B lifetimes and mixing from LEP

Richard Hawkings (CERN, OPAL collaboration)

- Introduction—LEP experimental techniques
- Lifetime measurements—specific b hadrons
- Oscillations—Measurement of $\Delta m_{\rm d}$
- Inclusive CP violation limits
- Trying to measure $\Delta m_{\rm s}$
- Summary and conclusions

A huge number of analyses—have to be selective and superficial...

See the individual papers for more details of particular analysis techniques.

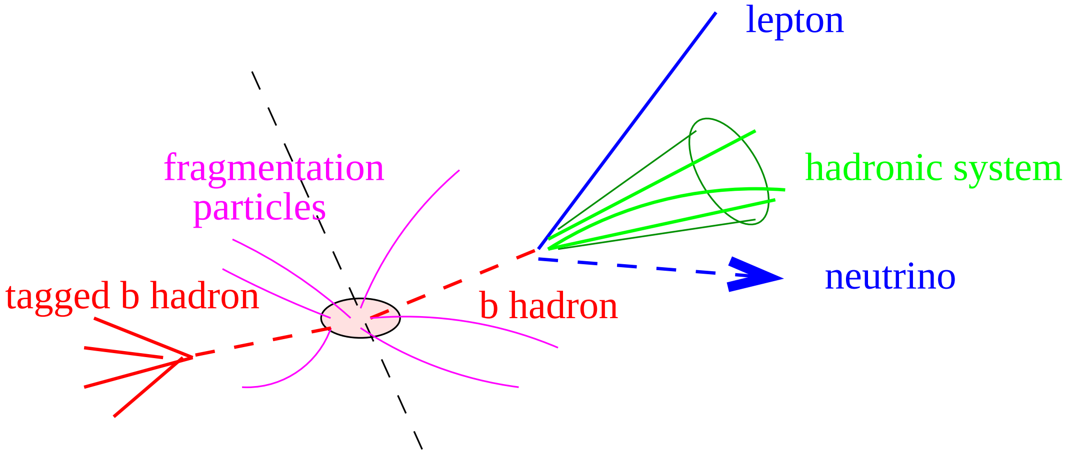
Thanks to LEP b-lifetime and b-oscillation working groups for combinations used in this talk.

http://lephfs.web.cern.ch/LEPHFS/

LEP Experimental Techniques

Each LEP experiment has 0.9 M $Z^0 \to b\overline{b}$ events.

- Clean separation of two b hadrons in event.
- Secondary vertex b-tagging (silicon) allows 90–99 % b event purity.



Large boost of b hadrons ($\langle p \rangle \sim 32$ GeV).

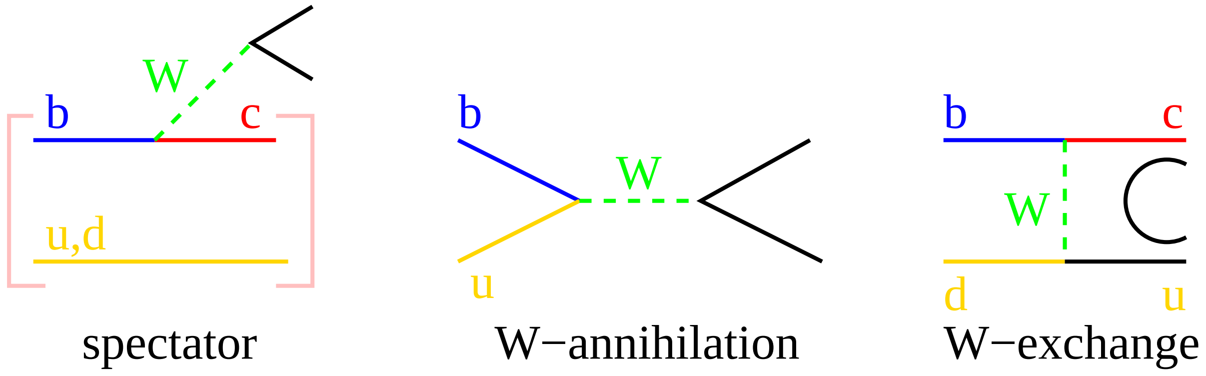
- Separate b-decay and fragmentation particles using kinematic information ($+$ vertexing for charged particles).
- b-decay products' momenta dominated by boost
- No $E_\mathrm{b} = E_\mathrm{beam}$ constraint, but b hadron energy can be determined inclusively from rest of event (resolution 3–5 GeV).
- b direction can be determined inclusively (20-50 mrad).

Neutrino can be reconstructed from missing energy/momentum.

LEP analyses mature: data and MC well understood, sophisticated multivariate techniques, neural networks. . .

Measuring b lifetimes

- Spectator model of heavy hadron decays predicts all b lifetimes equal.



- But non-spectator processes (e.g. W-annihilation, W-exchange, final state interactions) change e.g. τ_{B^+} wrt τ_{B^0}.
- These effects scale like $1/m_Q^3$ for mesons and $1/m_Q^2$ between mesons and baryons—expect 5–10 % differences in b hadrons.
- Important to test predictions—laboratory for testing QCD and HQET, will be needed to study CP violation in b decays.

Experimentally, measuring b hadron lifetimes requires:

- Isolation of b-hadron species under study (from other b hadrons and non-b background).
- Measurement of proper time of each event.
- Understanding of backgrounds, systematics, biases *etc*.

Various different approaches have been used...

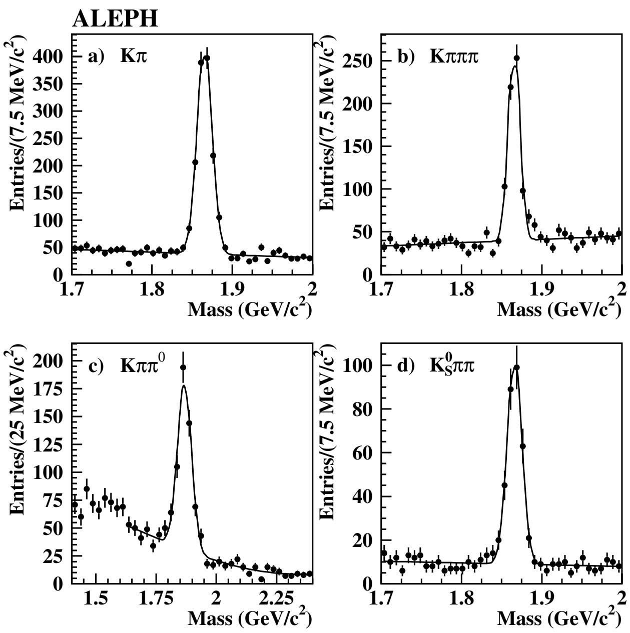
Exclusive measurements

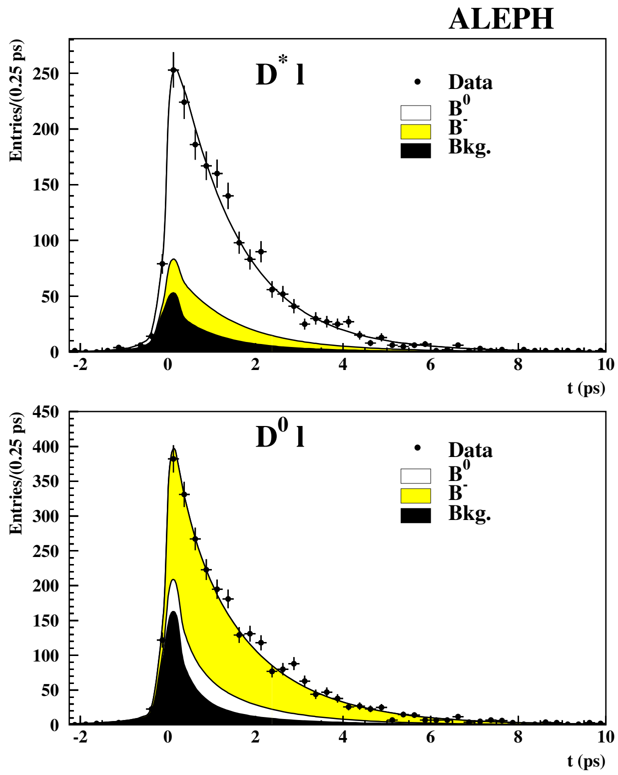
Exclusive reconstruction of B^+ and B^0 in specific final states gives purest samples of individual b hadrons:

e.g. Updated analysis by ALEPH (full reprocessed LEP1 data sample):

