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Measurements of the B_s Lifetime and Search for a Lifetime Difference $\frac{\Delta\Gamma}{\Gamma}$

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MEASUREMENTS OF THE B_s LIFETIME AND SEARCH FOR A LIFETIME DIFFERENCE $\frac{\Delta\Gamma}{\Gamma}$

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The various B_s^0 lifetime measurements, both at LEP and at the Tevatron, are reviewed. Recent upper limits on the difference of the lifetimes for the two B_s mass-eigenstates are also presented.

1 Introduction

The measurements of B lifetimes are important for the determination of elements of the Cabibbo-Kobayashi-Maskawa matrix. Moreover, measurements of the lifetimes of B-hadrons probe decay mechanisms beyond the simple spectator quark decay model. Lifetime differences can arise from unequal amplitudes for the annihilation and W-exchange diagrams, as well as from final state Pauli interference effects. In the case of charm mesons, such differences have been observed to be quite large ($\tau(D^+)/\tau(D^0) \sim 2.5$). Among bottom hadrons, the lifetime differences are expected to be smaller due to the heavier bottom quark mass. Phenomenological models predict a difference between the B^+ and B^0 meson lifetimes of the order of 5%, and very similar B^0 and B_s^0 lifetimes [1]. Whereas in the $B_d^0 - \overline{B}_d^0$ system the relative difference between the width of the two mass eigenstates is expected to be less than 1%, for the $B_s^0 - \overline{B}_s^0$ system $\Delta\Gamma/\Gamma$ has been predicted to be sizeable: $10 - 30\,\%$ [2]. In the Standard Model, the ratio $\Delta\Gamma_s/\Delta m_s$ is given by a kinematical factor and by QCD corrections which have been calculated recently [3]:

$$\left(\frac{\Delta\Gamma}{\Delta m_s}\right)_{B_s^0} = (5.6 \pm 2.6) \times 10^{-3} \qquad (1)$$

Therefore, from a direct measurement of $\Delta\Gamma_s$ an indirect Δm_s measurement can be obtained. Finally, from the ratio $\Delta m_d/\Delta m_s$ it is possible to determine the ratio $|V_{td}/V_{ts}|$ of the Cabibbo-Kobayashi-Maskawa matrix elements.

From the experimental point of view, the direct measurements of Δm_s and $\Delta\Gamma_s$ are complementary: the higher the Δm_s the more difficult the oscillation $B_s^0 - \overline{B}_s^0$ measurement, whereas the simpler the $\Delta\Gamma_s$ measurement, because a larger $\Delta\Gamma_s$ results from Eq.1.

The paper is organized as follows. We first discuss the various B_s lifetime measurements, in the various channels: semileptonic, more inclusive, exclusive. Then we discuss the recent $\Delta\Gamma/\Gamma$ searches. Finally we conclude by summarizing all of the results.

2 B_s^0 Lifetime Measurements

2.1 Channels

The possible channels that can be used for a B_s lifetime measurement are the following:

- Exclusive channels: $J/\psi\phi$, $D_s^{(*)+}D_s^{(*)-}$, etc.: this is in principle the best approach, but at the moment is statistically limited.
- Semileptonic channel: $D_s^-\ell^+$ [a] where the D_s^- can be fully or partially reconstructed. With the current available statistics this approach gives the best measurement of B_s lifetime both at LEP and at CDF.
- More inclusive channels: $D_s^- + \text{hadron(s)}^+$, inclusive D_s^-, $\phi - \ell^-$ correlations. This approach has been used only at LEP, because a clean event topology and good particle identification are necessary. However, these analyses are less powerful than the semileptonic ones but can be combined to improve the sensitivity. Recently [12] a completely inclusive analysis has been done by L3 for the $\Delta\Gamma/\Gamma$ search.

