EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CERN–PPE/97–143
November 12, 1997

Heavy quark spectroscopy, lifetimes and oscillations

O. Schneider

PPE Division, CERN
CH-1211 Geneva 23, Switzerland

e-mail: Olivier.Schneider@cern.CH

Abstract

The experimental status of the spectroscopy of heavy flavoured hadrons is presented. Lifetime and particle-antiparticle mixing measurements are reviewed. The most recent results are emphasized and world averages are given. Implications for the CKM matrix elements are discussed.

Invited talk at the 18th International Symposium on Lepton-Photon Interactions, 28 July – 1 August 1997, Hamburg, Germany.

HEAVY QUARK SPECTROSCOPY, LIFETIMES AND OSCILLATIONS

O. SCHNEIDER
CERN, CH-1211 Geneva 23
E-mail: Olivier.Schneider@Cern.CH

The experimental status of the spectroscopy of heavy flavoured hadrons is presented. Lifetime and particle-antiparticle mixing measurements are reviewed. The most recent results are emphasized and world averages are given. Implications for the CKM matrix elements are discussed.

1 Introduction

The primary goal in heavy flavour physics is to study and understand the weak interaction. This will eventually be achieved through precise measurements of all elements of the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix which relates the flavour and mass eigenstates of the quarks. Together with future observations of CP violation in the heavy flavour sector, such accurate measurements will provide non-trivial consistency checks of the CKM picture and fundamental tests of the Standard Model. One of the most interesting questions in this context is the origin of CP violation, which is allowed in the Standard Model by the structure of the CKM matrix with three generations of quarks, but which could perhaps also be due to new physics, as explained by Y. Nir.[1]

Quarks are confined inside hadrons by the colour force. As a result, quantum chromodynamics (QCD) is also involved in the weak decay of hadrons, and non-perturbative strong effects often make the extraction of the weak physics difficult or uncertain. A subsidiary goal in heavy flavour studies is therefore to understand these long-distance QCD effects.

The theoretical framework for the description of the properties of hadrons containing a heavy quark of mass m_{Q} is based on the "heavy-quark symmetry": in the limit $m_{\mathrm{Q}} \to \infty$, the light degrees of freedom become insensitive to the flavour and the spin of the heavy quark. In practice this symmetry of the effective strong interactions is only approximate and valid for $m_{\mathrm{Q}} \gg \Lambda_{\mathrm{QCD}}$, where $\Lambda_{\mathrm{QCD}} \sim 0.2$ GeV is the strong interaction scale. This condition defines a "heavy quark" and is satisfied by the charm (c) and bottom (b) quarks with masses $m_{\mathrm{c}} \sim 1.5$ and $m_{\mathrm{b}} \sim 4.5$ GeV/c^2 respectively (the top quark, which is even heavier, is not considered because it decays before it can hadronize). The long-distance physics due to confinement is addressed using tools such as QCD sum rules, lattice QCD, Heavy Quark Effective Theory (HQET) and Heavy Quark Expansions (HQE). Their latest developments are summarized by C. Sachrajda.[2]

On the experimental side, the bottom sector has been much more active in the recent years than the charm sector. This review therefore emphasizes bottom physics. Hidden heavy flavour is not considered here except for a discussion on prompt quarkonium production where new data is available. Recent progress in open heavy flavour spectroscopy is then reported. Lifetime and mixing measurements are finally reviewed and relevant world averages are presented. Experimental results on heavy flavour decays and CP violation are covered by P. Drell[3] and A.J.S. Smith.[4]

2 Production of heavy flavoured hadrons

2.1 Experimental environments, data samples and rates

Over the past few years, large samples of bottom hadrons have been produced in three different ways:

a) $e^+e^- \to \Upsilon(4S) \to B\bar{B}$: e^+e^- annihilations at the $\Upsilon(4S)$ resonance produce roughly equal rates of $B^0\bar{B}^0$ and B^+B^- pairs. These B mesons are almost at rest and can therefore not be used for bottom spectroscopy, lifetime or oscillation studies (except for B^0 and B^+ mass measurements). But the large numbers of charm hadrons produced either in B decays or in the $e^+e^- \to c\bar{c}$ continuum can be exploited for charm spectroscopy. The CLEO experiment at the CESR collider has already collected ~ 5 pb^{-1} of data at or just below the $\Upsilon(4S)$ resonance, i.e. about 10 times the statistics recorded by ARGUS at the DORIS ring.

b) $e^+e^- \to Z \to b\bar{b}$: e^+e^- annihilations at the Z resonance provide a much broader spectrum of b hadrons, as a result of the fragmentation of the $b\bar{b}$ pairs produced in 21.7% [5] of the hadronic Z decays; after the strong decay of resonances, the fractions of weakly decaying b hadrons are roughly 40% B^0, 40% B^+, 10% B^0_s and 10% b baryons (mostly Λ_b). These hadrons have an average energy of 32 GeV and a mean decay length of 3 mm. In addition, b and $\bar{b}$ hemispheres are well separated. The environment is therefore well suited for bottom spectroscopy, lifetime and oscillation measurements. Until 1995 the four experiments at the LEP collider (ALEPH, DELPHI, L3 and OPAL) each collected approximately 4 million hadronic Z decays; up to now, the SLD experiment at the SLC collider has recorded 0.2 million of such decays with polarized beams.

c) $p\bar{p} \to b\bar{b}$: very large numbers of b hadrons are produced in hadronic collisions, mainly through two-gluon initial state processes, but in conjunction with an enormous background: at the Tevatron collider ($\sqrt{s} = 1.8$ TeV), the $b\bar{b}$ production cross section is ~ 4000 times larger than at LEP or SLC, but only represents $\sim 0.1\%$ of the inelastic cross section. Triggering is therefore a critical issue. The fractions of weakly decaying b hadrons are expected to be similar to those from Z decays but their spectrum is softer resulting in a mean decay length of 1–2 mm. Since 1992 the CDF and D0 experiments have each collected close to 130 pb^{-1} of data at the Tevatron, triggering on lepton pairs or single leptons.

Heavy flavour production at hadron machines, which is of considerable interest for future CP violation measurements, is less well understood than at e^+e^- machines, despite intense theoretical and experimental studies. Perturbative next-to-leading order (NLO) QCD has been used to describe $b\bar{b}$ production in $p\bar{p}$ interactions,[6] leading to predictions for the shape of differential cross sections in good agreement with data. However, the predicted absolute rate, which depends on inputs with large uncertainties (Λ_{QCD}, m_b, and the QCD renormalization and factorization scale μ), is consistently lower than the measurements performed by CDF [7] and D0 [8] at $\sqrt{s} = 1800$ GeV and earlier by UA1 [9] at the $Sp\bar{p}S$ collider at $\sqrt{s} = 630$ GeV.

Both CDF [10] and D0 [11] have now preliminary results from data collected during a special Tevatron run at 630 GeV in December 1995. These confirm the UA1 measurements and the discrepancy with NLO QCD calculations, as can be seen in Fig. 1a from which a combined

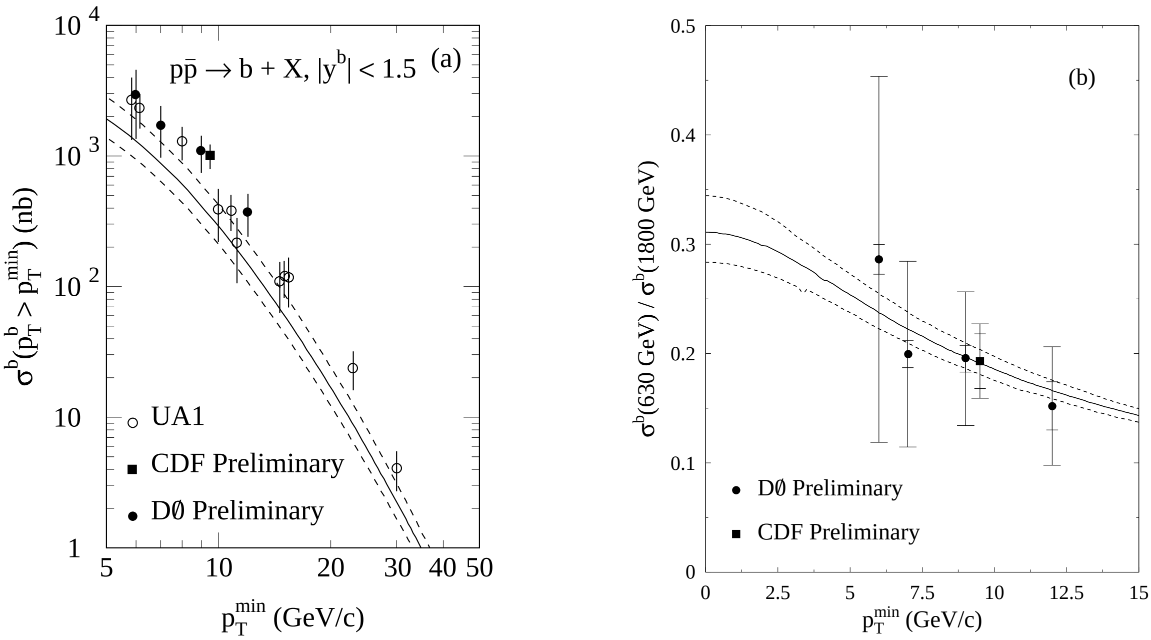

Figure 1: (a) b quark production cross section at $\sqrt{s} = 630$ GeV as a function of the minimum transverse momentum p_T of the b quark, measured by UA1,[9] CDF[10] and D0 [11] in the central pseudo-rapidity region $|y^b| < 1.5$. (b) Ratio of these cross sections at $\sqrt{s} = 630$ and 1800 GeV. The solid curves are predictions based on NLO QCD calculations.[6] The dashed curves show theoretical uncertainties due to $m_b = 4.75 \pm 0.25$ GeV$/c^2$ and $\mu = (1.0^{+1.0}_{-0.5})\sqrt{m_b^2 + (p_T^b)^2}$.

data/theory ratio of 2.1 ± 0.2 is derived.[11] However, the predicted ratio between the cross sections at 630 and 1800 GeV is in good agreement with data (Fig. 1b). This should provide confidence in extrapolations to higher energies based on the energy dependence predicted by theory.

Although charm physics can be addressed in the clean environment of e^+e^- collisions, dedicated charm experiments boost their statistics by taking advantage of huge yields obtained with high intensity beams on fixed targets. For example, E687 (photo-production, 200 GeV photon beam) and E791 (hadro-production, 500 GeV π^- beam), which took data during the 1990–1991 Tevatron fixed-target run, contributed significantly to charm spectroscopy, lifetime and mixing studies. Charm is also produced at the HERA ep collider and detected by the H1 and ZEUS experiments.

Most measurements in heavy flavour physics rely on the ability to detect the secondary vertices from bottom or charm decays and resolve them from the primary interaction vertex. This is of course essential for lifetime and oscillation measurements, but also extremely useful for background rejection, especially in the harsh environments of hadro- and photo-production. The technology of silicon detectors, which provide an adequate spatial resolution, has therefore played (and continues to play) a major role in heavy flavour experimentation.