- $\mathrm{B}^- \rightarrow \mathrm{D}^0 \ell \bar{\nu}$ with $\mathrm{D}^0 \rightarrow \mathrm{K}^-\pi^+$, $\mathrm{K}^-\pi^+\pi^-\pi^+$, $\mathrm{K}^-\pi^+\pi^0$, $\mathrm{K}^0_\mathrm{s}\pi^+\pi^-$
- $\bar{\mathrm{B}}^0 \rightarrow \mathrm{D}^{*+} \ell \bar{\nu}$ with $\mathrm{D}^{*+} \rightarrow \mathrm{D}^0 \pi^+$ and D^0 reconstructed as above.
- Reconstruct decay length and momentum of each b hadron candidate.
- Fit distribution of proper times to extract lifetimes.

Limited by relatively low statistics (few thousand events), and cross contamination of B^+ and B^0 samples (due to missing slow pion from D^{*+} and $\bar{\mathrm{B}} \rightarrow \mathrm{D}^{*+}\mathrm{h}\,\ell^- \bar{\nu}$ decays).





Topological measurements I

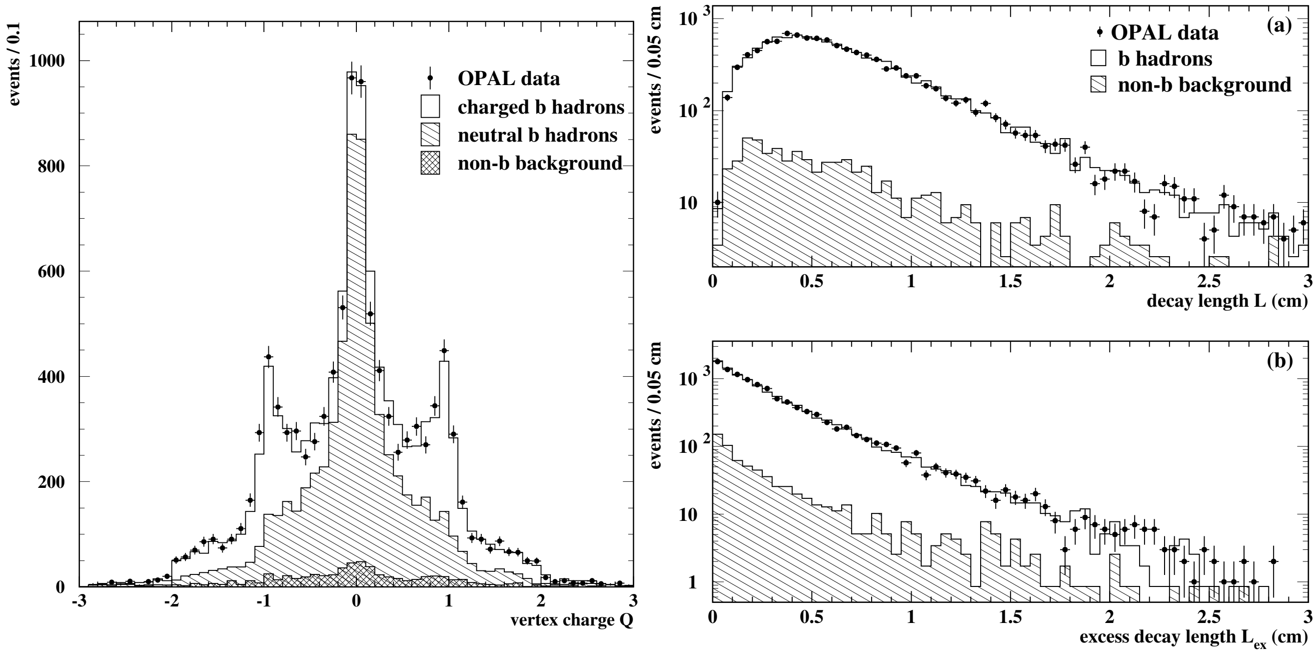
Vertex based b-tagging allows very large samples of b hadrons to be isolated. . . how to exploit for lifetime studies ?

- B^+ and B^0 can be separated by reconstructing vertex charge of secondary vertex—separates charged and neutral b hadrons.
- Lifetime bias from vertex tag can be removed by a cut on minimum proper time, or using excess decay length technique.

e.g. in OPAL analysis, look for veritices where each track is unambiguously assigned to primary or secondary vertex.

Calculate vertex charge and uncertainty based on track secondary vertex probabilities, weight each event appropriately.

Translate b hadron tracks back towards primary vertex, point where vertex becomes ‘ambiguous’ defines the excess decay length which follows a lifetime exponential form.



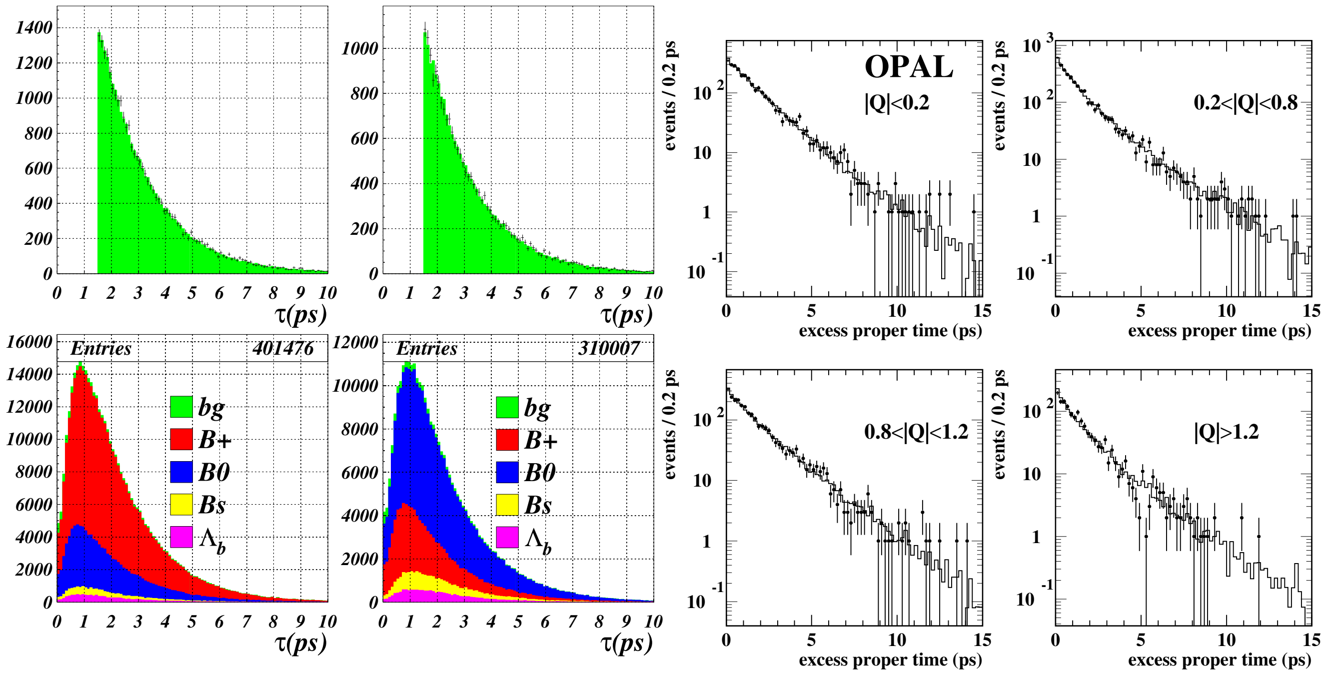
Topological measurements II

Samples of tens of thousands of events, with 60–80 % purity in chosen b hadron (B^+ or B^0).