2.2 Semileptonic channel

CDF measurement

Let us consider in some detail the CDF measurement of the B_s lifetime using the semileptonic decay $B_s^0 \to D_s^-\ell^+\nu$, where the D_s^- candidates are reconstructed in four decay modes:

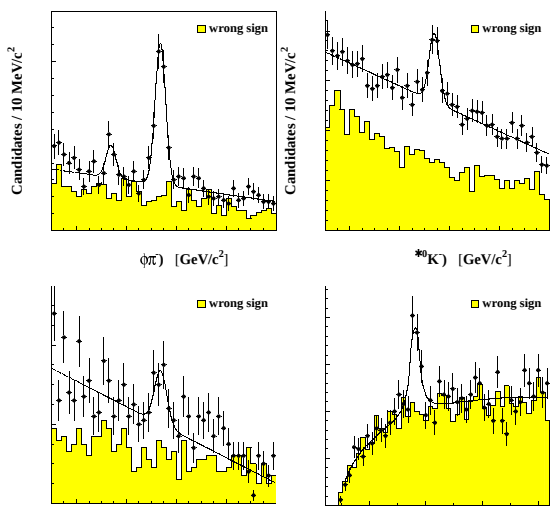
1. $D_s^- \to \phi\pi^-$, $\phi \to K^+K^-$
2. $D_s^- \to K^{*0}K^-$, $K^{*0} \to K^+\pi^-$
3. $D_s^- \to K_s^0K^-$, $K_s^0 \to \pi^+\pi^-$
4. $D_s^- \to \phi\mu^-\nu$, $\phi \to K^+K^-$

For the first three decay modes the reconstruction is based on a single lepton trigger data set with a principal lepton p_t threshold of about $8\,GeV/c$, while the semileptonic D_s^- decay mode is based on a dimuon data sample

[a] Charge conjugate modes are always implied.

obtained with a trigger requirement of $m(\mu\mu) < 2.8\,GeV$ and a muon p_t threshold of about $2\,GeV/c$. The total number of signal events, out of a data sample of about $110\,pb^{-1}$ of $p\overline{p}$ collisions at $\sqrt{s} = 1.8\,TeV$, is ~ 600: this is the world largest sample of semileptonic B_s^0 decays.

In the figure below all four mass spectra are shown. Notice that for the semileptonic D_s^- decay mode the invariant mass distribution is for the pair K^+K^-: the peak is the ϕ signal. In all four decay modes, the shaded histograms are the wrong-sign combinations, which means: same sign $D_s^\pm \ell^\pm$ events for the three hadronic D_s^- decay modes, and same sign $K^\pm K^\pm$ or $\mu^\pm\mu^\pm$ events for the semileptonic mode. As expected, there is no evidence for a signal in the wrong-sign mass spectrum. Notice that, in the $D_s^- \to \phi\pi^-$ mode, there is also evidence for the Cabibbo-suppressed decay $D^- \to \phi\pi^-$.



In the $D_s^- \to K^{*0}K^-$ and $D_s^- \to K_s^0 K^-$ decays there is significant background from $B_d^0 \to D^-\ell^+X$ decays with $D^- \to K^{*0}\pi^-$ or $D^- \to K_s^0\pi^-$, where the pion is misassigned as a kaon. This kind of background is more relevant at CDF than at LEP experiments, because the particle identification at CDF provides a pion/kaon separation (through dE/dx) of only about one standard deviation in this momentum range. The fraction of the signal coming from real D_s^- decays has been measured in two different ways. First, because of the large difference between the D_s^- and D^- lifetimes, the D_s^- and D^- fractions can be determined from a two-component fit of the proper decay length distribution, where the lifetimes of D_s^- and D^- are fixed to the world average. The second method is a simultaneous fit to the D_s^- and D^- mass distributions, where the D^- mass distribution has been created from the data by switching the mass assignment on the third track of the D_s^- candidate from a kaon to a pion. Each of the two mass distributions is fit with a Gaussian for the corresponding signal, a linear background, plus the shape of the events coming from the reflection as determined with Monte Carlo.
The fraction of signal coming from real D_s^- decays is obtained from the weighted average of the two independent measurements, which gives about 70 % for both decay modes.