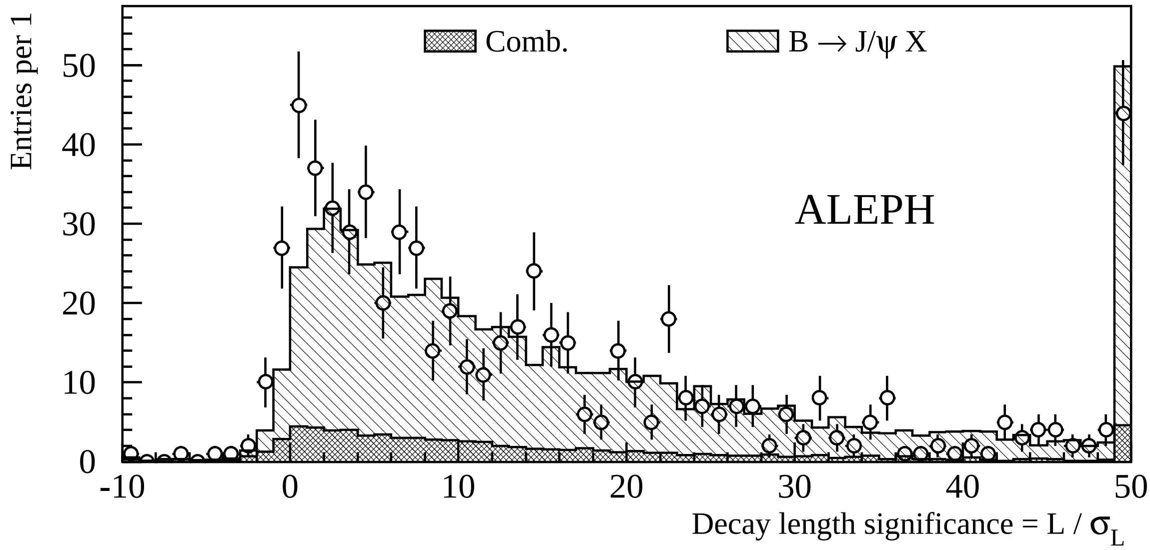

Figure 2: Apparent decay length significance for J/ψ candidates reconstructed in the ALEPH data (open circles and error bars). The estimated contributions from combinatorial background (fake J/ψ) and real J/ψ from b hadron decays are shown as histograms. The small excess of 46 ± 12 events visible at zero decay length is attributed to prompt J/ψ production.[19]

2.2 Prompt quarkonia production

With their first silicon vertex detector installed for the 1992–1993 Tevatron run, CDF unambiguously observed yields of prompt J/ψ and ψ(2S) mesons (i.e. not from b decays) much larger than expected. Since then, the production of quarkonia ($c\bar{c}$ or $b\bar{b}$ bound states) became a field of intense experimental and theoretical study; new results are still coming in, and the understanding of quarkonium production, although completely revised since 1993, still seems incomplete.

According to leading order calculations based on the colour-singlet (CS) model,[12] direct J/ψ and ψ(2S) production should be suppressed. This implies that prompt J/ψ mesons should predominantly be due to radiative decays of χ_c mesons produced at the primary vertex, and that the prompt ψ(2S) signal should be very weak as long as no heavy charmonia decaying to ψ(2S) exist. However, predicted rates [13] for both direct J/ψ and direct ψ(2S) fall a factor ~ 50 below the CDF measurements.[14] Similarly, CS predictions for Υ production at the Tevatron disagree with CDF data.[15] In order to resolve these discrepancies, higher orders in α_s and colour-octet (CO) mechanisms were considered. In these new models,[16] where quarkonia are first produced as colour-octet states before evolving into colour-singlet states via soft gluon emission, certain non-perturbative matrix elements were tuned to reproduce the CDF data.[17] It is therefore desirable to test the CO models on different processes.

Prompt J/ψ mesons in Z decays were first observed by OPAL,[18] and ALEPH now also measures a signal (see Fig. 2) with reduced systematics and model-dependence.[19] The two results are consistent and can be combined to give $\mathcal{B}(\mathrm{Z} \to \text{prompt J}/\psi) = (2.5 \pm 0.5_{\text{stat}} \pm 0.3_{\text{syst}} \pm 0.3_{\text{model}}) \times 10^{-4}$. According to theoretical calculations,[20] the CS and CO contribu-

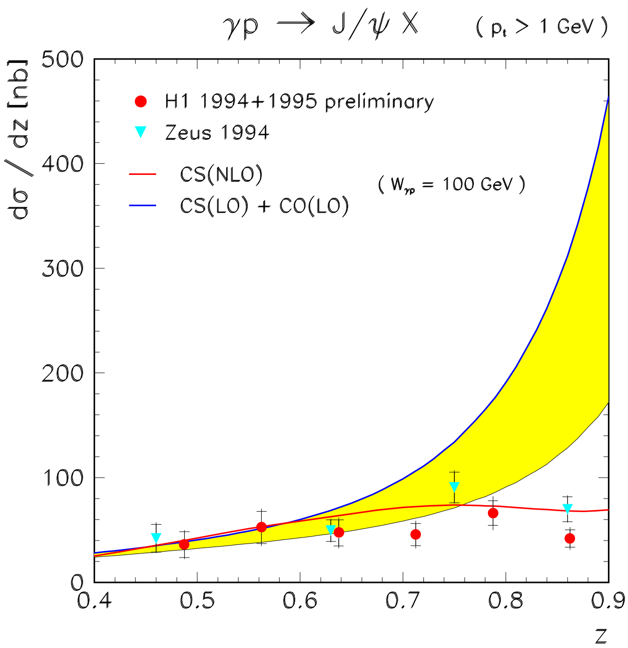

Figure 3: Inelastic J/ψ photo-production at HERA. The data[25,26] agree with the NLO CS predictions.[27] It has been argued[28] that the CS+CO predictions could be lower than the origin estimate,[24] hence the band to reflect theoretical uncertainties.

tions to this branching ratio are dominated by c quark and gluon fragmentation respectively and are predicted to be 0.8×10^{-4} (CS) and 1.9×10^{-4} (CO), with a factor ~ 2 uncertainty on the latter. The data disfavour CS as the sole production mechanism at the $2.5\,\sigma$ level but are compatible with CS+CO production. In the $\mathrm{b\bar{b}}$ meson sector, a new limit from L3, $\mathcal{B}(\mathrm{Z}\to\Upsilon(1\mathrm{S},2\mathrm{S},3\mathrm{S})) < 7.6\times10^{-5}$ at 95% CL,[21] is very similar to the one reported last year by ALEPH,[22] and not inconsistent with the original OPAL measurement [23] which also favours CO production.

The HERA experiments have looked for evidence of the CO production mechanism in inelastic J/ψ photo-production via direct photon-gluon fusion. At leading order, this mechanism implies a dramatic increase [24] of the $\gamma\mathrm{p}\to\mathrm{J}/\psi\mathrm{X}$ cross section for large values of z, defined as the fraction of the photon energy carried by the J/ψ in the proton rest frame. But the most recent H1 [25] and ZEUS [26] data show no excess over (and are perfectly consistent with) the NLO calculations [27] in the frame of the CS model (see Fig. 3).

3 Spectroscopy of open heavy flavour

3.1 Weakly decaying bottom hadrons

Only four weakly decaying bottom hadrons have been solidly established: $\mathrm{B}^0(\bar{\mathrm{b}}\mathrm{d})$, $\mathrm{B}^+(\bar{\mathrm{b}}\mathrm{u})$, $\mathrm{B}^0_\mathrm{s}(\bar{\mathrm{b}}\mathrm{s})$, and $\Lambda_\mathrm{b}(\mathrm{bdu})$. The B^0 and B^+ masses were measured many years ago by ARGUS and CLEO and are now known to better than 2 MeV/c^2.[29] B^0_s and Λ_b mass measurements were performed originally at LEP based on a handful of fully reconstructed candidates, but

Table 1: $L = 0$ and $L = 1$ states for the B^+ and B^0 mesons. The four $L = 1$ (orbitally excited) states are often called "B^{**}". A similar spectrum exists for the B^0_s meson, except that $B^{**}_s \to B^*K$ due to isospin conservation.

L	j_q	J^P	state	main decay mode	
0	$\frac{1}{2}$	0^-	B	weak	
		1^-	B^*	$B\gamma$	
1	$\frac{1}{2}$	0^+	B^*_0	$B\pi$	S-wave, broad
		1^+	B_1	$B^*\pi$	
1	$\frac{3}{2}$	1^+	B_1	$B^*\pi$	D-wave, narrow
		2^+	B^*_2	$B^{(*)}\pi$	

CDF eventually had enough statistics in the $B^0_s \to J/\psi\phi$ and $\Lambda_b \to J/\psi\Lambda$ channels to perform the most accurate determinations,[30] which now dominate the world averages of 5369.7 ± 2.4 and 5624 ± 5 MeV/c^2 respectively.

The $B^+_c(\bar{b}c)$ meson is the last weakly decaying bottom meson to be measured. Its mass is predicted from potential models to be in the range 6.24–6.31 GeV/c^2.[31] Its production rate in Z decays or at the Tevatron is expected to be 2–3 orders of magnitude smaller than that of the B^+, so a few reconstructed candidates could be observed at LEP or CDF with present statistics in channels with branching ratios of order 1%. Searches performed so far [32–35] in the $J/\psi\pi^+$, $J/\psi\pi^+\pi^-\pi^+$ and $J/\psi\ell^+\nu$ channels have only led to upper limits on $\sigma\mathcal{B}$, some of them being a function of the unknown B^+_c lifetime (expected in the range 0.4–1.4 ps). Since last year, ALEPH has a very clean $B^+_c \to J/\psi\mu^+\nu_\mu$ candidate, with an estimated background of 0.002 event and a measured mass of $5.96^{+0.25}_{-0.19}$ GeV/c^2.[34] A new preliminary OPAL analysis [35] finds two $B^+_c \to J/\psi\pi^+$ candidates with an expected background of 0.32 ± 0.11 events; the masses of these candidates are 6.29 ± 0.17 and 6.33 ± 0.06 GeV/c^2.

Indirect evidence for Ξ_b(bsu,bsd) baryons has existed for some time in the form of branching ratio products and lifetime measurements using same sign $\Xi^-\ell^-$ pairs at LEP,[36] but no mass measurement has been performed yet.

3.2 Heavy meson spectroscopy

Heavy quark symmetry implies that, in a $Q\bar{q}$ bound state, the spin of the heavy quark $\vec{S}_Q$, and the total angular momentum of the light antiquark, $\vec{j}_q = \vec{S}_q + \vec{L}$ where $\vec{L}$ is the orbital angular momentum, are conserved separately; the $Q\bar{q}$ meson has a total angular momentum $\vec{J} = \vec{S}_Q + \vec{j}_q$, so there is an almost degenerate "hyperfine doublet" for each possible pair of values for L and j_q, with a mass splitting proportional to $1/m_Q$. Table 1 shows the list of the 1S and 1P bottom meson states with their main decay modes, predicted by HQET. There is a similar picture for the corresponding charm mesons, except that the strong decay $D^* \to D\pi$ is possible due to the larger mass splitting.

In the charm sector, all six $L = 0$ mesons are well established and all six $L = 1$ narrow states have been observed.[29] However, no broad $L = 1$ resonance has been reported yet. In a new preliminary search for excited D mesons,[37] DELPHI see a peak of 62 ± 14 events in

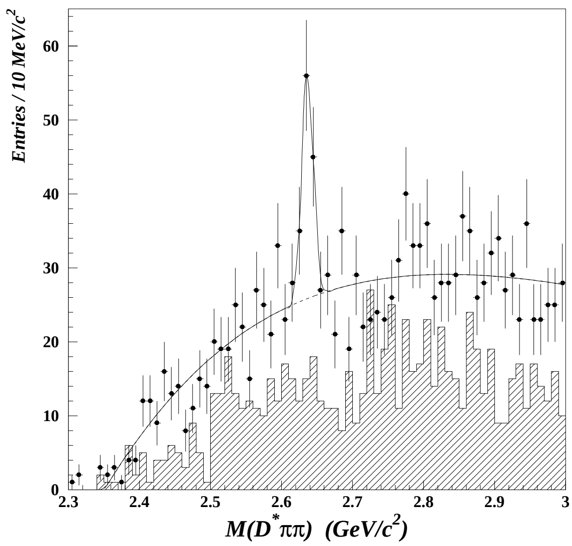

Figure 4: New preliminary $D^{*\prime} \to D^{*+}\pi^+\pi^-$ signal from DELPHI. No excess is seen in the wrong sign $D^{*+}\pi^-\pi^-$ combinations (hatched histogram).