Seperation between b hadrons can be further enhanced:

- Correlation between hemispheres in $b\bar{b}$ event: B^+ meson cannot be opposite another B^+, only B^- or neutral b hadron.
- DELPHI also uses kaon and proton ID in 'signal' hemisphere to suppress B_s and Λ_b background.

Finally extract lifetimes using fit to time distibutions, mean lifetime or via Monte Carlo reweighting.



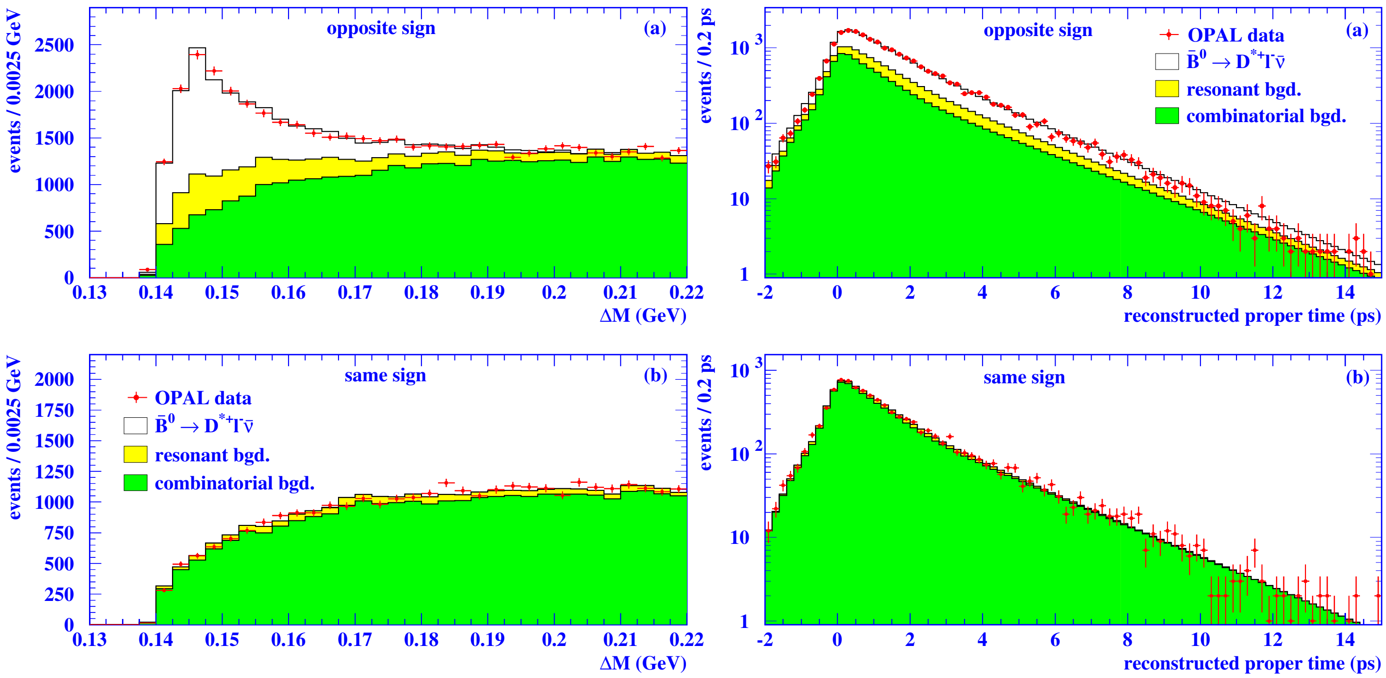
B^0 lifetime via slow pion

Topological B^0 lifetime measurements limited by $\mathrm{B_s}$ and Λ_b contamination (other neutral b hadrons—irreducible using vertex charge).

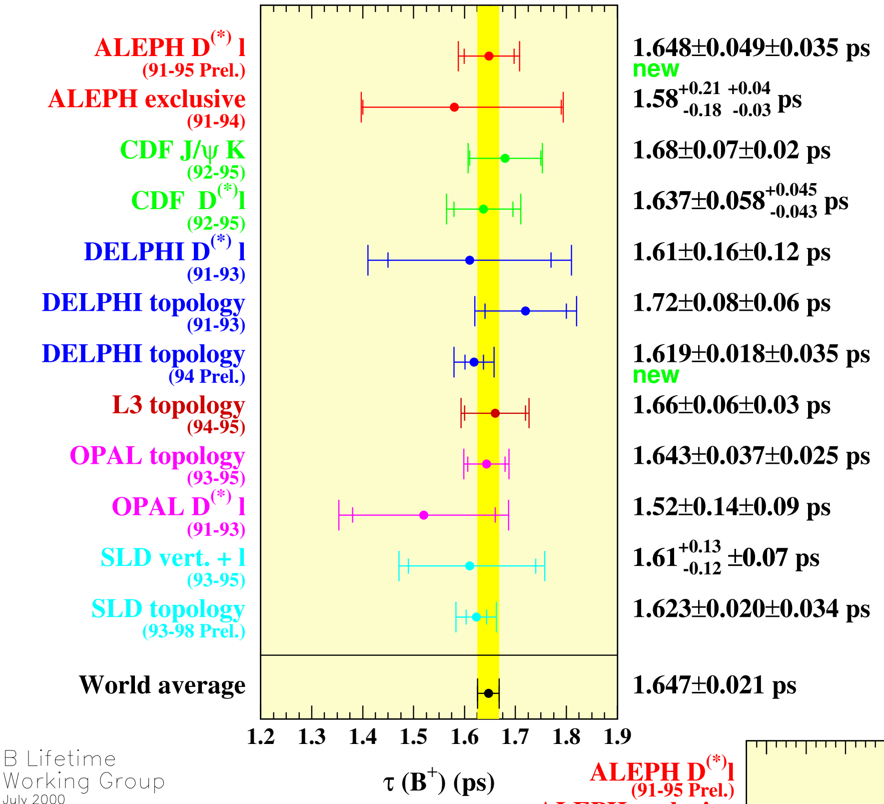
Alternative: partially reconstruct $\bar{\mathrm{B}}^0 \to \mathrm{D}^{*+}\ell^-\bar{\nu}$ decays looking only for lepton and slow pion in $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+$ transition.

- Reconstruct D^0 direction inclusively, look for π^+ with correct sign and small mass difference ΔM when combined with D^0.
- Background is mainly combinatorial, with some contribution from $\bar{\mathrm{B}} \to \mathrm{D}^{*+}\mathrm{h}\,\ell^-\bar{\nu}$ decays—cross contamination from B^+.
- Combinatorial background is mainly b hadrons, level and lifetime can be accurately estimated from sideband and wrong sign events.

Analysis performed by DELPHI, L3 and OPAL, latter is most precise τ_{B^0}.



B^+ and B^0 lifetime results



B^+ world average:

$$\tau_{B+} = 1.647 \pm 0.021 \text{ ps}$$

Dominated by topological measurements from DELPHI, OPAL, SLD.