For all of the four decays modes there are the following possible sources of real physics backgrounds:

1. $B_d^0 \to D_s^{(*)-} D^{(*)+} X$ and $B^- \to D_s^{(*)-} D^{(*)0} X$ with the $D^{(*)}$ decaying semi-leptonically;
2. $B_s \to D_s^{(*)-} D_s^{(*)+}$ with one $D_s^{(*)}$ decaying semi-leptonically;
3. $B^0/B^- \to D_s^- K\ell^+\nu X$

The last decay has not yet been established, therefore the fraction is assumed negligible, but a small possible contamination is taken into account as systematic error. By using the branching ratios from the PDG, and the relative efficiencies from Monte Carlo, the fraction of the first two type of backgrounds have been estimated to be only a few percent of the signal.

The proper decay length is determined as follows:

$$t = F_{corr} \cdot \frac{M(B_s) \cdot L_{xy}^B}{p_t(D_s\ell)} \qquad (2)$$

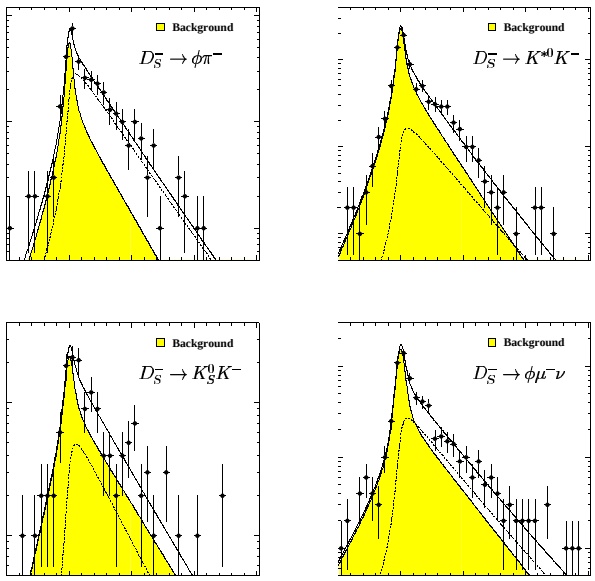
where L_{xy}^B is the decay length of the B_s^0 in the transverse plane, defined as the distance between the beam spot and the B_s^0 vertex. The latter is determined from the intersection of the lepton with the D_s direction. The correction factor F_{corr} is determined from Monte Carlo to take into account that the B_s^0 is not fully reconstructed, hence the momentum of the system $D_s^0\ell$ must be corrected to obtain the B_s^0 momentum.

A simultaneous unbinned likelihood fit of the four samples is used to extract the B_s^0 lifetime. The probability distribution of the signal consists of an exponential function, convoluted with the distribution of the correction factor and the resolution function. The combinatorial background is parametrized with three components: a Gaussian for the prompt component, and two exponentials convoluted with a Gaussian for the left ($c\tau < 0$) and right ($c\tau > 0$) tails. For each sample, the proper time distribution of the events in the signal mass region is fitted simultaneously with the one of the sideband mass regions and the wrong-sign combinations, to model the combinatorial background. For the D^- reflection contamination in the $K^{*0}K^-$ and K_sK^- samples, the lifetime is fixed to world average B_d^0 lifetime. For the physics background $B \to D_s^{(*)} D_s^{(*)} X$ and $B_s \to D_s^{*-} D_s^{*+}$ the

lifetimes are fixed to the effective ones as measured in the Monte Carlo. The final result, shown in the figure below is:

$$\tau_s = 1.36 \pm 0.09(stat)\ ^{+0.06}_{-0.05}(syst)\ ps \qquad (3)$$

This is the most precise B_s^0 lifetime measurement from a single experiment.