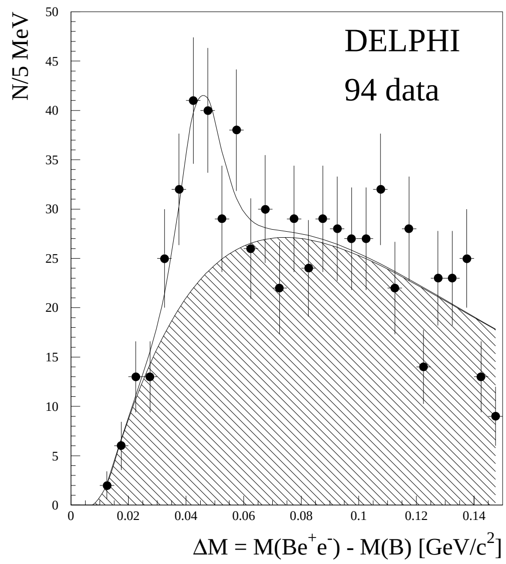

Figure 5: New preliminary $B^* \to Be^+e^-$ signal from DELPHI. The hatched area represents the background.

the $D^{*+}\pi^+\pi^-$ channel, at a mass of $2637 \pm 2 \pm 6$ MeV/c^2, which is interpreted as the first evidence for a radially excited (2S) charm meson (see Fig. 4). Note that DELPHI claimed last year the first preliminary evidence for radially excited bottom mesons.[38]

The mass difference between the pseudoscalar B mesons and their hyperfine partners, the vector B^* mesons, is less than 50 MeV/c^2, and therefore B^* mesons decay to B via emission of a low energy photon. At LEP, the observation of B^* has been possible using inclusively reconstructed bottom hadron candidates combined with a photon measured in a high resolution crystal calorimeter (L3) or identified by its e^+e^- conversion pair in the material of the beam pipe or detector (ALEPH, DELPHI, OPAL).[39,40] Large signals are observed, which are mixtures of B^{*0}, B^{*+} and B_s^{*0}, and the following quantities are extracted (LEP averages): the mass splitting $m_{B^*} - m_B = 45.7 \pm 0.5$ MeV/c^2, the fraction of vector meson production $\sigma_{B^*}/(\sigma_{B^*} + \sigma_B) = 0.75 \pm 0.04$, and the relative contribution to the B^* rate of the longitudinal polarization states $\sigma_L/(\sigma_L + \sigma_T) = 0.33 \pm 0.04$. The last two results are in agreement with simple spin counting predictions, whereas the first one is consistent with $(m_{B^*} - m_B)/(m_{D^*} - m_D) \simeq m_c/m_b$, as predicted by HQET. New preliminary results on B^* Dalitz decay by DELPHI (see Fig. 5) yield $\Gamma(B^* \to Be^+e^-)/\Gamma(B^* \to B\gamma) = (4.8 \pm 0.9 \pm 0.9) \times 10^{-3}$, consistent with QED expectations.[41]

$B^{**} \to B^{(*)}\pi$ signals have been observed by ALEPH,[40] DELPHI[42] and OPAL[43] as a wide resonant structure in the distribution of the mass difference $\Delta M = M(B\pi) - M(B)$ where "B" is an inclusively reconstructed bottom hadron candidate and "π" a charged track consistent with a pion from the interaction vertex. However, their decomposition into individual contributions from the narrow and broad orbital excitations is not conclusive. Hints of narrow structures have been seen by ALEPH using fully reconstructed B^0 and B^+

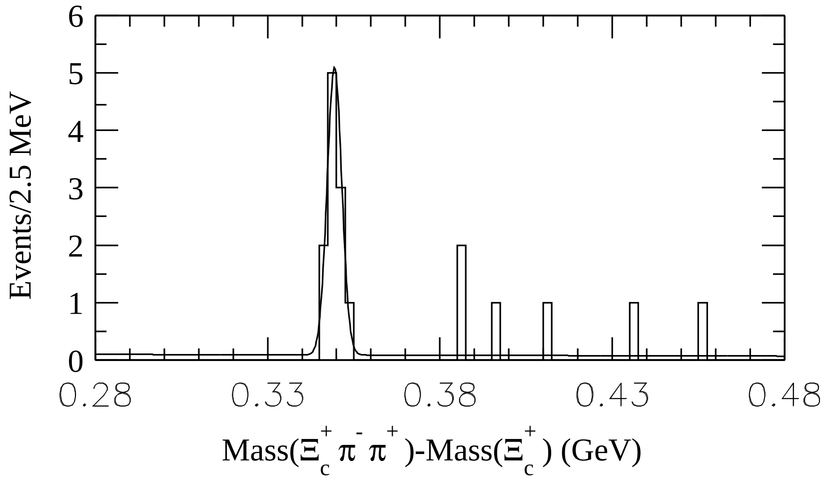

Figure 6: New preliminary $\Xi_c^{**+} \to \Xi_c^{*0}\pi^+ \to \Xi_c^+\pi^-\pi^+$ signal from CLEO.[50]

mesons.[44] The observed ratio $B^{**}/B \sim 30\%$ is interesting in regard of the possibility of tagging the particle or antiparticule state of B^0 mesons with the charge of the pion from a charged B^{**} decay. $B_s^{**} \to B^{(*)}K$ signals have been reported by OPAL[43] and DELPHI.[42]

3.3 Heavy baryon spectroscopy

The charm baryon spectroscopy is progressing well, thanks to many recent CLEO results. New preliminary evidence for $\Xi_c^{0\prime} \to \Xi_c^0\gamma$ and $\Xi_c^{+\prime} \to \Xi_c^+\gamma$ signals[45] complete the observation of all members of the $L = 0$, $J^P = 1/2^+$ singly-charmed baryon sextuplet of the quark model. For the associated $3/2^+$ sextuplet, only the Σ_c^{*+} and Ω_c^{*0} states still remain unseen, after the observation of the decays $\Xi_c^{*0} \to \Xi_c^+\pi^-$, $\Xi_c^{*+} \to \Xi_c^0\pi^+$, $\Sigma_c^{*++} \to \Lambda_c^+\pi^+$ and $\Sigma_c^{*0} \to \Lambda_c^+\pi^-$ by CLEO.[46] Two orbitally excited Λ_c^+ baryons decaying to $\Lambda_c^+\pi^+\pi^-$, $\Lambda_c(2593)^+$ and $\Lambda_c(2625)^+$, consistent with the $J^P = 1/2^-$ and $3/2^-$ states of a $L = 1$ doublet (where L is the orbital angular momentum of the light ud diquark with respect to the heavy c quark), have been established in the last few years by ARGUS,[47] E687[48] and CLEO.[49] CLEO also has a new preliminary evidence for a "Ξ_c^{**}" state, reconstructed as $\Xi_c^{**+} \to \Xi_c^{*0}\pi^+ \to \Xi_c^+\pi^-\pi^+$ (see Fig. 6) and consistent with $L = 1$ and $J^P = 3/2^-$.[50]

No progress on bottom baryon spectroscopy was reported in the last two years since the preliminary DELPHI results on $\Sigma_b, \Sigma_b^* \to \Lambda_b\pi$.[51] If one accepts the DELPHI and CLEO interpretations of their mass peaks, then $(m_{\Sigma_b^*} - m_{\Sigma_b})/(m_{\Sigma_c^*} - m_{\Sigma_c}) \simeq 0.85 \neq m_c/m_b \simeq 0.33$, in violation of the $1/m_Q$ scaling predicted for hyperfine mass splittings. This can cast doubt on the quantum number assignment of some of the heavy baryons, and a new interpretation has been suggested.[52]

4 Lifetimes

In the spectator model, where the heavy quark decays weakly without interacting with the other light quark(s) in the hadron, all the hadrons containing the same heavy quark are predicted to have equal lifetimes. This model fails dramatically for charm lifetimes, which have been measured to range between 0.064 ± 0.029 ps for the Ω_c^0 and 1.057 ± 0.015 ps for the D^+.[29] These lifetime differences can be accounted for, at least qualitatively, by considering effects like final state interference, W exchange or annihilation diagrams, and helicity suppression. In particular, these phenomenological descriptions could explain the measured ratio $\tau_{D^+}/\tau_{D^0} = 2.55 \pm 0.04$.[29] However, a more systematic QCD-based theoretical treatment has been developed,[53] where the decay rates of a heavy hadrons are expressed as expansions in powers of $1/m_Q$. In this approach, lifetime differences only arise at order $1/{m_Q}^2$ between hadrons and mesons, whereas differences between mesons emerge at order $1/{m_Q}^3$. The success of the application of this heavy quark expansion (HQE) to charm lifetimes is reasonable, but also remarkable given the size of the expansion parameter.[54] Lifetime differences in bottom lifetimes are smaller due to the larger b quark mass, and HQE predictions should be more reliable.

Whereas theorists agree that τ_{B^0} and $\tau_{B_s^0}$ should be equal at the percent level and that $\tau_{\text{b-baryon}}/\tau_{B^0}$ lie between 0.9 and 1.0, there seem to be less consensus on the ratio τ_{B^+}/τ_{B^0}: Bigi[54] predicts $\tau_{B^+}/\tau_{B^0} = 1 + 0.05(F_B/200 \text{ MeV})^2$ where F_B is the B decay constant, but Neubert[55] argues that, without strong model-dependent assumptions, the whole range $0.8 - 1.2$ is allowed for this ratio. As in the K^0 system, the neutral B mesons have two mass eigenstates with decay widths Γ_L and Γ_S. Here τ_{B^0} and $\tau_{B_s^0}$ represent averages over these states: $1/\tau = \Gamma = (\Gamma_S + \Gamma_L)/2$. The relative width differences $(\Gamma_S - \Gamma_L)/\Gamma$ are due to channels common to both particle and antiparticle, like $B^0, \bar{B}^0 \to D^+D^-$ (CKM suppressed) and $B_s^0, \bar{B}_s^0 \to D_s^+D_s^-$ (not CKM suppressed); these ratios are expected to be less than 1% for the B^0 and potentially much larger for the B_s^0, for which a recent prediction[56] is $0.16^{+0.11}_{-0.09}$.

4.1 Individual bottom hadron lifetimes[a]

The lifetime of a specific bottom hadron is usually measured from a fit to a proper time distribution, where the proper time of each candidate is computed from estimates of its decay length and momentum. The decay length resolution depends primarily on the vertexing capabilities of the experiment, but also to some extent on the energy spectrum and size of the luminous region provided by the collider. In this respect the best conditions are realized at SLD/SLC, where a 3-D CCD pixel detector is installed at a minimum radius of 2.5 cm from an interaction region with transverse and longitudinal dimensions of $2\mu\text{m} \times 1\mu\text{m}$ and 0.7 mm.

The cleanest way to measure the lifetimes of the individual bottom hadrons is to fully reconstruct specific hadronic decays. In this case, the decay vertex and momentum are well determined. A mass peak is observed, and the background, which is only combinatorial, can be handled easily. However, the current statistics limit the precision of these measurements. The best examples of such results are provided by CDF, which, with 824 ± 36 and 436 ± 27 exclusively reconstructed B^+ and B^0 mesons in various channels such as $J/\psi K^+$ and $J/\psi K^*(892)^0$, measure $\tau_{B^+}/\tau_{B^0} = 1.06 \pm 0.07_{\text{stat}} \pm 0.01_{\text{syst}}$.[57]

[a]Included in this review are updated[57–61] and new[62] lifetime results that became available during or just after this conference, and were published or submitted to the EPS-HEP conference in Jerusalem.

Another approach, aiming for larger statistics, is to select semileptonic b decays in a semi-inclusive manner, associating a fully reconstructed charm hadron with a lepton of appropriate charge. The vertex resolution is still good due to the presence of the lepton, but the missing decay products (at least the neutrino) prevent the mass reconstruction and degrade the momentum resolution. Also physics backgrounds can become an issue, like the B^+ and B^0 cross-contamination in the $\bar{D}^0\ell^+$ and $D^{*-}\ell^+$ samples due to $B \to D^{**}$ semileptonic decays. This leads to measurements which have systematic uncertainties related to the modelling of the b hadron decays. However, this technique is currently the best for B^0_s and Λ_b lifetime measurements,[57–59,63,64] because it provides reasonable efficiency while maintaining a good purity thanks to the selection of the appropriate charm hadron, a D_s^- or Λ_c^+ respectively. A few variants of this approach have been used, for example measuring the B^0_s lifetime with $\phi\ell^-$ pairs or a D_s^- sample (without requiring a lepton),[59,65] or using $p\ell^-$, $\Lambda\ell^-$, $\Lambda\ell^+\ell^-$ and $\Xi^-\ell^-$ correlations for the b baryon lifetimes.[36,63,64] For B^0 lifetime measurements, the decay $B^0 \to D^{*-}\ell^+\nu X$ can also be partially reconstructed by combining the lepton with the slow π^- from the decay $D^{*-} \to \bar{D}^0\pi^-$, without fully reconstructing the $\bar{D}^0$.[60,62]

A third approach is based on pure topological vertexing: b decay vertices are reconstructed inclusively and the b hadron charge is determined from the total charge of the tracks associated with its vertex. This method is very efficient, but relies heavily on the Monte Carlo simulation for the estimate of the sample composition and resolution. The SLD collaboration has been very successful with this technique, obtaining very competitive measurements of the B^+ and B^0 lifetimes, $\tau_{B^+}/\tau_{B^0} = 1.07 \pm 0.05_{\rm stat} \pm 0.04_{\rm syst}$,[61,66] despite their relatively small data sample.