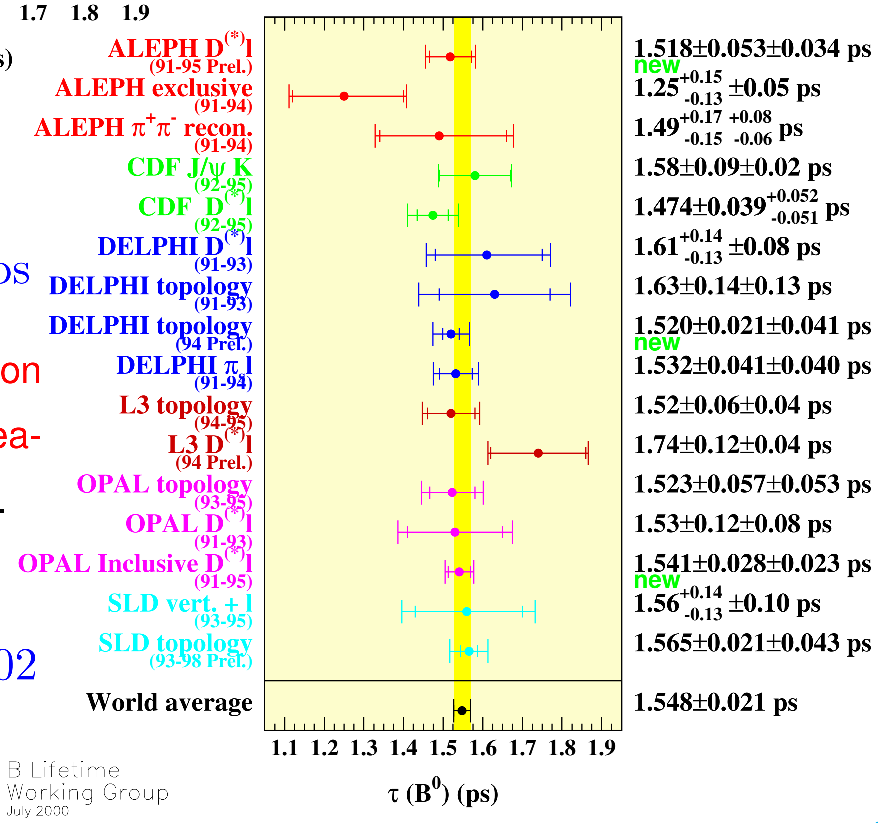
B^0 world average:

$$\tau_{B+} = 1.548 \pm 0.021 \text{ ps}$$

Dominated by slow pion (OPAL) and toplogical measurements (DELPHI,SLD).

Ratio:

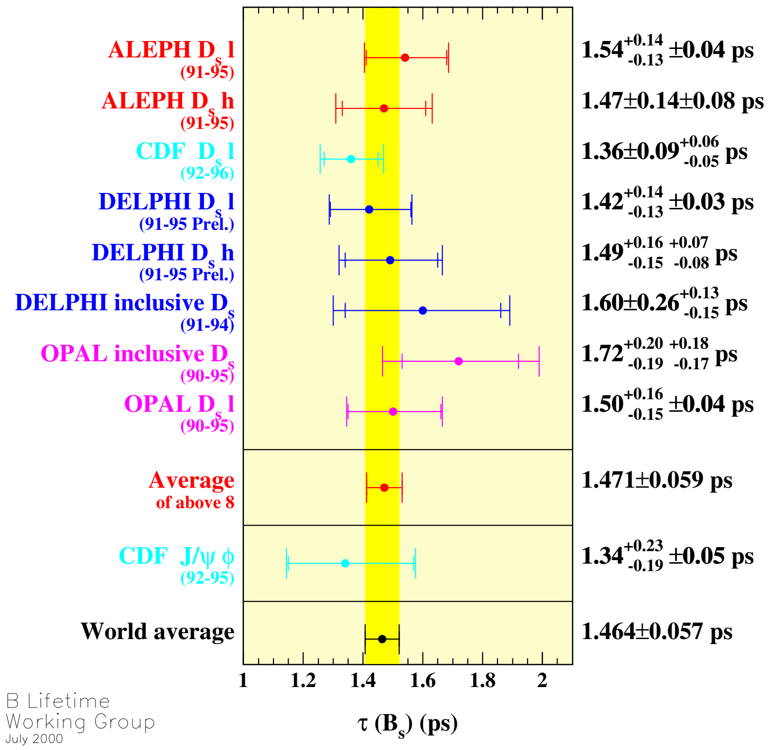
$$\tau_{B+}/\tau_{B^0} = 1.066 \pm 0.02$$



$\mathrm{B_s}$ lifetime measurements

Only 10 % of produced b hadrons are $\mathrm{B_s}$—difficult to isolate a pure sample except by exclusive reconstruction.

- $\mathrm{B_s} \to \mathrm{D_s}\ell\bar{\nu}$ channel with $\mathrm{D_s} \to \phi\pi^-, \mathrm{K^{*0}K^-}, \mathrm{K^0_sK^-}, \phi\ell\bar{\nu} \ldots$ gives highest purity, but still background from $\mathrm{B} \to \mathrm{D_sD}$ decays.
- $\mathrm{B_s} \to \mathrm{D_sh}$ and inclusive $\mathrm{D_s}$ samples—more events, higher background.



If Δm_s is large, may see significant width difference $\Delta\Gamma_s$ between CP-even and CP-odd $\mathrm{B_s}$ decay eigenstates.

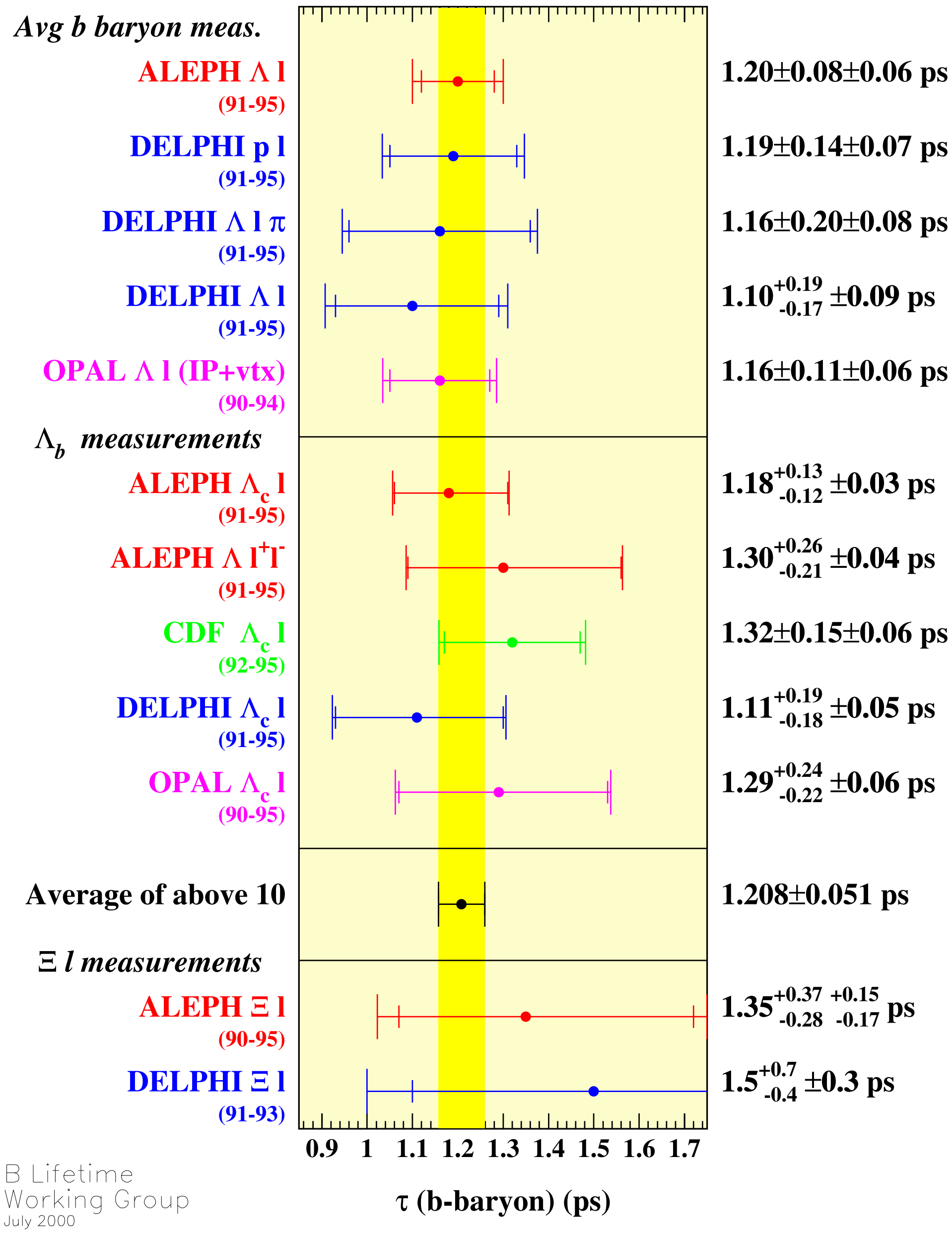
Can set limits via measuring lifetimes of CP eignestates (e.g. $\mathrm{D_s^+D_s^-}$, $\mathrm{J}/\psi\phi$) or looking for non-exponential behaviour in inclusive samples.

