some analyses.

QCD corrections, f_{B_q} is the disintegration constant of the B_q meson and B_{B_q}, the bag factor, represents the contribution of non-perturbative QCD effects [2]. As $|V_{tb}| \simeq 1$, V_{td} can be directly evaluated from the well measured value of Δm_d, but the result is spoiled by the large uncertainty on the non-perturbative contributions. On the other hand, the ratio between Δm_s and Δm_d is

$$\frac{\Delta m_s}{\Delta m_d} = \frac{M_{B_s^0}}{M_{B^0}} \xi^2 \left| \frac{V_{ts}}{V_{td}} \right|^2 , \tag{4}$$

where $\xi = f_{B_s^0}\sqrt{B_{B_s^0}}/f_{B^0}\sqrt{B_{B^0}} = 1.14 \pm 0.06$ is affected by much lesser theoretical uncertainties [3], thus providing a stronger constraint on the CKM matrix.

3. Statistical methods

In principle, using Eq. (3), is possible to measure the oscillation frequency Δm_s, provided that, for every B_s^0 meson produced, one measures (a) the flavour state at production time, (b) the flavour state at decay time, and (c) the proper decay time t. The last quantity implies in fact the measurement of the decay length and the momentum of the B_s^0. The initial flavour state is determined using, for example, jet and vertex charges or high momentum leptons in the hemisphere opposite to the B_s^0, fragmentation kaons in the same hemisphere, or the forward-backward asymmetry (available only to SLD, because if the SLC e^- beam polarization).

In a real analysis, the ability to measure Δm_s will be limited by the proper time resolution σ_t, the mistag rate for the initial and the final flavour states η, and the purity $f_{B_s^0}$ of the selected sample in B_s^0 candidates. The most convenient way to show the agreement of the data with a certain hypothesis for the value of Δm_s is the so-called "amplitude method" [4], consisting in fitting the amplitude A of the oscillating term in Eq. (3). It is expected for A to be compatible with 1 near the true value of Δm_s and with zero otherwise. The significance of the fit is approximately expressed as:

$$S \equiv \frac{1}{\sigma_A} \propto \sqrt{N} f_{B_s^0}(1-2\eta) \exp\left[-\frac{1}{2}(\Delta m_s \sigma_t)^2\right] , \tag{5}$$

where σ_A is the fitted amplitude error and N is the number of selected B_s^0 mesons.

The lower limit on Δm_s at a 95% confidence level is defined as the smallest value of Δm_s for which an amplitude $A = 1$ is excluded at a 95% C.L., *i.e.* which satisfies:

$$A(\Delta m_s) + 1.645 \cdot \sigma_A(\Delta m_s) = 1. \tag{6}$$

In addition, the sensitivity of a measurement is defined as the expected 95% C.L. lower limit on Δm_s if the true value of Δm_s is infinite, *i.e.* the value for which:

$$1.645 \cdot \sigma_A(\Delta m_s) = 1. \tag{7}$$

4. Analysis techniques

Analyses for the measurement of the B_s^0 mixing have been performed at e^+e^- colliders (LEP, SLC) and $p\bar{p}$ colliders (Tevatron). Several analysis methods have been developed, but they can be classified in terms of the kind of selection is applied to B_s^0 mesons. Three classes are defined: (a) inclusive analyses, (b) semi-exclusive analyses, and (c) exclusive analyses. In the following, the most relevant analyses at present are briefly described.

Analyses selecting inclusively semileptonic B decays ("inclusive leptons") have been published by most LEP collaborations [5–7] and SLD [8]. Hadronic jets with energetic leptons are selected, and inclusive D vertices are reconstructed by means of topological algorithms. All species of B mesons are selected, although the data sample can be divided into subsamples having different B_s^0 purities, which are nonetheless relatively low. The final state flavour tag is simply given by the charge of the lepton. The best performing analysis comes from ALEPH, being also the most sensitive single analysis at present. As shown in Fig. 2, the sensitivity is 9.6 ps^{-1} and the limit is $\Delta m_s > 9.5$ ps^{-1} at 95% C.L.

SLD has performed an inclusive analysis that does not require a high momentum lepton in the jet [8]. This technique, referred to as "Vertex charge dipole analysis", relies on an algorithm able to reconstruct B and D decay vertices exploiting their collinearity, and uses the decay distance between the B and the D vertex signed by the vertex charge difference in order to tag the B_s^0 decay flavour. This tag is found to give the correct result in the 79% of cases (Fig. 2). The achieved sensitivity is 5.4 ps^{-1} and the limit is $\Delta m_s > 4.4$ ps^{-1}.