The many measurements of the individual bottom hadron lifetimes are summarized in the tables of Fig. 7, together with the world averages computed by the LEP B lifetime working group.[67] The current world average ratios $\tau_{B^+}/\tau_{B^0} = 1.07 \pm 0.04$ and $\tau_{B^0_s}/\tau_{B^0} = 0.95 \pm 0.05$ indicate no significant lifetime differences between the three B mesons and are in good agreement with HQE predictions. There is no evidence for lifetime differences among b baryons either, within the still poor experimental sensitivity. The ratio $\tau_{\text{b-baryon}}/\tau_{B^0} = 0.78 \pm 0.04$ is significantly different from unity and also significantly smaller than usual HQE predictions. Although it has been shown that there still is a small region of parameter space where theory could accommodate the data,[55] this discrepancy, which could be a potential problem for heavy quark theory, is being actively investigated.[2] At present, there is no experimental evidence for long and short lifetime components in the B^0_s system,[57] nor in the B^0 system.

4.2 Average bottom hadron lifetime

Some measurements of the average lifetime $\langle\tau_b\rangle$ over all bottom hadron species are based on the impact parameters of tracks from b decays, generally leptons. Such impact parameters are proportional to the lifetime and have the advantage to be only very mildly dependent on the b hadron boost. A second method uses topological vertexing to measure directly a decay length; in this case, a good estimate of the (average) boost is critical to determine the lifetime. The precise measurements of $\langle\tau_b\rangle$ are dominated by systematic uncertainties,

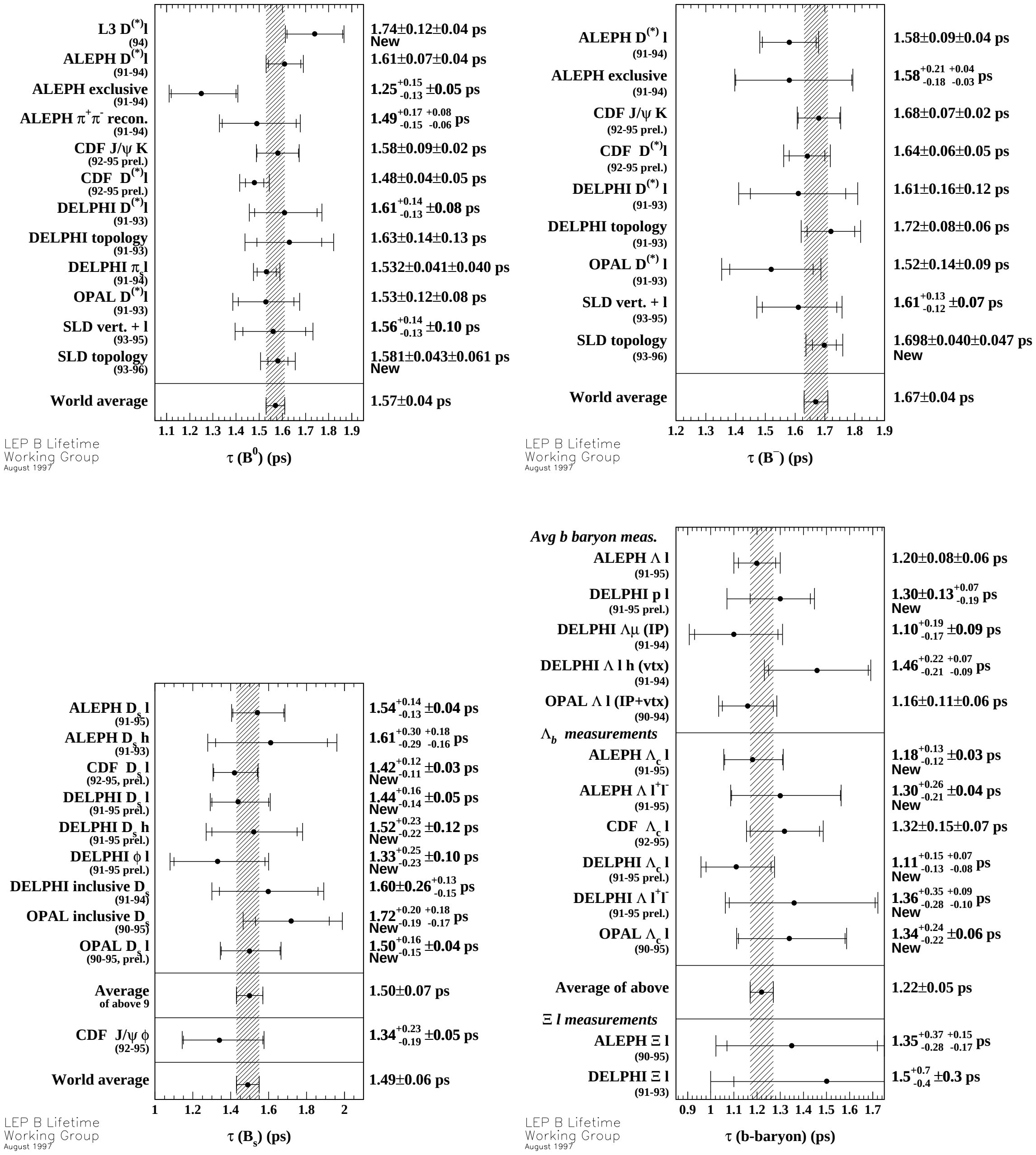

Figure 7: Individual b hadron lifetime measurements and averages.[67] On these tables and those of Figs. 9 and 11, the outer error bars represent the total uncertainties and the inner error bars, when shown, the statistical uncertainties; when two uncertainties are quoted for a result, the first is statistical and the second systematic. Results that are new or have been updated since the 1996 summer conferences are listed in the references;[57–66] the full list of references is available elsewhere.[67]

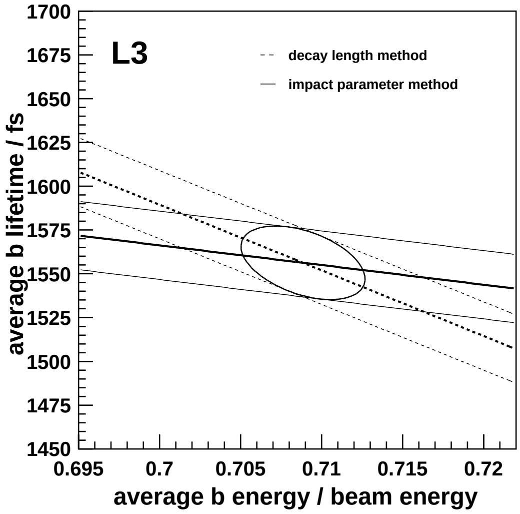

Figure 8: New preliminary measurement of $\langle\tau_{\mathrm{b}}\rangle$ from L3 using inclusive hadronic Z decays.[70]

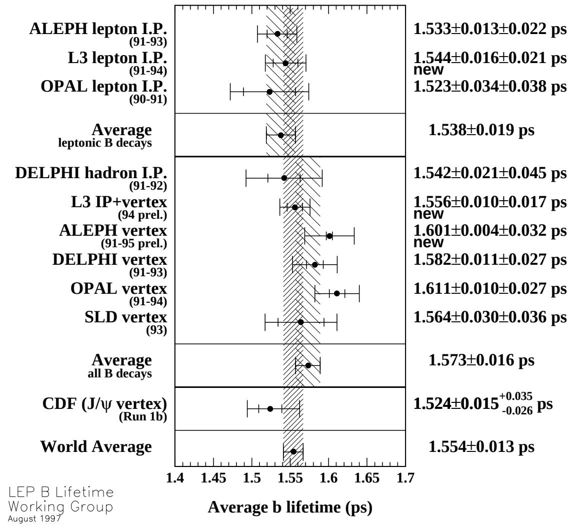

Figure 9: Average bottom hadron lifetime measurements [67–70] and averages.[67]

including our limited knowledge on the b fragmentation.

Since the last summer conferences, fresh measurements are available from OPAL,[68] ALEPH[69] and L3.[70] In a new preliminary analysis, L3 apply both an impact parameter and a decay length technique to the same data sample. The two resulting lifetime measurements are performed as a function of the assumed value of $\langle x_E\rangle_{\mathrm{b}}$, the ratio of the mean b hadron energy to the beam energy, and then combined to yield $\langle\tau_{\mathrm{b}}\rangle = 1556 \pm 10_{\mathrm{stat}} \pm 17_{\mathrm{syst}}$ and $\langle x_E\rangle_{\mathrm{b}} = 0.709 \pm 0.004_{\mathrm{tot}}$ (see Fig. 8). These results are the most precise from a single analysis. If taken at face value, they would imply that L3 has a measurement of $\langle x_E\rangle_{\mathrm{b}}$ twice as precise as the average value recommended by the LEP electroweak working group, 0.702 ± 0.008.[71]

All recent measurements of $\langle\tau_{\mathrm{b}}\rangle$ are shown in Fig. 9 together with the averages from the LEP lifetime working group.[67] It should be noted that different analyses do not necessarily select the same mixture of b hadrons and therefore do not measure exactly the same quantity; for example, assuming that the semileptonic branching ratios scale with the lifetimes and using the b hadron fractions given in Sect. 5.3, one expects the results based on leptons to be $\sim 0.7\%$ larger than the unbiased (truly inclusive) results. It is intriguing to note that an opposite trend is observed in the data.

5 Particle-antiparticle mixing

The D^0 $(\mathrm{c\bar{u}})$, B^0 $(\mathrm{d\bar{b}})$, and $\mathrm{B}^0_{\mathrm{s}}$ $(\mathrm{s\bar{b}})$ mesons are allowed to undergo particle-antiparticle mixing, due to second order weak interactions (see Fig. 10), which can be described with the same formalism as for the K^0 $(\mathrm{d\bar{s}})$. If CP violation is neglected, the CP eigenstates of the $\mathrm{B}^0\bar{\mathrm{B}}^0$ system, $\mathrm{B}_{\mathrm{S,L}} = (\mathrm{B}^0 \pm \bar{\mathrm{B}}^0)/\sqrt{2}$ are also mass eigenstates, with masses $m_{\mathrm{S,L}} = m \mp \Delta m/2$

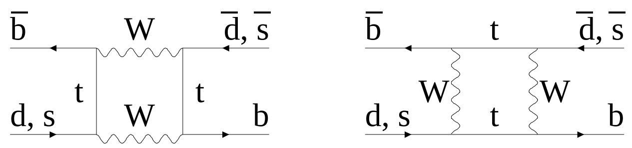

Figure 10: Dominant box diagrams for the $B^0 \to \bar{B}^0$ and $B^0_s \to \bar{B}^0_s$ transitions. The corresponding diagrams for $D^0 \to \bar{D}^0$ involve d or s quark exchange.

and total decay width $\Gamma_{S,L} = \Gamma \pm \Delta\Gamma/2$. The expression

$$\frac{\Gamma^2 - (\Delta\Gamma/2)^2}{2\Gamma}\, e^{-\Gamma t} \left[\cosh\left(\frac{\Delta\Gamma}{2} t\right) \pm \cos\left(\Delta m\, t\right)\right] dt$$

gives the probability for an initially pure B^0 or $\bar{B}^0$ state to decay after a proper time t as the same ("+" sign) or charge conjugate ("−" sign) flavour state. The time-integrated mixing probability is

$$\chi = \frac{1}{2}\,\frac{\Delta m^2 + (\Delta\Gamma/2)^2}{\Delta m^2 + \Gamma^2}\,.$$

5.1 D^0–$\bar{D}^0$ *mixing*

In the Standard Model, the D^0 mixing rate is very small, $R_{\rm mix} \equiv \chi/(1-\chi) < 10^{-7}$, and dominated by long-distance effects rather than the box diagram contributions.[72] With current experimental sensitivities in the range $10^{-2} - 10^{-3}$, observation of D^0 mixing would indicate physics beyond the Standard Model, for example a new heavy particle exchanged in the box diagrams.