$\Delta\Gamma_s/\Gamma_s < 0.31$ at 95 % CL, assuming $\tau_{\mathrm{B_s}}=\tau_{\mathrm{B^0}}$

Λ_b lifetime measurements

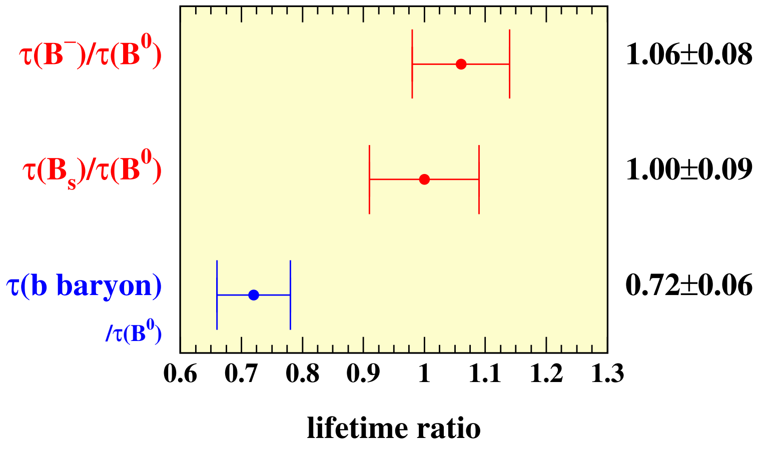
Weakly decaying b-baryons: Λ_b^0, Ξ_b, Ω_b

- Mixture produced at LEP dominated by Λ_b^0 but somewhat uncertain.
- Lepton-baryon correlations define one 'mixture'.
- Lepton-Λ_c correlations give purer sample of Λ_b^0.

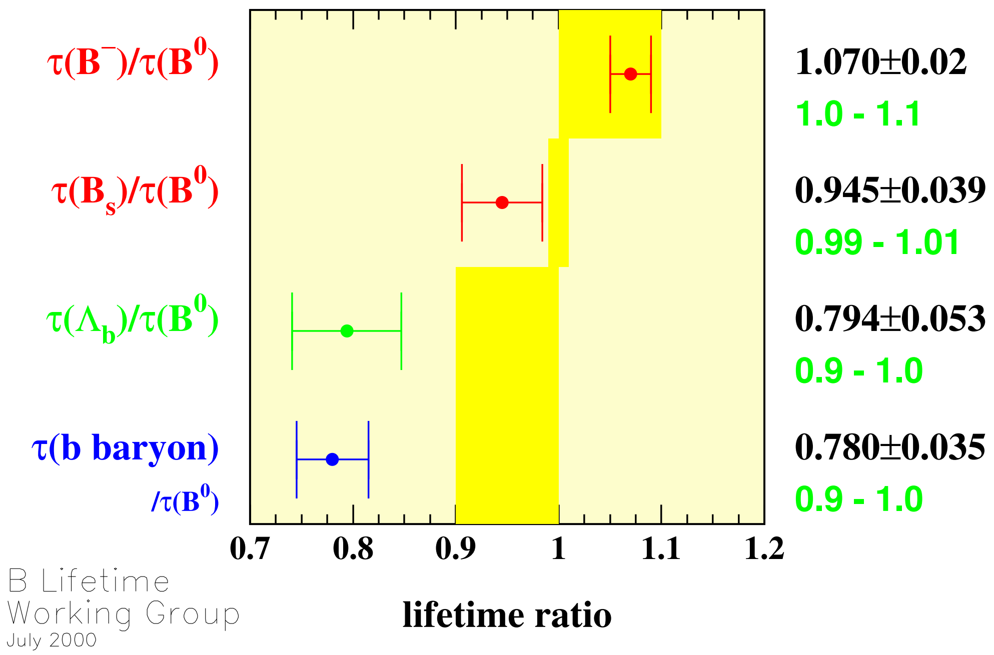


Lifetimes Perspective

Results from Moriond 1995 (M. Jimack), last year of LEP1 data taking:



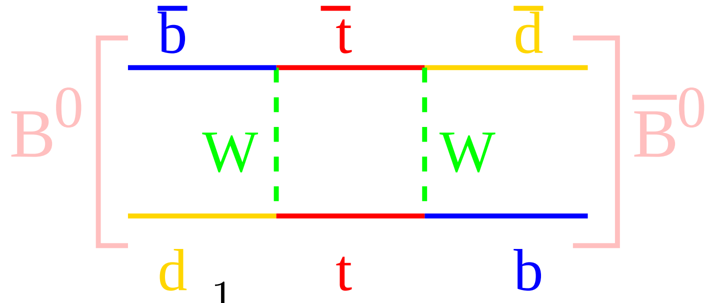
Results from summer 2000, with theoretical expectation:



- Huge improvements in precision of lifetime measurements. . . .
- Meson lifetime differences are in excellent agreement with theory.
- b-baryon lifetime is still significantly smaller than expected—not understood !

Oscillation Measurements

In neutral B-mesons (B^0 and $\mathrm{B_s}$), weak and mass eigenstates are not the same, leading to $\mathrm{B}^0 \leftrightarrow \bar{\mathrm{B}}^0$ transitions via box diagrams.



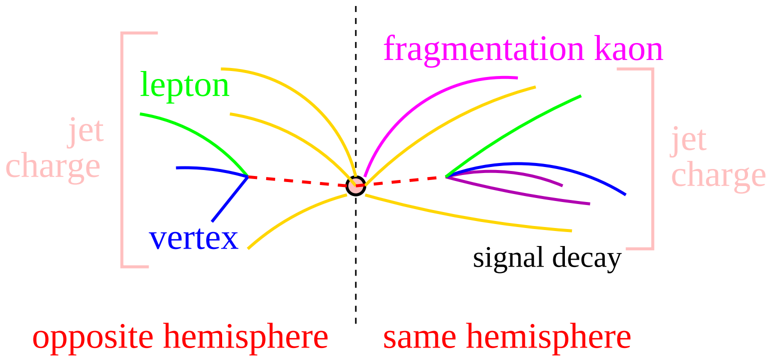
$$P(\mathrm{B}^0 \rightarrow \bar{\mathrm{B}}^0) = \frac{1}{2}(1 - \cos \Delta m_{\mathrm{d}} t),$$ same for Δm_{s}

In principle, $|V_{\mathrm{td}}|$, can be extracted from Δm_{d} but theoretically limited.