LEP measurements

- ALEPH [5]: four million hadronic Z^0 decays collected from 1991 to 1995 have been used in this analysis. Leptons (electrons or muons) are combined with opposite sign D_s^- candidates reconstructed in seven different decay modes: $\phi\pi^-; K^{*0}K^-; K_s^0K^-; \phi\pi^+\pi^-\pi^-; K^{*0}K^{*-}; \phi e^-\nu$; $\phi\mu^-\nu$ where: $\phi \to K^-K^+; K^{*0} \to K^+\pi^-; K_s^0 \to \pi^+\pi^-$. 277 candidates in the signal mass window have been selected: the B_s^0 estimated purity is larger than 60%. The measured B_s^0 lifetime is:

$$\tau_s = 1.54\ ^{+0.14}_{-0.13}(stat) \pm 0.04(syst)\, ps \qquad (4)$$

- DELPHI [9]: four million hadronic Z^0 decays collected from 1991 to 1995 have been used in this analysis. 278 $D_s^-\ell^+$ signal events reconstructed in eight decay modes: $\phi\pi^-; K^{*0}K^-; K_s^0K^-; \phi\pi^-\pi^+\pi^-; \phi\pi^-\pi^0; K^{*0}K^{*-}$; $\phi e^-\nu; \phi\mu^-\nu$. The measured B_s^0 lifetime is:

$$\tau_s = 1.47\ ^{+0.13}_{-0.12}(stat.) \pm 0.03(syst.)\, ps \qquad (5)$$

- OPAL [11]: 4.4 million hadronic Z^0 decays collected from 1990 to 1995 have been used in this analysis. Leptons (electrons or muons) are combined with opposite sign D_s^- candidates reconstructed in five different decay modes: $\phi\pi^-; K^{*0}K^-; K_s^0K^-; \phi e^-\nu; \phi\mu^-\nu$, where: $\phi \to K^-K^+$; $K^{*0} \to K^+\pi^-$; $K_s^0 \to \pi^+\pi^-$. In total 199 ± 26 $D_s^-\ell^+$ candidates in the mass peak are observed: of these, 172 are attributed to B_s^0. The B_s^0 lifetime results:

$$\tau_s = 1.50\ ^{+0.16}_{-0.15}(stat) \pm 0.04(syst) ps \qquad (6)$$

2.3 *More inclusive channels*

D_s^- hadron(s)$^+$

- ALEPH [6]: four million hadronic Z^0 decays collected from 1991 to 1995 have been used in this analysis. One or more tracks (excluding leptons to keep this analysis statistically independent of the $D_s^-\ell^+$ channel) are combined with D_s^- candidates reconstructed in the following channels: $\phi\pi^-; K^{*0}K^-; K_s^0K^-; \phi e^-\nu; \phi\mu^-\nu$, where: $\phi \to K^-K^+; K^{*0} \to K^+\pi^-; K_s^0 \to \pi^+\pi^-$. Also the semileptonic channel $D_s^-\ell^+$, where the D_s^- is reconstructed in the mode $\phi\rho^-$, $\phi \to K^+K^-$, $\rho^- \to \pi^-\pi^0$, $\pi^0 \to \gamma\gamma$, has been included in this analysis. The total number of data candidates in the signal mass region is 1620, with an estimated B_s^0 purity of 22%. The measured B_s^0 lifetime results:

$$\tau_s = 1.47 \pm 0.14(stat) \pm 0.08(syst)\, ps \qquad (7)$$

- DELPHI [8]: one track (not lepton) h^+ is combined with D_s^- candidates reconstructed in the two channels: $\phi\pi^-; K^{*0}K^-$, where: $\phi \to K^-K^+$; $K^{*0} \to K^+\pi^-$. The measured B_s^0 lifetime results:

$$\tau_s = 1.52\ ^{+0.23}_{-0.22}(stat)\ \pm 0.12(syst)\, ps \qquad (8)$$

inclusive D_s^-

- OPAL [10]: 3.7 million hadronic Z^0 decays collected from 1991 and 1995 have been used in this analysis. Only the D_s^- mesons are reconstructed, without any additional accompanying track, in the two channels: $\phi\pi^-; K^{*0}K^-$, where: $\phi \to K^-K^+; K^{*0} \to K^+\pi^-$. The total number of andidates in the mass peak is 911 ± 83, of which about 57% are expected to be from B_s^0 decay. The B_s^0 lifetime results:

$$\tau_s = 1.72\ ^{+0.20}_{-0.19}(stat)\ ^{+0.18}_{-0.17}(syst)\, ps \qquad (9)$$