The D^0 particle-antiparticle state can easily be tagged with the sign of the pion from a $D^{*+} \to D^0\pi^+$ decay. If the D^0 candidate is reconstructed in the $K^-\pi^+$ or $K^-\pi^+\pi^-\pi^+$ channel, the sign of the kaon determines the decaying state. However, the doubly-Cabibbo suppressed (DCS) decays $D^0 \to K^+\pi^-$ and $D^0 \to K^+\pi^-\pi^-\pi^+$ have the same signature as the mixing signal and yield a fake rate $R_{\rm DCS}$. Furthermore, the mixing and DCS amplitudes can interfere to produce an overall rate $R = R_{\rm mix} + R_{\rm DCS} + \cos\varphi\sqrt{2R_{\rm mix}R_{\rm DCS}}$, where φ is an unknown phase.[73] CLEO measured $R = \mathcal{B}(D^0 \to K^+\pi^-)/\mathcal{B}(D^0 \to K^-\pi^+) = (0.77 \pm 0.35)\%$ [74] but could not separate the two contributions. If proper time information is available, this can be done by fitting the expression [73]

$$\Gamma\, e^{-\Gamma t} \left[R_{\rm DCS} + \cos\varphi\, \sqrt{2R_{\rm DCS}R_{\rm mix}}\, \Gamma t + R_{\rm mix}\, (\Gamma t)^2/2\right] dt$$

to the data with mixing signature. Assuming $\cos\varphi = 0$, E791 now find $R_{\rm mix} < 0.33\%$ at 90% CL,[75] which is similar to the old E691 result, $R_{\rm mix} < 0.37\%$ at 90% CL,[76] and slightly more stringent than $R_{\rm mix} < 0.76\%$, a preliminary 95% CL limit reported last year by ALEPH using the $K^+\pi^-$ channel only.[77] Allowing for the interference term (and even possible CP violation in it), the E791 result becomes $R_{\rm mix} < 0.85\%$ at 90% CL.[75]

E791 also find no mixing signal in the $D^0 \to K^+\ell^-\bar{\nu}$ channel (which is not contaminated by DCS decays), and derive $R_{\rm mix} < 0.33\%$ at 90% CL.[78]

5.2 Methods for B^0 *and* $\mathrm{B_s^0}$ *oscillation analyses*

Mixing in the B sector is large in the Standard Model, dominated by top quark exchange in the box diagrams. Time-integrated measurements were performed already a decade ago by UA1 and ARGUS,[29] and since then by many different experiments. These were typically based on counting same-sign and opposite-sign lepton pairs, like a very recent L3 result.[79] At high energy colliders, such analyses cannot separate the B^0 and $\mathrm{B_s^0}$ contributions and are less sensitive than the time-dependent analyses aiming for the direct measurement of the oscillation frequencies Δm_{d} and Δm_{s} (of the B^0 and $\mathrm{B_s^0}$ systems respectively) from the proper time distributions of events suitably tagged as mixed or unmixed. This is particularly true for the $\mathrm{B_s^0}$ system where the large value of Δm_{s} implies maximal mixing, i.e. $\chi_{\mathrm{s}} \simeq 1/2$.

The statistical significance $\mathcal{S}$ of an oscillation signal can approximately be written as [80]

$$\mathrm{S} \approx \sqrt{N/2}\, f_{\mathrm{sig}}\, (1 - 2\eta)\, e^{-(\Delta m\, \sigma_t)^2/2}$$

where N and f_{sig} are the number of candidates and the fraction of signal in the selected sample, η is the mistag probability, and σ_t is the proper time resolution. The quantity $\mathcal{S}$ decreases very quickly as Δm increases; this dependence is controlled by σ_t, which is therefore a critical parameter for Δm_{s} analyses. The proper time resolution $\sigma_t \sim \sigma_L m/\langle p\rangle \oplus t(\sigma_p/p)$ includes a constant contribution due to the decay length resolution σ_L (typically 0.1–0.3 ps) and a term due to the relative momentum resolution σ_p/p (typically 10–20%) that increases with proper time.

In order to tag a B candidate as mixed or unmixed, it is necessary to determine its particle-antiparticle state both at production (initial state) and at decay (final state). The initial and final state mistag probabilities, η_i and η_f, degrade $\mathcal{S}$ by a total factor $(1 - 2\eta) = (1 - 2\eta_i)(1 - 2\eta_f)$. In inclusive lepton analyses, the final state is tagged by the charge of the lepton from $\mathrm{b} \to \ell^-$ decays; the biggest contribution to η_f is then due to $\bar{\mathrm{b}} \to \bar{\mathrm{c}} \to \ell^-$ decays. Alternatively, the charge of a reconstructed charm meson (D^{*-} from B^0 or $\mathrm{D_s^-}$ from $\mathrm{B_s^0}$) or that of a kaon thought to come from a $\mathrm{b} \to \mathrm{c} \to \mathrm{s}$ decay [81] can be used. For fully inclusive analyses based on topological vertexing, final state tagging techniques include jet charge [69] and charge dipole methods.[81]

The initial state tags are somewhat less dependent on the procedure used to select B candidates. They can be divided in two groups: the ones that tag the initial charge of the $\bar{\mathrm{b}}$ quark contained in the B candidate itself (same side tag), and the ones that tag the initial charge of the other b quark produced in the event (opposite side tag). On the same side, the charge of a track from the primary vertex is correlated with the production state of the B if that track is a decay product of a B^{**} state or the first particle in the fragmentation chain.[82,83] Jet charge techniques work on both sides. Finally the charge of a lepton from $\mathrm{b} \to \ell^-$ or of a kaon from $\mathrm{b} \to \mathrm{c} \to \mathrm{s}$ can be used as opposite side tags, keeping in mind that their performance depends on integrated mixing. At SLC, the beam polarization produces a sizeable forward-backward asymmetry in the $\mathrm{Z} \to \mathrm{b\bar{b}}$ decays and provides another very interesting and effective initial state tag based on the polar angle of the B candidate.[81] Initial state tags have also been combined to reach $\eta_i = 26\%$ at LEP,[83,84] or even 16% at SLD,[81] with full efficiency.

Since no measurement of $\Delta\Gamma$ exist and $\Delta\Gamma \ll \Delta m$ is predicted, oscillation analyses typically neglect $\Delta\Gamma$ and describe the data with the physics functions $\Gamma e^{-\Gamma t}(1 \pm \cos\Delta m t)/2$. Whereas measurements of $\Delta m_{\rm d}$ are usually extracted from the data using a maximum likelihood fit, no significant $\rm B^0_s$ oscillations have been seen so far, and all $\rm B^0_s$ analyses set lower limits on $\Delta m_{\rm s}$. The original technique used to set such limits was to study the likelihood as a function of $\Delta m_{\rm s}$. However, these limits turned out to be difficult to combine. A new method was therefore developed,[80] in which a $\rm B^0_s$ oscillation amplitude $\mathcal{A}$ is measured at each fixed value of $\Delta m_{\rm s}$, using a maximum likelihood fit based on the functions $\Gamma e^{-\Gamma t}(1 \pm \mathcal{A}\cos\Delta m_{\rm s} t)/2$. To a very good approximation, the statistical uncertainty on $\mathcal{A}$ is Gaussian and equal to $1/\mathcal{S}$.[85] Measurements of $\mathcal{A}$ performed at a given value of $\Delta m_{\rm s}$ can be averaged easily. If $\Delta m_{\rm s} = \Delta m_{\rm s}^{\rm true}$, one expects $\mathcal{A} = 1$ within the total uncertainty $\sigma_{\mathcal{A}}$; however, if $\Delta m_{\rm s}$ is far from its true value, a measurement consistent with $\mathcal{A} = 0$ is expected. A value of $\Delta m_{\rm s}$ can be excluded at 95% CL if $\mathcal{A} + 1.645\,\sigma_{\mathcal{A}} \le 1$. The lower limit on $\Delta m_{\rm s}$ is defined as the highest value below which all values of $\Delta m_{\rm s}$ are excluded. If $\Delta m_{\rm s}^{\rm true}$ is very large, one expects $\mathcal{A} = 0$, and all values of $\Delta m_{\rm s}$ such that $1.645\,\sigma_{\mathcal{A}}(\Delta m_{\rm s}) < 1$ are expected to be excluded at 95% CL. Because of the proper time resolution, the quantity $\sigma_{\mathcal{A}}(\Delta m_{\rm s})$ is an increasing function of $\Delta m_{\rm s}$ and one therefore expects to be able to exclude individual $\Delta m_{\rm s}$ values up to $\Delta m_{\rm s}^{\rm sens}$ where $\Delta m_{\rm s}^{\rm sens}$, called here the sensitivity of the analysis, is defined by $1.645\,\sigma_{\mathcal{A}}(\Delta m_{\rm s}^{\rm sens}) = 1$. This "amplitude method" was first used by ALEPH [87] before being adopted more widely;[59,83–86] it is now recommended by the LEP B oscillations working group as the framework in which $\Delta m_{\rm s}$ limits are combined.

5.3 Discussion of $\Delta m_{\rm d}$ and $\Delta m_{\rm s}$ results [b]

A total of 22 different analyses have been performed to measure $\Delta m_{\rm d}$, of which 4 are new and 10 have been updated since summer 1996 (see Fig. 11). Although many different techniques have been used, the results have remarkably similar precision. The systematic uncertainties are not negligible; they are often dominated by sample composition, mistag probability, or b hadron lifetime contributions. Averaging all direct $\Delta m_{\rm d}$ measurements from LEP, SLD and CDF, and accounting for all identified correlations, yields $0.472 \pm 0.018~\rm ps^{-1}$.[92] World averages, including CLEO and ARGUS measurements of $\chi_{\rm d}$, are $\Delta m_{\rm d}^{\rm world} = 0.463 \pm 0.018~\rm ps^{-1}$ and $\chi_{\rm d}^{\rm world} = 0.172 \pm 0.010$. These can be used to improve our knowledge on the fractions of weakly decaying bottom hadron in $\rm Z \to b\bar{b}$ events. The $\rm B^0_s$ and b baryon fractions, $f_{\rm B^0_s}$ and $f_{\text{b-baryon}}$, can be extracted from branching ratio measurements. However, if one assumes $\chi_{\rm s} = 1/2$ and $f_{\rm B^0} = f_{\rm B^+} = (1 - f_{\rm B^0_s} - f_{\text{b-baryon}})/2$, another estimate of $f_{\rm B^0_s}$ can be extracted from $\chi_{\rm d}^{\rm world}$, the inclusive integrated mixing rate $\bar{\chi}$ measured at LEP, the estimate of $f_{\text{b-baryon}}$ from branching ratios and the b hadron lifetimes. Combining all the information yields $f_{\rm B^0_s} = (10.3^{+1.6}_{-1.5})\%$, $f_{\text{b-baryon}} = (10.6^{+3.7}_{-2.7})\%$ and $f_{\rm B^0} = f_{\rm B^+} = (39.5^{+1.6}_{-2.0})\%$. These results, including $\Delta m_{\rm d}^{\rm world}$, have been obtained by the LEP B oscillations working group in a consistent way, taking into account the fact that many $\Delta m_{\rm d}$ analyses depend on the b hadron fractions and might have used different values

[b] This review includes new and updated $\rm B^0_s$ oscillation results that became available from DELPHI [59] between this conference and the EPS-HEP conference in Jerusalem.