If Δm_{s} can also be measured, can extract ratio $|V_{\mathrm{td}}|/|V_{\mathrm{ts}}|$ with better theoretical precision... but Δm_{s} is large—very fast oscillations.

Requirements for measuring oscillations:

- Isolate sample of appropriate b hadron species (as in lifetimes).
- Measure decay proper time of each event (as in lifetimes, but for Δm_{s} good time resolution essential).
- Measure b hadron flavour at decay (lepton charge) and production (combination of tags from both hemispheres, typical mistag 28–30 %.)

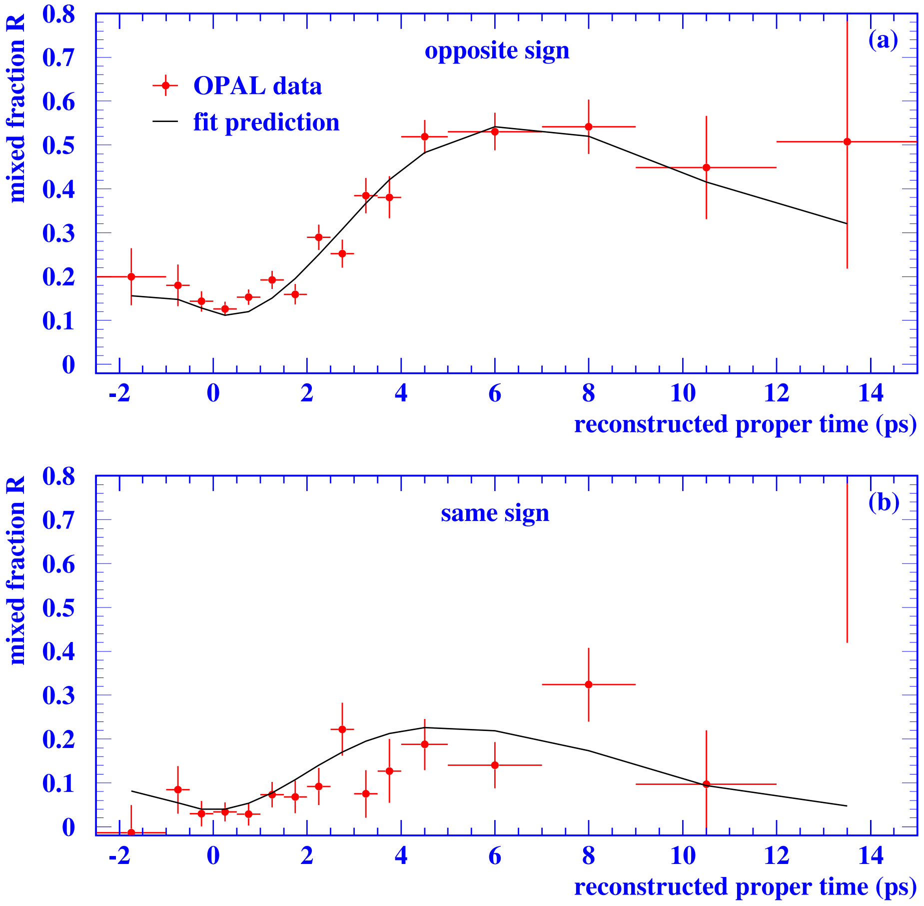


Measuring $\Delta m_{\rm d}$

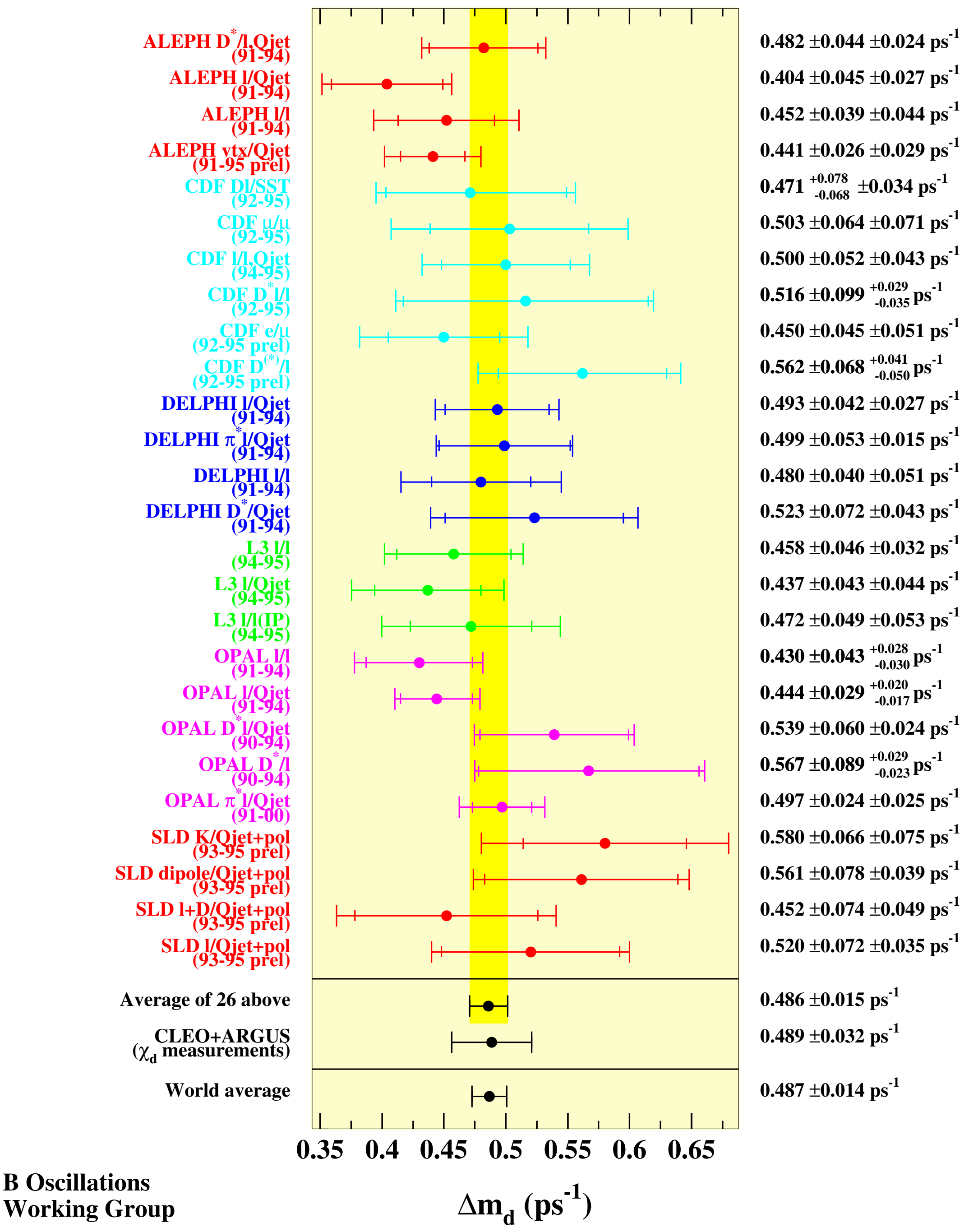
Well established precision measurements, using similar data samples to B^0 lifetime analyses (but only semileptonic decays—decay flavour tag).