- DELPHI [8]: only the D_s^- mesons are reconstructed in the two channels: $\phi\pi^-; K^{*0}K^-$, where: $\phi \to K^-K^+$; $K^{*0} \to K^+\pi^-$. The total number of data candidates in the mass peak is 342 ± 41, with an

estimated B_s^0 purity of 55%. The B_s^0 lifetime results:

$$\tau_s = 1.60 \pm 0.26(stat)\,^{+0.13}_{-0.15}(syst)\,ps \qquad (10)$$

$\phi\ell$ correlations

The DELPHI collaboration[8] also measures τ_s in a more inclusive sample requiring a lepton together with a ϕ meson in the same jet. The estimated B_s^0 purity is about 50%. The measured B_s^0 lifetime results:

$$\tau_s = 1.76 \pm 0.20(stat)\,^{+0.15}_{-0.10}(syst)\,ps \qquad (11)$$

2.4 Exclusive channels

$J/\psi\phi$

The only fully reconstructed B_s^0 channel used so far is the $J/\psi\phi$ final state by CDF[13]. Out of $110\,pb^{-1}$ of $p\bar{p}$ collisions, 58 ± 12 signal events have been reconstructed from the dimuon trigger data set. The lifetime fit, performed simultaneously to the mass fit, gives:

$$\tau_s = 1.34\,^{+0.23}_{-0.19}(stat)\,\pm 0.05(syst)\,ps \qquad (12)$$

$D_s^{(*)+}D_s^{(*)-}$

Recently the ALEPH Collaboration[7] has used the $\phi\phi X$ final state to partially reconstruct the decay $B_s^0 \to D_s^{(*)+}D_s^{(*)-}$. From about four million hadronic Z^0 decays (1992-1995) 32 ± 17 pure signal events have been collected, and the lifetime fit gives:

$$\tau_s = 1.42 \pm 0.23(stat) \pm 0.16(syst)\,ps \qquad (13)$$

By assuming that only the CP-even component contributes to the channel $D_s^{(*)+}D_s^{(*)-}$ (indeed it is a mixture of CP-even and CP-odd states, but it is expected to be CP-even dominated), and therefore that the above τ_s measurement gives the lifetime of the light eigenstate (the CP violation is negligible); and by assuming that the world τ_s average is the mean of the lifetimes of the light and heavy mass eigenstates, then it results:

$$\frac{\Delta\Gamma}{\Gamma} = (24 \pm 35)\% \qquad (14)$$

3 $\Delta\Gamma/\Gamma$ search

There are essentially three ways to measure $\Delta\Gamma/\Gamma$:

1. The lifetime distribution of the semileptonic sample $B_s^0 \to D_s^- \ell^+ \nu$ can be fitted with a sum of two exponentials, one for the light and one for the heavy states:
$$\text{const} \cdot \left(e^{-\Gamma_L t} + e^{-\Gamma_H t}\right) \qquad (15)$$
where the normalization takes into account the fact that the width, not the branching ratio, for the semileptonic channel is the same for the two mass eigenstates. By rewriting Γ_L and Γ_H in terms of $\Gamma = (\Gamma_L + \Gamma_H)/2$ and $\Delta\Gamma = \Gamma_L - \Gamma_H$ then $\Delta\Gamma/\Gamma$ can be fitted.
Using this method, and by fixing $\tau_s = \tau_d$ (because from the theory we expect the two lifetimes to be the same within 1%), both DELPHI and CDF set an upper limit at 95% *C.L.*:
$$\frac{\Delta\Gamma}{\Gamma} < \begin{matrix} 0.46 & (DELPHI) \\ 0.83 & (CDF) \end{matrix} \qquad (16)$$

2. The exclusive channels, like $J/\psi\phi$ or $D_s^{(*)+}D_s^{(*)-}$, are a mixture of the CP-even and CP-odd states. These two components can be separated with an angular analysis[4] and then from the lifetime fit of the CP-even (CP-odd) component the lifetime of the light (heavy) eigenstate can be determined. In practice this method is difficult and suffers from low statistics, expecially for the CP-odd component because these exclusive decays are CP-even dominated. A more realistic approach is described below.