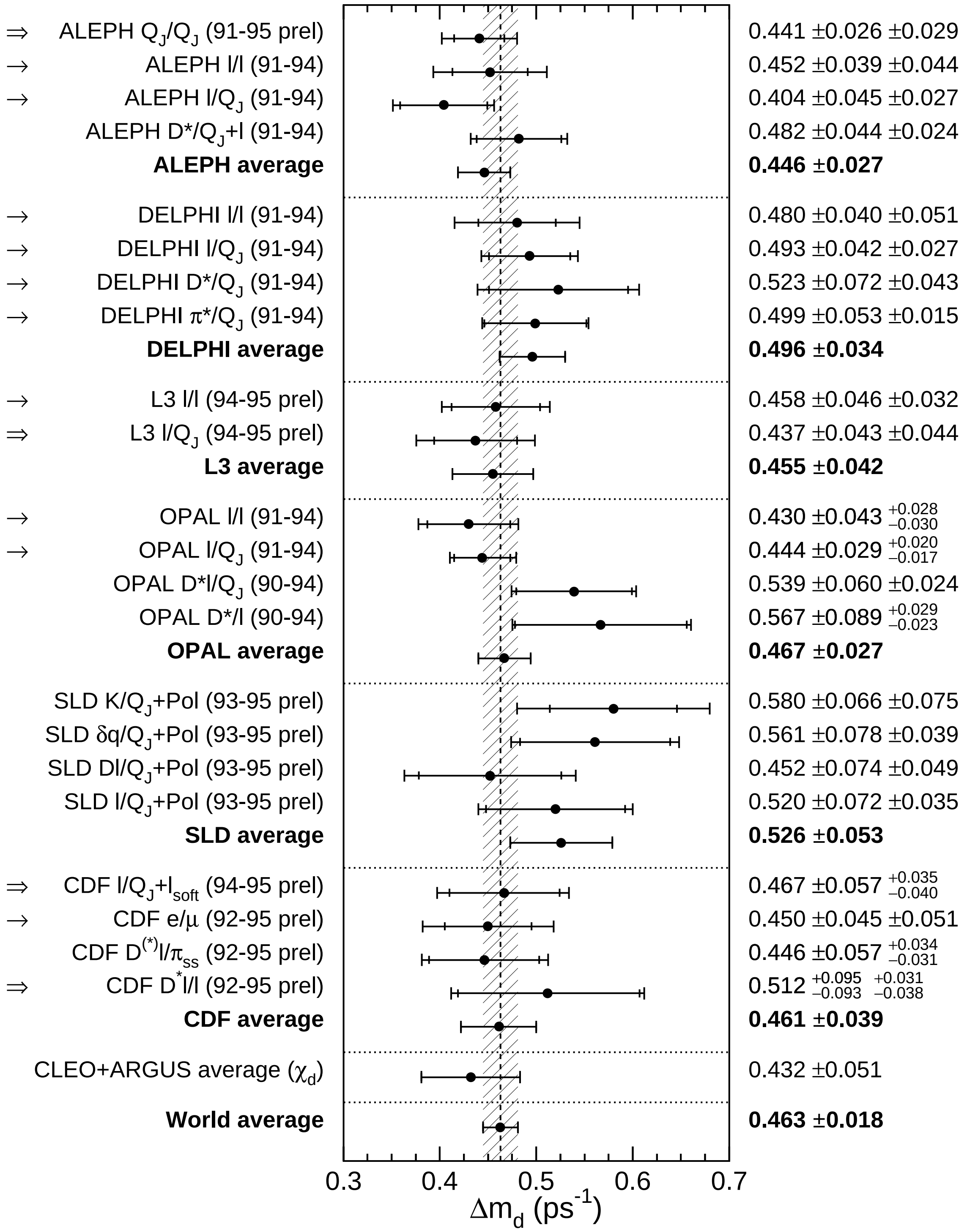

Figure 11: Summary of Δm_d measurements [57,69,81,82,86,88–91] and averages.[92] The CLEO+ARGUS average is derived from published χ_d and τ_{B^0} data.[29] New (updated) measurements since the 1996 summer conferences are marked with a double (single) arrow.

as input.[92]

The CKM matrix element $V_{\rm td}$ can be extracted from $\Delta m_{\rm d}^{\rm world}$ using the following relation obtained from the box diagram calculations,

$$\Delta m_{\rm d} = |V_{\rm tb}^* V_{\rm td}|^2 \, \frac{G_{\rm F}^2}{6\pi^2} \, m_{\rm B^0} \, m_{\rm W}^2 \, S_0\left(\frac{m_{\rm t}^2}{m_{\rm W}^2}\right) \eta_{\rm B} \, F_{\rm B^0}^2 \, B_{\rm B^0} \, ,$$

where $|V_{\rm tb}| \simeq 1$, $S_0(x) = 0.784\,x^{0.76}$ and $\eta_{\rm B} = 0.55 \pm 0.01$ (short-distance QCD correction).[93] Using a running top quark mass of[93] $m_{\rm t} = 167 \pm 6$ GeV/c^2 and[2] $F_{\rm B^0}\sqrt{B_{\rm B^0}} = 195^{+30}_{-40}$ MeV, where $F_{\rm B^0}$ and $B_{\rm B^0}$ are the $\rm B^0$ decay constant and non-perturbative correction factor, one gets $|V_{\rm td}| = (8.8 \pm 0.2_{\Delta m_{\rm d}} \mp 0.2_{m_{\rm t}} \mp ^{1.4}_{1.8}{}_{F\sqrt{B}}) \times 10^{-3}$, with an uncertainty completely dominated by theoretical uncertainties. The $\rm B_s^0$ oscillation frequency is related to $V_{\rm ts}$ in a similar way. However, many uncertainties cancel in the frequency ratio, yielding

$$\frac{\Delta m_{\rm s}}{\Delta m_{\rm d}} = \frac{m_{\rm B_s^0}}{m_{\rm B^0}} \, \xi^2 \left| \frac{V_{\rm ts}}{V_{\rm td}} \right|^2 \, ,$$

were $\xi^2 = 1.30 \pm 0.18$ is determined from lattice QCD and QCD sum rules.[2] This relation can be used in fits of the CKM matrix, together with many other experimental and theoretical inputs including unitarity constraints, to derive $\Delta m_{\rm s}$ predictions within the Standard Model. Assuming Gaussian theoretical uncertainties, Paganini et al.[94] obtain $\Delta m_{\rm s} = 10^{+5}_{-3}$ ps^{-1} and $\Delta m_{\rm s} < 21$ ps^{-1} at 95% CL, whereas Buras and Fleischer[93] predict $\Delta m_{\rm s} = 15.2 \pm 5.5$ ps^{-1}, or $8.0 < \Delta m_{\rm s} < 25.4$ ps^{-1} with weaker assumptions on the theoretical uncertainties.

$\rm B_s^0$ oscillation has been the subject of many recent studies: in the last year, OPAL[86] have updated their inclusive lepton and dilepton results (from analyses which also yield $\Delta m_{\rm d}$ measurements), while both ALEPH and DELPHI have significantly improved their analyses dedicated to $\Delta m_{\rm s}$. DELPHI[59,84] take advantage of their 1994–1995 data reprocessed with an improved tracking algorithm to boost the sensitivity of their $\rm D_s^- \ell^+$ analysis; they now also use $\phi\ell^+$ and $\rm D_s^-$hadron$^+$ combinations. ALEPH[83] update their results with fully reconstructed $\rm D_s^-$ mesons, and optimize their inclusive lepton analysis resulting in enhanced time resolution and $\rm B_s^0$ purity at an acceptable cost in statistics. Figure 12 shows the $\Delta m_{\rm s}$ ranges excluded at 95% CL by the various analyses, together with their sensitivities as determined from the amplitude uncertainty. Most of these analyses are combined to yield the amplitudes shown in Fig. 13 as function of $\Delta m_{\rm s}$. The combined 95% CL limit from the data is $\Delta m_{\rm s} > 10.2$ ps^{-1}; together with $\Delta m_{\rm d}^{\rm world}$, it implies $|V_{\rm ts}/V_{\rm td}| > 3.8$ at 95% CL. The combined sensitivity for 95% CL exclusion of $\Delta m_{\rm s}$ values is found to be 13.0 ps^{-1}, above the actual limit. This is due to a positive excursion of the combined amplitude in the region 10–18 ps^{-1}, which is more or less where $\Delta m_{\rm s}$ is expected in the Standard Model. However, the statistical significance of this excursion is low and no signal can be claimed. It should be noted however, that with the current sensitivity one would expect to see an oscillation signal with a significance of at least 3σ if $\Delta m_{\rm s}$ was less than 9 ps^{-1}. The fact that the combined sensitivity now reaches the range of $\Delta m_{\rm s}$ values expected in the Standard Model, means that the results of the $\rm B_s^0$ analyses provide a significant constraint on the CKM matrix, as illustrated in Fig. 14.

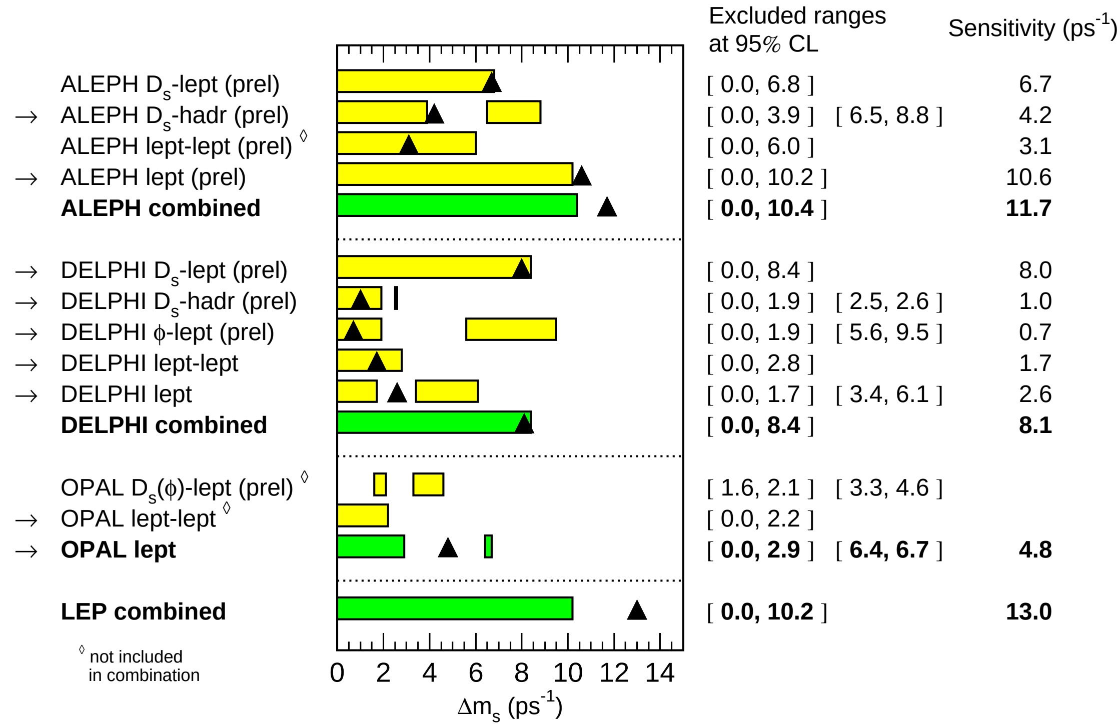

Figure 12: Excluded values of Δm_s (shaded bars) and sensitivities (triangles) of the various B_s^0 oscillation analyses.[59,83–86,95] Sensitivities are only quoted for analyses based on the amplitude method and represent the frequency at which $\sigma_{\mathcal{A}} = 1/1.645$. Arrows are as for Fig. 11.