Semi-exclusive analyses require usually that a $D_s^{\pm}$ meson coming from a semileptonic B_s^0 decay is reconstructed ("$D_s^{\pm}$-lepton"). This allows to achieve a higher sample purity and a better proper time resolution, but at the expense of a lower efficiency. ALEPH [9] and DELPHI [10] have performed similar analyses; the latter is also the second best single available measurement. The $D_s^{\pm}$ mesons are selected in the hadronic decay modes $D_s^+ \to \Phi\pi^+$, $K^{*0}K^+$, $K_S^0K^+$, $\Phi\pi^+\pi^+\pi^-$, $K^{*+}K^{*0}$, $\Phi\rho^+$, and in the semileptonic decay modes $\Phi e^+\nu_e$, $\Phi\mu^+\nu_\mu$. The $D_s^{\pm}$ charge tags the final flavour state. Special care must be taken of the physical background, consisting in $B \to DD_s^{\pm}X$ events, where the D meson undergoes a semileptonic decay. The DELPHI

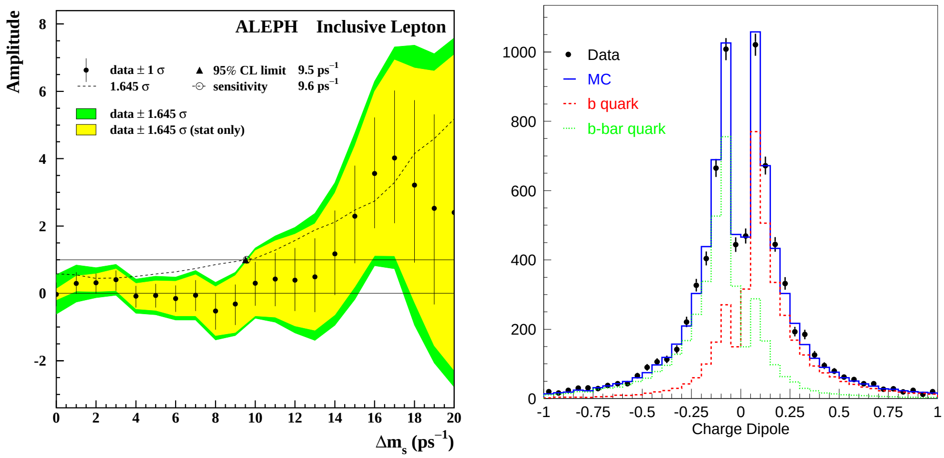

Fig. 2. (left) Amplitude vs. Δm_s for the inclusive lepton analysis by ALEPH. (right) Distribution of the vertex charge dipole in the SLD analysis.

analysis achieves an average B_s^0 purity of 53%. The sensitivity and the lower limit on Δm_s are respectively 8.1 and 7.4 ps^{-1}.

Also $D_s^{\pm}$-hadron correlations have been studied by ALEPH [11] and DELPHI [12]; $B_s^0 \to D_s^- +$hadron(s) decays are reconstructed, which have a much larger branching ratio than $D_s^- \ell^+$ decays, but a lower selection purity. Anyway, they are an event sample uncorrelated with other analyses, and give a sizeable contribution to the combined $D_s^{\pm}$X limit.

A search for B_s^0 oscillations using the $B_s^0 \to \Phi \ell^+ X \nu$ channel has been performed by CDF [13]. Neutral Φ candidates must form a D_s^- candidate with a charged track h^-, and, together with a lepton ℓ^+, must be selected as B_s^0 semileptonic decays. The final data sample consists in 1068 candidates, with a purity of $61.0^{+4.4}_{-7.0}$%. Another lepton, coming from a semileptonic decay of the other b-hadron, is required in order to determine the initial flavour of the B_s^0; the mistag rate is found from data to be 0.24 ± 0.08. A 95% C.L. lower limit for Δm_s of 6.2 ps^{-1} is derived, with a sensitivity of 5.8 ps^{-1} (Fig. 3).