- Particular decay modes (e.g. $\bar{\mathrm{B}}^0 \rightarrow \mathrm{D}^{*+}\ell^-\bar{\nu}$) or inclusive lepton events ($\mathrm{b} \rightarrow \ell\mathrm{X}$)—no need to remove B^+ as they do not oscillate.
- High statistics samples, good control of systematics from backgrounds, tagging, time resolution.

e.g. Recent OPAL analysis (inclusive slow pion $\bar{\mathrm{B}}^0 \rightarrow \mathrm{D}^{*+}\ell^-\bar{\nu}$:)



$\Delta m_{\rm d}$ results



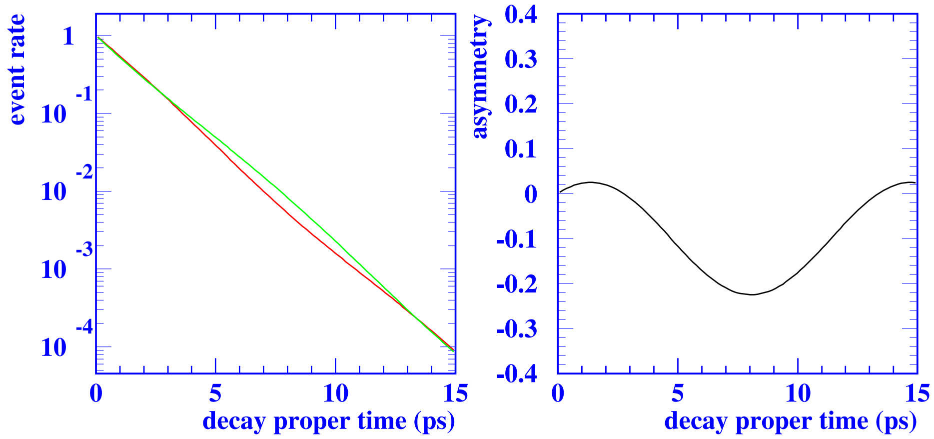
$\Delta m_{\rm d} = 0.487 \pm 0.014\,{\rm ps}^{-1}$ (2.9 % precision, dominated by LEP).

Inclusive CP-violation limits

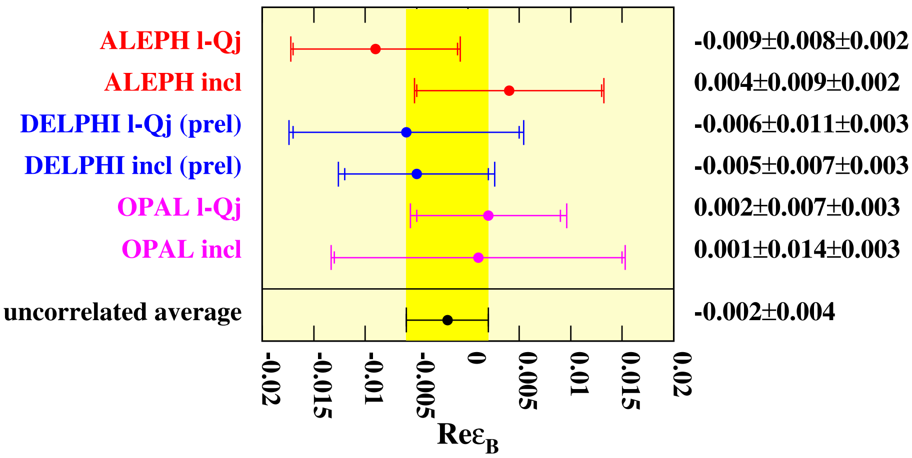
As in K^0 system, indirect CP violation can occur in B^0 system, if weak eigenstates B^0 and $\bar{\mathrm{B}}^0$ differ from mass eigenstates B_1 and B_2:

$$
\begin{aligned}
|\mathrm{B}_1> &= (1+\epsilon_\mathrm{B})|\mathrm{B}^0> + (1-\epsilon_\mathrm{B})|\bar{\mathrm{B}}^0> \\
|\mathrm{B}_2> &= (1+\epsilon_\mathrm{B})|\mathrm{B}^0> - (1-\epsilon_\mathrm{B})|\bar{\mathrm{B}}^0>
\end{aligned}
$$

ϵ_B parameterises indirect CP violation—different time evolution of B^0, $\bar{\mathrm{B}}^0$:



Effects can be searched for in inclusive lepton and fully inclusive samples (no decay flavour tag), reusing tagging and analysis from Δm_d.



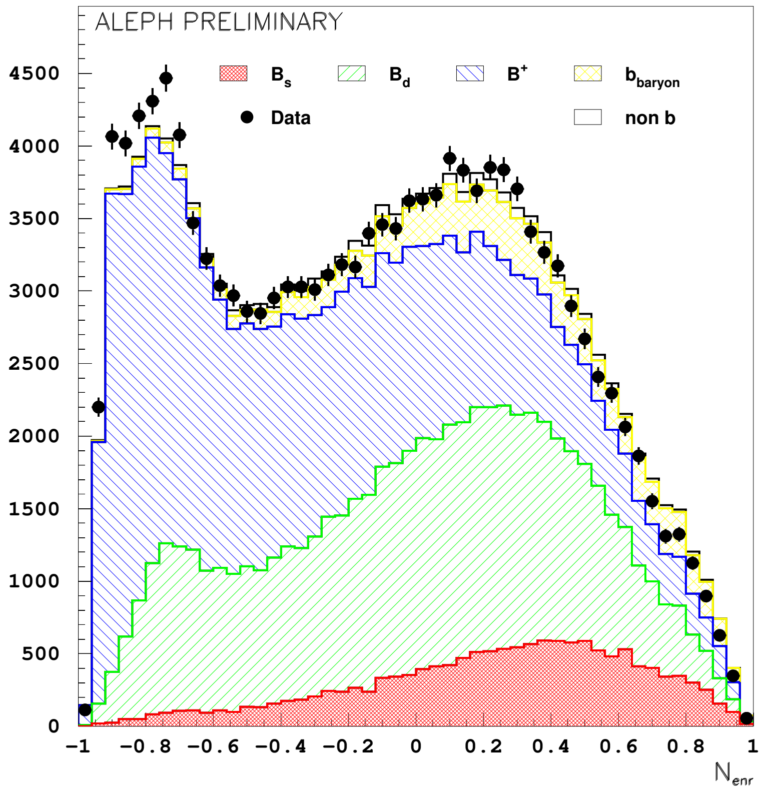
No evidence of CP violation, (SM CKM 10^{-3}, superweak 10^{-2}).

Searching for $\mathrm{B_s}$ oscillations I

Extremely sophisticated analyses to maximise sensitivity to Δm_{s}.

Most sensitive analysis technique is inclusive lepton, look for fast oscillating component from $\mathrm{B_s}$ in $\mathrm{b} \to \ell$ decays.

- Only about 10 % of b hadrons are $\mathrm{B_s}$, but can enhance $\mathrm{B_s}$ fraction by using vertex charges, fragmentation and decay kaons up to about 30 %.