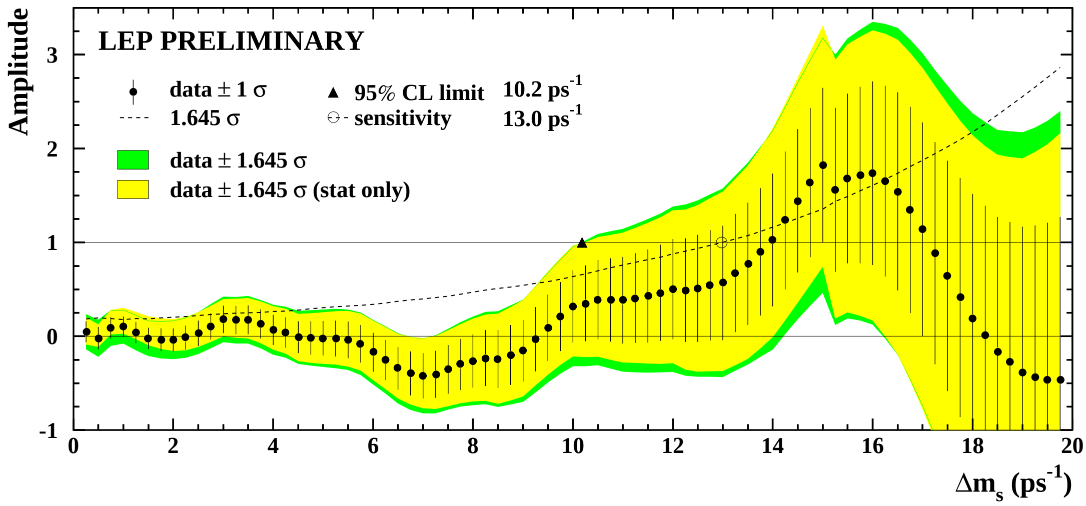

Figure 13: Combined measurements of the B_s^0 oscillation amplitude as a function of Δm_s.[92] The measurements are dominated by statistical uncertainties. Neighbouring points are statistically correlated, the scale of the correlation length being $1/\tau_{B_s^0}$. The frequencies up to which measurements are provided differ between analyses, causing possible discontinuities in the data (for example at 15 ps^{-1}).

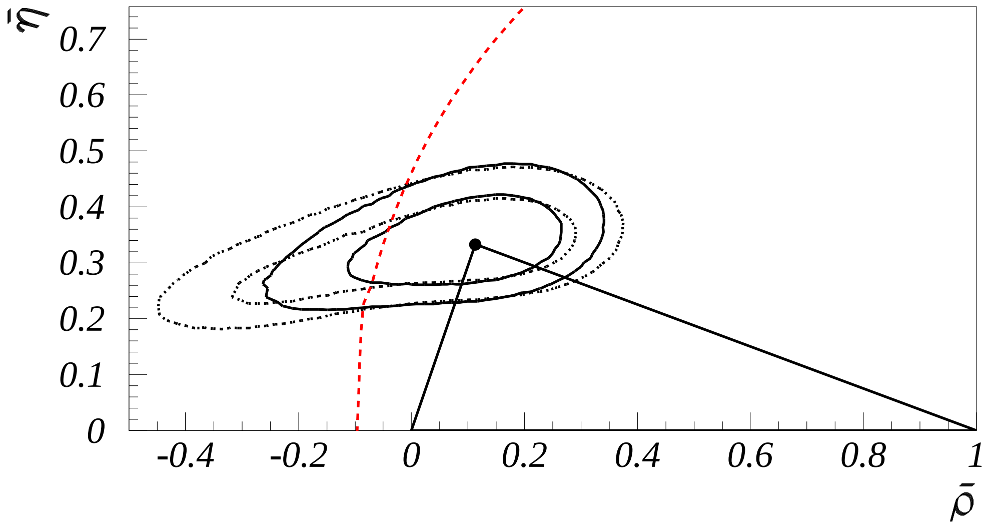

Figure 14: Results of CKM fits [94] shown in the $(\bar{\rho}, \bar{\eta})$ plane. Gaussian theoretical uncertainties are assumed. The preferred position of the unitarity triangle apex is indicated with a solid dot. The solid (dotted) closed curves represent the 68% and 95% CL contours with (without) the constraint from the combined B_s^0 oscillation amplitude results of Fig. 13. The dashed arc of circle centered on (1,0) corresponds to the limit $\Delta m_s > 10.2\ \mathrm{ps}^{-1}$ at 95% CL, but only partially represents the constraint from the combined Δm_s results.

6 Summary and prospects

Our understanding of heavy flavour production is still not complete: b quark production at hadronic machines is still larger than NLO QCD predictions, and a consistent description of direct quarkonia production has not yet been fully established, although the colour-octet models seem promising.

The spectroscopy of charm hadrons is still very active, with many new baryon states discovered in the last couple of years, contrary to charm lifetimes where no new measurements have been reported recently. Current limits on D^0–$\bar{D}^0$ mixing are still very far from the Standard Model prediction, leaving quite some unexplored room for possible new physics. Many new charm results are expected in the near future, in particular from CLEO II, who continuously increase their statistics, and from new photo-production experiment E831/FOCUS. This is an upgraded version of E687 which already recorded more than 10 times the E687 statistics during the present fixed-target Tevatron run, and which aims for $\sim 10^6$ fully reconstructed charm decays, including $\sim 20\,000$ charm baryons.

In the longer term, several new experiments will be able to study D^0–$\bar{D}^0$ mixing with improved sensitivity and perform new charm spectroscopy and lifetime measurements, in particular on the yet unobserved doubly-charmed baryons: CLEO III with an upgraded detector (1998–), BABAR and BELLE at the B factories (1999–), as well as the COMPASS spectrometer at CERN which could start operation in 1999 and accumulate the statistics for its full charm program in 2002.[96] If approved, a proposed B physics experiment at the Tevatron, B-TeV,[97] could also contribute to charm physics in its first phase with a wire target (2001 ?).

No spectacular progress in bottom spectroscopy has been made in the last couple years. Although a few isolated B_c^+ candidates have been observed at LEP, the B_c^+ discovery will most probably be left for the Tevatron. The B^+, B^0 B_s^0 and b baryon lifetime measurements are now quite precise (4% or less) and in good agreement with theoretical predictions, except for the b baryons where a long standing discrepancy remains. The B^0–$\bar{B}^0$ oscillation frequency is also measured with similar accuracy, but the hadronic uncertainty currently limits the extracted value of $|V_{td}|$ to an accuracy of $\sim 20\%$. Measurements of the B_s^0–$\bar{B}_s^0$ oscillation frequency still don't exist, but improved limits nevertheless provide a non-negligible constraint on the CKM matrix.

The potential for new or improved results from LEP on lifetimes and excited b hadrons now depends on possible new analysis ideas and improvements to existing reconstruction algorithms, since no more substantial running at the Z pole is foreseen. SLD, however, is still running, aiming for 0.5 million $Z \to q\bar{q}$ events. With these statistics and the excellent resolution of their new vertex detector, SLD expect an ultimate Δm_s sensitivity of 15 ps^{-1}.[98] CDF should also be able to participate in the search for B_s^0 oscillation with their current data. However, it seems probable that Δm_s will remain unmeasured at least until the next round of data to be collected by HERA-B at DESY (1998–) and CDF+D0 at Fermilab (1999–), but it should certainly be measured by the LHC experiments (2005–), in particular LHC-B. The individual b hadron lifetimes will be measured with an increasing precision in future hadronic collider runs, starting with Tevatron run II, using large samples of fully reconstructed decays. This is also true for the width difference in the B_s^0 system which could be extracted from the comparison of B_s^0 lifetime measurements performed on specific channels corresponding to different mixtures of CP-odd and CP-even states, like $D_s^- \ell^+ \nu$ and $J/\psi\phi$. It is worth noting that the prediction [56] $\Delta\Gamma_s/\Delta m_s = 197 \pm 83$, although plagued by the large hadronic uncertainty, does not depend on CKM matrix elements and has therefore an interesting consequence: the more difficult it might be to observe Δm_s, the easier it should be to observe $\Delta\Gamma_s$, and vice versa.

In conclusion, with all the new planned experiments, the field of heavy quark spectroscopy, lifetimes and oscillations still has a very bright future, although one might have to wait a few years for substantial progress in the bottom sector.

Acknowledgments

I would like to thank the representatives of the various collaborations who provided results for this review; interacting with them was very useful, and their answers and help before the conference was appreciated. I am thankful to Achille Stocchi who kindly agreed to rerun CKM fits and provided Fig. 14, and to Roger Forty for the many useful suggestions that came out of our discussions. The work of the members of the LEP B lifetime working group and of my colleagues of the LEP B oscillations working group is gratefully acknowledged.

References [c]

1. Y. Nir, these proceedings.
2. C. Sachrajda, these proceedings.
3. P. Drell, these proceedings.
4. A.J.S. Smith, these proceedings.
5. S. Dong, these proceedings.
6. P. Nason, S. Dawson and R.K. Ellis, Nucl. Phys. B**303**, 607 (1988); B**327**, 49 (1989); M.L. Mangano, P. Nason and G. Ridolfi, Nucl. Phys. B**373**, 295 (1992).
7. F. Abe et al., CDF collab., Phys. Rev. Lett. **75**, 1451 (1995).
8. S. Abachi et al., D0 collab., Phys. Rev. Lett. **74**, 3548 (1995); Phys. Lett. B**370**, 239 (1996).
9. C. Albajar et al., UA1 collab., Phys. Lett. B**213**, 405 (1988); B**256**, 121 (1991); Z. Phys. C**61**, 41 (1994).
10. CDF collab., "Measurement of the ratio of b-quark production cross sections at $\sqrt{s}$ = 630 GeV and $\sqrt{s} = 1800$ GeV", FERMILAB-CONF-96/176-E, ICHEP96-PA04-059.
11. D0 collab., "Determination of the b-quark production cross section in $p\bar{p}$ collisions at $\sqrt{s} = 630$ GeV", LP97-093.
12. R. Baier and R. Rückl, Phys. Lett. B**102**, 364 (1981); Z. Phys. C**19**, 251 (1983).
13. E. Braaten et al., Phys. Lett. B**333**, 548 (1994); M. Cacciari and M. Greco, Phys. Rev. Lett. **73**, 1586 (1994).
14. F. Abe et al., CDF collab., Phys. Rev. Lett. **79**, 572, 578 (1997)
15. F. Abe et al., CDF collab., Phys. Rev. Lett. **75**, 4358 (1995).
16. E. Braaten and S. Fleming, Phys. Rev. Lett. **74**, 3327 (1995); P. Cho and M. Wise, Phys. Lett. B**346**, 129 (1995); G.T. Bodwin, E. Braaten and P. Lepage, Phys. Rev. D**51**, 1125 (1996).
17. M. Cacciari et al., Phys. Lett. B**356**, 553 (1995); P. Cho and A.K. Leibovich, Phys. Rev. D**53**, 150, 6203 (1996).
18. G. Alexander et al., OPAL collab., Phys. Lett. B**384**, 343 (1996).
19. ALEPH collab., "Study of prompt J/ψ production in hadronic Z decays", LP97-265.
20. P. Cho, Phys. Lett. B**368**, 171 (1996), with updated matrix elements from P. Cho and A.K. Leibovich, Phys. Rev. D**50**, 6203 (1996).
21. L3 collab., "Upsilon production in Z decays", LP97-086.
22. ALEPH collab., "Inclusive Υ production in hadronic Z decays", ICHEP96-PA05-066.
23. G. Alexander et al., OPAL collab., Phys. Lett. B**370**, 185 (1995).
24. M. Cacciari and M. Krämer, Phys. Rev. Lett. **76**, 4128 (1996).

[c] Abbrevations:

LP97-...	= contributed paper to the 18th International Symposium on Lepton-Photon Interactions, 28 July – 1 August 1997, Hamburg, Germany (this conference).
EPS97-...	= contributed paper to the International Europhysics Conference on High Energy Physics, 19–26 August 1997, Jerusalem, Israel.
ICHEP96-...	= contributed paper to the 28th International Conference on High Energy Physics, 25–31 July 1996, Warsaw, Poland.
EPS95-...	= contributed paper to the International Europhysics Conference on High Energy Physics, 27 July – 2 August 1995, Brussels, Belgium.