The last category corresponds to B_s^0 oscillation analyses where the B_s^0 meson is completely reconstructed in one or more hadronic decay channels. ALEPH [9] and DELPHI [12] have published preliminary results for the decay channels $B_s^0 \to D_s^- \pi^+$, $B_s^0 \to D_s^- a_1^+$, $B_s^0 \to \overline{D}^0 K^- \pi^+$, and $B_s^0 \to \overline{D}^0 K^- a_1^+$ (the last two channels only in the DELPHI analysis), with the D_s^- and D^0 mesons reconstructed in various decay modes. The sizes of the selected samples are very small, but they are characterized by a very precise measurement of the B_s^0 proper time, due to the fact that all the particles

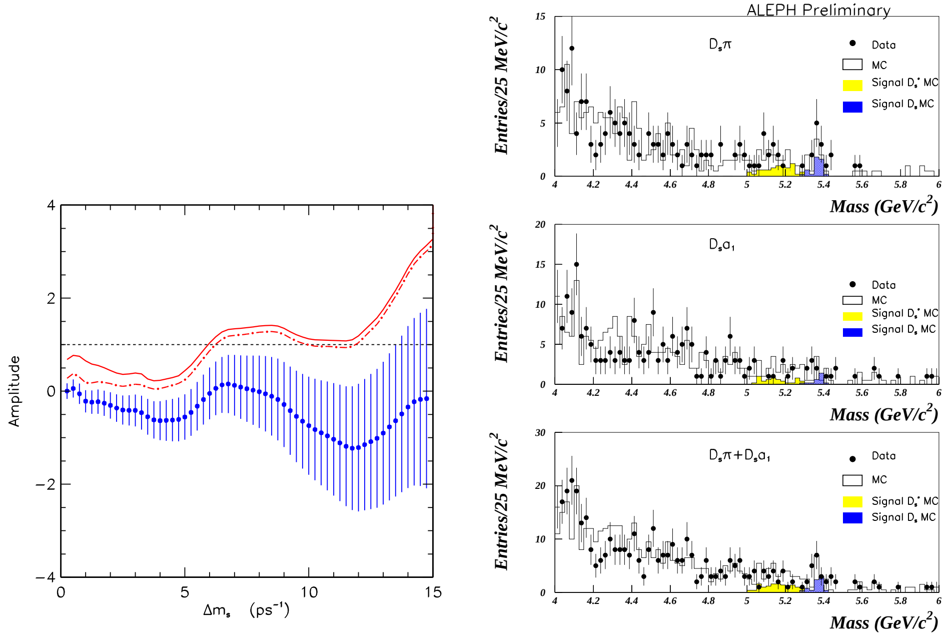

Fig. 3. (left) The measured amplitude (points with error bars) as a function of Δm_s for the CDF analysis. (right) The signal in the ALEPH exlcusive analysis.

produced in the B_s^0 decay are reconstructed. These analyses have therefore a significant impact in the amplitude measurement for large values of Δm_s, as it is evident from Eq. (5). In Fig. 3 the invariant mass distributions of the events selected by the ALEPH analysis are shown.

5. Conclusions

The most recent results from the various B_s^0 oscillation analyses performed by the LEP, SLD and CDF collaborations have been combined by the LEP B Oscillations Working Group [14], after rescaling all the analyses to the same values of the b-hadron fractions and lifetimes and Δm_d. The amplitude plot for the combination (Fig. 4) allows to put a 95% C.L. lower limit on Δm_s of 14.6 ps^{-1}, while the sensitivity is 14.6 ps^{-1}. From a study of the likelihood function value as a function of Δm_s, a minimum for the likelihood is found at 17.1 ps^{-1} with a corresponding probability of finding a lower minimum (which gives the significance of the minimum) of approximately 3%.

It is foreseen for the near future the publication of new analyses both from SLD ("D_s+tracks", "lepton+kaon") and from DELPHI (a fully inclusive analysis), and the update of existing analyses from ALEPH ("inclusive

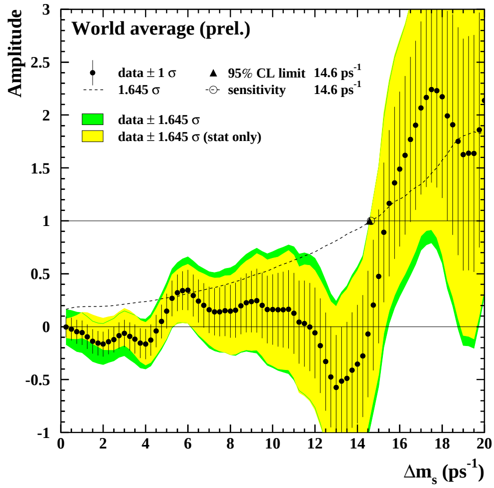

Fig. 4. Amplitude plot for the world combination

leptons") and OPAL ("inclusive leptons" and "D_s-lepton"). In the next years the data collected at Tevatron, LHC and HERA-B are expected to increase the sensitivity of the B_s^0 mixing measurements up to 30-50 ps^{-1}.

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