3. This approach combines the two previous ones as follows. From the exclusive decays, by assuming that the CP-even component is completely dominant, the lifetime of the light eigenstate is measured. The measurement of the B_s^0 lifetime in the semileptonic channel gives instead the weighted average of the lifetimes of the light and heavy states, where the weights are given by the corresponding branching ratios. By combining these two measurements, $\Delta\Gamma/\Gamma$ can be extracted. A simplified version of this method has been used by ALEPH, as described in the previous section.

A completely new, totally inclusive technique has been used recently by the L3 collaboration[12] to search for $\Delta\Gamma/\Gamma$. The main idea is that value of $\Delta\Gamma \neq 0$ causes significant deviations in the *inclusive* $b-$hadron decay time distribution as compared to a single average b lifetime. The deviations occur at long time scales. The analysis was performed on the 1994-1995 data sample which consists of ~ 2 million hadronic Z^0 decays. After requiring two secondary vertices, the analysis combines a measurements of the b decay time, based on the impact parameter of tracks reconstructed at the secondary vertices, and of the b hadron charge, based on the weighted average of the charge of tracks reconstructed at the secondary vertices. By splitting the sample in *neutral* and *charged* according to the b hadron charge, and in *b-enriched* and *b-reduced* according to the decay length in the opposite hemisphere,

and then by performing a grand-fit in which all possible sources with non-zero lifetime are taken properly into account, the following upper limit was set:

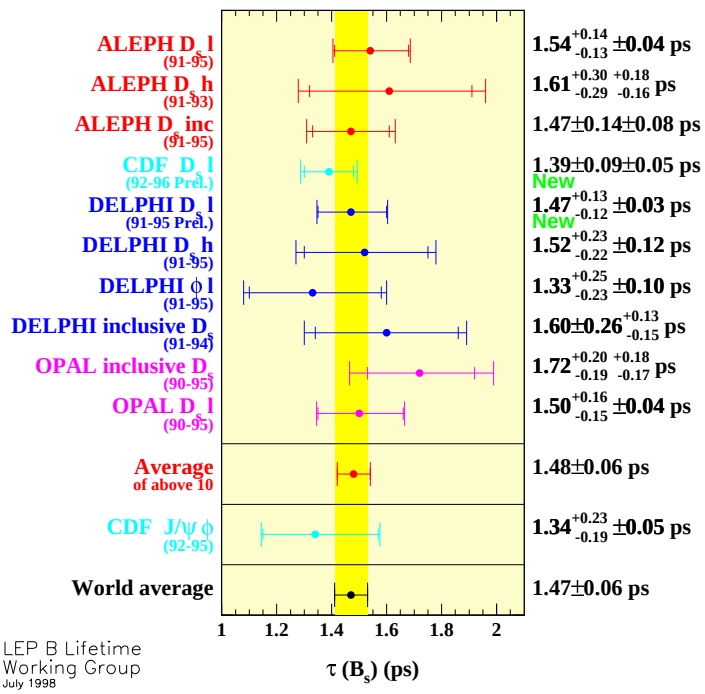
$$\Delta\Gamma/\Gamma < 0.67 \qquad (95\% C.L.) \qquad (17)$$

4 Summary

The table below summarizes all of the $\Delta\Gamma/\Gamma$ searches:

Exp.	Meas.	Limit (95% CL)	Ch.
DELPHI	-	0.46	$D_s^- \ell^+$
L3	$0.00\,^{+0.30}_{-0.00}$	0.67	incl.
ALEPH	0.24 ± 0.35	-	$D_s^{(*)} D_s^{(*)}$
CDF	$0.49\,^{+0.25}_{-0.49}$	0.83	$D_s^- \ell^+$

The table below summarizes all of the τ_s measurements [b].



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[b] Notice that the value reported here for the CDF measurement in the semileptonic channel is slightly older than the updated value quoted in this paper.