25. S. Aid et al., H1 collab., Nucl. Phys. B**472**, 3 (1996); updated in "Diffractive and non-diffractive photoproduction of J/ψ at H1", ICHEP96-PA02-085.
26. J. Breitweg et al., ZEUS collab., DESY 97–147, hep-ex/9708010, July 1997.
27. M. Krämer et al., Phys. Lett. B**348**, 657 (1995);
    M. Krämer, Nucl. Phys. B**459**, 3 (1996).
28. M.A. Sanchis-Lozano and B. Cano-Coloma, hep-ph/9701210.
29. R.M. Barnett et al., Particle Data Group, Phys. Rev. D**54**, 1 (1996).
30. F. Abe et al., CDF collab., Phys. Rev. D**53**, 3496 (1996); D**55**, 1142 (1997).
31. E.J. Eichten and C. Quigg, Phys. Rev. D**49**, 5845 (1996);
    S.S. Gershtein et al., Phys. Rev. D**51**, 3613 (1995).
32. F. Abe et al., CDF collab., Phys. Rev. Lett. **77**, 5176 (1996).
33. P. Abreu et al., DELPHI collab., Phys. Lett. B**398**, 207 (1997).
34. R. Barate et al., ALEPH collab., Phys. Lett. B**402**, 213 (1997).
35. OPAL collab., "Search for the B_c^+ meson in Z decays", LP97-293.
36. P. Abreu et al., DELPHI collab., Z. Phys. C**68**, 541 (1995);
    D. Buskulic et al., ALEPH collab., Phys. Lett. B**384**, 449 (1996).
37. DELPHI collab., "First evidence for a radially excited $D^{*\prime}$ meson", DELPHI 97–102 CONF 84, LP97.
38. DELPHI collab., "First observation of radially excited B mesons", ICHEP96-PA01-021.
39. M. Acciari et al., L3 collab., Phys. Lett. B**345**, 589 (1995);
    P. Abreu et al., DELPHI collab., Z. Phys. C**68**, 353 (1995);
    K. Ackerstaff et al., OPAL collab., Z. Phys. C**74**, 413 (1997), LP97-114.
40. D. Buskulic et al., ALEPH collab., Z. Phys. C**69**, 393 (1996).
41. DELPHI collab., "First observation of the B^* Dalitz decay $B^* \to Be^+e^-$", LP97-307.
42. P. Abreu et al., DELPHI collab., Phys. Lett. B**345**, 598 (1995); "Observation of orbitally excited B and B_s mesons", DELPHI 95-105 PHYS 540, EPS95-0563.
43. R. Akers et al., OPAL collab., Z. Phys. C**66**, 19 (1995).
44. ALEPH collab., "Resonant structure and flavour-tagging in the $B\pi^\pm$ system using fully reconstructed B decays", ICHEP96-PA01-070.
45. J. Bartelt, "Charm hadron spectroscopy", proceedings of the 7th International Symposium on Heavy Flavour Physics, Santa Barbara CA, USA, July 1997, World Scientific; CLEO collab., "Observation of two narrow states decaying into $\Xi_c^+\gamma$ and $\Xi_c^0\gamma$", CLEO-CONF 97-29, EPS97-393 (not submitted to this conference).
46. P. Avery et al., CLEO collab., Phys. Rev. Lett. **75**, 4364 (1995);
    L. Gibbons et al., CLEO collab., Phys. Rev. Lett. **77**, 810 (1996);
    G. Brandenburg et al., CLEO collab., Phys. Rev. Lett. **78**, 2304 (1997).
47. H. Albrecht et al., ARGUS collab., Phys. Lett. B**317**, 227 (1993); B**402**, 207 (1997).
48. P.L. Frabetti et al., E687 collab., Phys. Rev. Lett. **72**, 961 (1994); Phys. Lett. B**365**, 461 (1996).
49. K.W. Edwards et al., CLEO collab., Phys. Rev. Lett. **74**, 3331 (1995).
50. CLEO collab., "Evidence for a new state decaying to $\Xi_c^{*0}\pi^+$", CLEO CONF 97-17, LP97-284.

51. DELPHI collab., "First evidence for $\Sigma_{\rm b}$ and $\Sigma_{\rm b}^*$ baryons", DELPHI 95-107 PHYS 542, EPS95-0565.
52. A.F. Falk, Phys. Rev. Lett. **77**, 223 (1996).
53. I.I. Bigi, N.G. Uraltsev and A. Vainshtein, Phys. Lett. B**293**, 430 (1992); B**297**, 477 (1993); N. Blok and M. Shifman, Nucl. Phys. B**399**, 441, 459 (1993).
54. I.I. Bigi, Nuovo Cimento **109**A, 713 (1996).
55. M. Neubert, "Theory of beauty lifetimes", CERN-TH/97-148, hep-ph/9707217.
56. M. Beneke, G. Buchalla and I. Dunietz, Phys. Rev. D**54**, 4419 (1996).
57. CDF collab., `http://www-cdf.fnal.gov/physics/new/bottom/bottom.html`
58. OPAL collab., "Measurements of the $\rm B_s^0$ and $\Lambda_{\rm b}$ lifetimes", OPAL physics note PN-305, EPS97-154/156.
59. DELPHI collab., "Search for $\rm B_s^0$–$\rm \bar{B}_s^0$ oscillations and measurement of the $\rm B_s^0$ lifetime", EPS97-457.
60. P. Abreu et al., DELPHI collab., Z. Phys. C**74**, 19 (1997).
61. SLD collab., "Measurement of the $\rm B^+$ and $\rm B^0$ lifetimes using tological vertexing at SLD", SLAC-PUB-7635, EPS97-127.
62. L3 collab., "Measurement of the $\rm B_d^0$ meson lifetime using the decay $\rm \bar{B}_d^0 \to D^{*+}X\ell^-\bar{\nu}$", EPS97-495.
63. R. Barate et al., ALEPH collab., "Measurement of the b baryon lifetime and branching fractions in Z decays", CERN-PPE/97-111, LP97-300, submitted to Z. Phys. C.
64. DELPHI collab., "Determination of average b-baryon lifetime at LEP", DELPHI 97-104 CONF 86, LP97, EPS97-454.
65. K. Ackerstaff et al., OPAL collab., "A measurement of the $\rm B_s^0$ lifetime using recontructed $\rm D_s^-$ mesons", CERN-PPE/97-095, LP97-309.
66. K. Abe et al., SLD collab., Phys. Rev. Lett. **79**, 590 (1997).
67. LEP B lifetimes working group, `http://wwwcn.cern.ch/~claires/lepblife.html`
68. K. Ackerstaff et al., OPAL collab., Z. Phys. C**73**, 397 (1997), LP97-112.
69. ALEPH collab., "Inclusive lifetime and mixing measurements using topological vertexing", LP97, EPS97-596.
70. L3 collab., "Measurement of the average lifetime of b hadrons in Z decays", LP97, EPS97-494.
71. LEP electroweak working group, "Presentation of the LEP electroweak heavy flavour results for summer 1996 conferences", LEPHF/96-01, ALEPH 96-099, DELPHI 96-67 PHYS 627, L3 1969, OPAL TN391.
72. For a recent review, see E. Golowitch, "Some possibilities for charm studies at B factories", proceedings of the 2nd International Conference on B Physics and CP Violation, Honolulu, HI, March 1997, World Scientific.
73. T. Liu, "An overview of $\rm D^0$–$\rm \bar{D}^0$mixing search techniques", Princeton-HEP-97-5, hep-ph/9706477; Princeton-HEP-95-6, hep-ph/9508415.
74. D. Cinabro et al., CLEO collab., Phys. Rev. Lett. **72**, 1406 (1994).
75. E.M. Aitala et al., E791 collab., "A search for $\rm D^0$–$\rm \bar{D}^0$ mixing and doubly Cabibbo suppressed decays of the $\rm D^0$ in hadronic final states", hep-ex/9608018, submitted to Phys. Rev. D.

76. J.C. Anjos et al., E691 collab., Phys. Rev. Lett. **60**, 1239 (1988).
77. ALEPH collab., “Study of D^0 mixing and double Cabibbo suppressed decay”, ICHEP96-PA05-064.
78. E.M. Aitala et al., E791 collab., Phys. Rev. Lett. **77**, 2384 (1996).
79. L3 collab., “Measurement of the B^0–$\bar{B}^0$ mixing parameter”, LP97, EPS97-490.
80. H.-G. Moser and A. Roussarie, Nucl. Instrum. Methods A**384**, 491 (1997).
81. SLD collab., “Measurement of time-dependent B^0_d–$\bar{B}^0_d$ mixing using inclusive semileptonic decays”, SLAC-PUB-7228, ICHEP96-PA08-026A; “Measurement of time-dependent B^0_d–$\bar{B}^0_d$ mixing using topology and charge selected semileptonic B decays”, SLAC-PUB-7229, ICHEP96-PA08-026B; “Preliminary measurements of the time dependence of B^0_d–$\bar{B}^0_d$ mixing with kaon and charge dipole tags”, SLAC-PUB-7230, ICHEP96-PA08-027/028.
82. CDF collab., “Observation of π–B meson charge-flavour correlations and measurement of time dependent $B^0\bar{B}^0$ mixing in $p\bar{p}$ collisions”, FERMILAB-CONF-96/175-E, ICHEP96-PA08-032.
83. ALEPH collab., “Study of B^0_s oscillations using fully reconstructed D^-_s decays”, LP97, EPS97-611; “Search for B^0_s oscillations using inclusive lepton events”, LP97-269, EPS97-612.
84. W. Adam et al., DELPHI collab., “Search for B^0_s–$\bar{B}^0_s$ oscillations”, CERN–PPE/97-114, submitted to Phys. Lett. B;
DELPHI collab., “Search for B^0_s–$\bar{B}^0_s$ oscillations. An update”, LP97-298.
85. ALEPH collab., “Combined limit on B^0_s oscillations”, ICHEP96-PA08-020.
86. K. Ackerstaff et al., OPAL collab., “A study of B meson oscillations using hadronic Z decays containing leptons”, CERN-PPE/97-036, submitted to Z. Phys. C; “An updated study of B meson oscillations using dilepton events”, CERN-PPE/97-064, LP97-123, submitted to Z. Phys. C.
87. ALEPH collab., “Time dependent B^0_s mixing from lepton-kaon correlations with the ALEPH detector”, EPS95-410.
88. D. Buskulic et al., ALEPH collab., Z. Phys. C**75**, 397 (1997).
89. P. Abreu et al., DELPHI collab., CERN-PPE/97-051, LP97-184, submitted to Z. Phys. C.
90. L3 collab., “Update of the B^0_d meson oscillation frequency measurement using dilepton events” and “Measurement of the B^0_d meson oscillation frequency using lepton-jet charge tagging”, LP97, EPS97-491.
91. G. Alexander et al., OPAL collab., Z. Phys. C**72**, 377 (1996).
92. LEP B oscillations working group, “Combined results on B^0 oscillations: update for the summer 1997 conferences”, LEPBOSC 97/2, ALEPH 97-083 PHYSIC 97-073, CDF internal note 4297, DELPHI 97-135 PHYS 722, L3 internal note 2161, OPAL technical note TN 502, SLD physics note 62; see also `http://www.cern.ch/LEPBOSC/`
93. A.J. Buras and R. Fleischer, “Quark mixing, CP violation and rare decays after the top quark discovery”, TUM-HEP-275-97, hep-ph/9704376, to appear in “Heavy Flavours II”, World Scientific (1997).

94. These CKM fits have been performed by A. Stocchi following P. Paganini et al., "Measurements of the ρ and η parameters of the CKM matrix and perspectives", DELPHI 97-137 PHYS 724, submitted to CERN-OPEN and Phys. Rev. D; the only difference is the use of the new value of $\Delta m_{\mathrm{d}}^{\mathrm{world}}$ and $A = 0.812 \pm 0.027$ (instead of $A = 0.81 \pm 0.04$) due the latest improvements in the $|V_{\mathrm{cb}}|$ measurements.[3]
95. OPAL collab., "Investigation of the $\mathrm{B_s^0}$ oscillation frequency using $\phi\ell$ and $\mathrm{D_s}\ell$ correlations", ICHEP96-PA08-014.
96. COMPASS collab., "Common muon and proton apparatus for structure and spectroscopy", CERN/SPSLC 96-14, SPSC/P 297, March 1996.
97. B-TeV collab., "An expression of interest for a heavy quark program at C0", LP97-006.
98. S. Willocq, private communication.