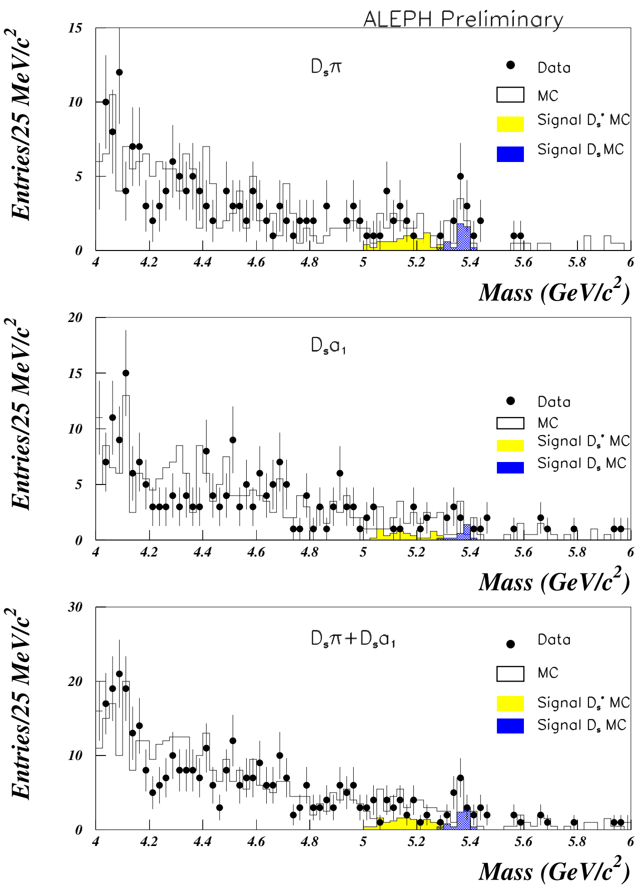


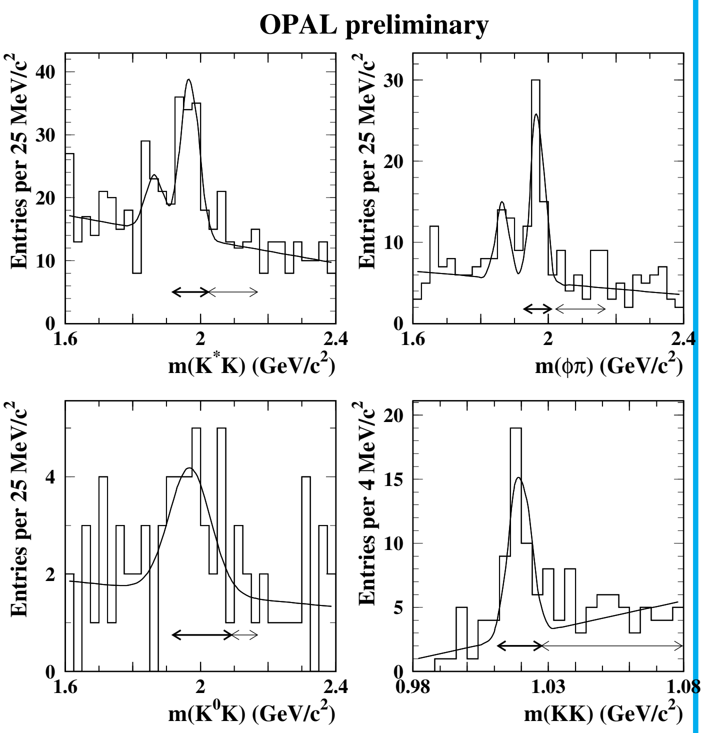
- Vertex reconstruction takes into account separate b and c decay points. Resolution determined event by event, typically $200\ \mu$m.

New ALEPH analysis has sensitivity up to 11.7 ps^{-1}.

Searching for $\mathrm{B_s}$ oscillations II

- $\mathrm{B_s} \rightarrow \mathrm{D_s}\ell\bar{\nu}$: better resolution and purity, lower statistics than $\mathrm{b} \rightarrow \ell$.
- Fully inclusive decays—get decay flavour from jet-charge like quantities (DELPHI). Huge statistics, but very low tagging purity (40 % mistag).
- Relatively new idea is full reconstruction of hadronic $\mathrm{B_s}$ decays (ALEPH, DELPHI): $\mathrm{B_s} \rightarrow \mathrm{D_s^-}\pi^+$ and $\mathrm{B_s} \rightarrow \mathrm{D_s^-}\mathrm{a_1^+}$. A handful of events, but excellent resolution (will be the 'method of choice' at future machines).



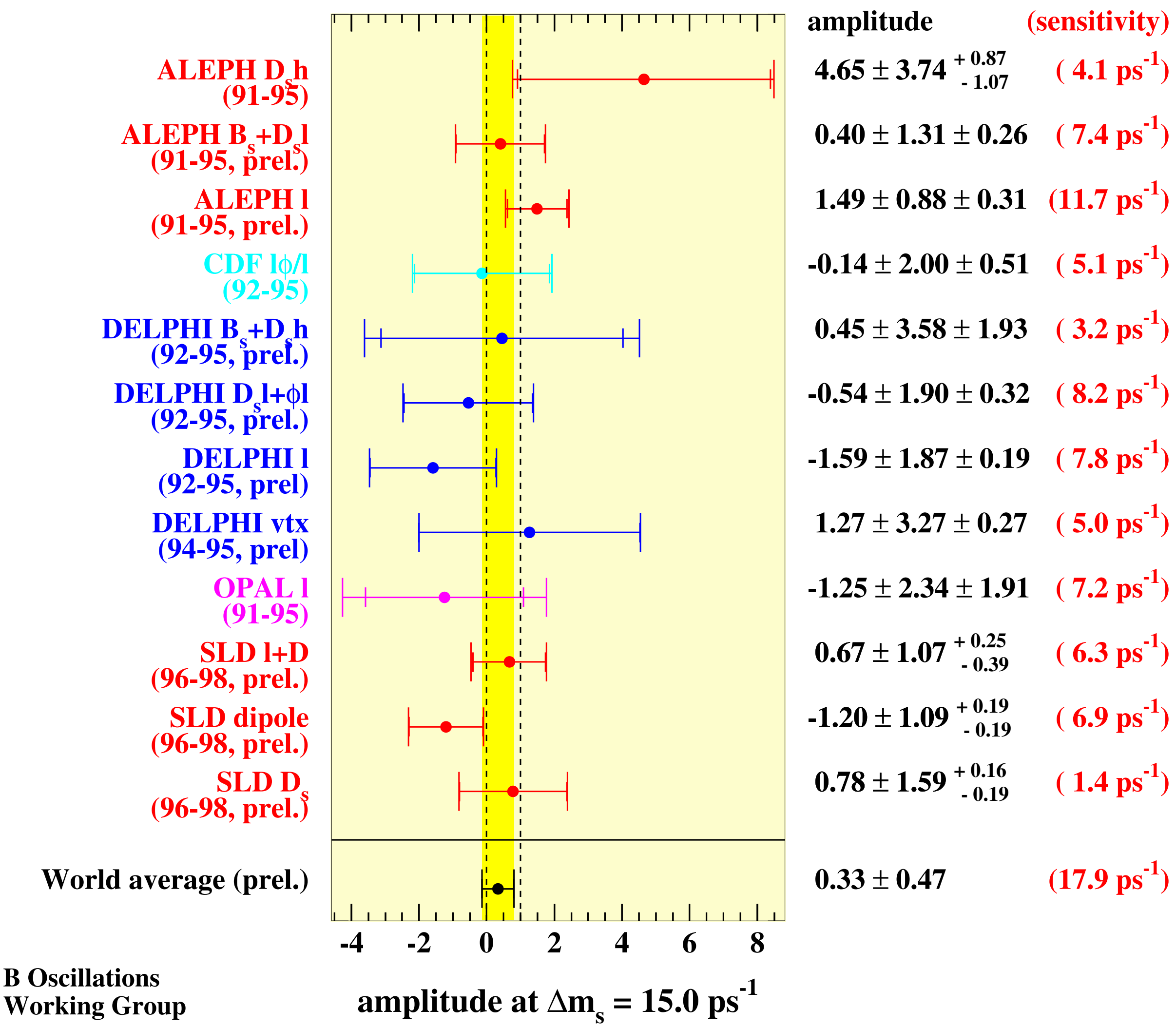


Every little helps in overall combination . . .

Amplitude Results

Measure amplitude A of oscillation at each test value of Δm_s; expect $A = 0$ far from true oscillation frequency where $A = 1$.

Amplitude measusments at $\Delta m_s = 15\,\mathrm{ps}^{-1}$ show contribution of each analysis in region of limit:



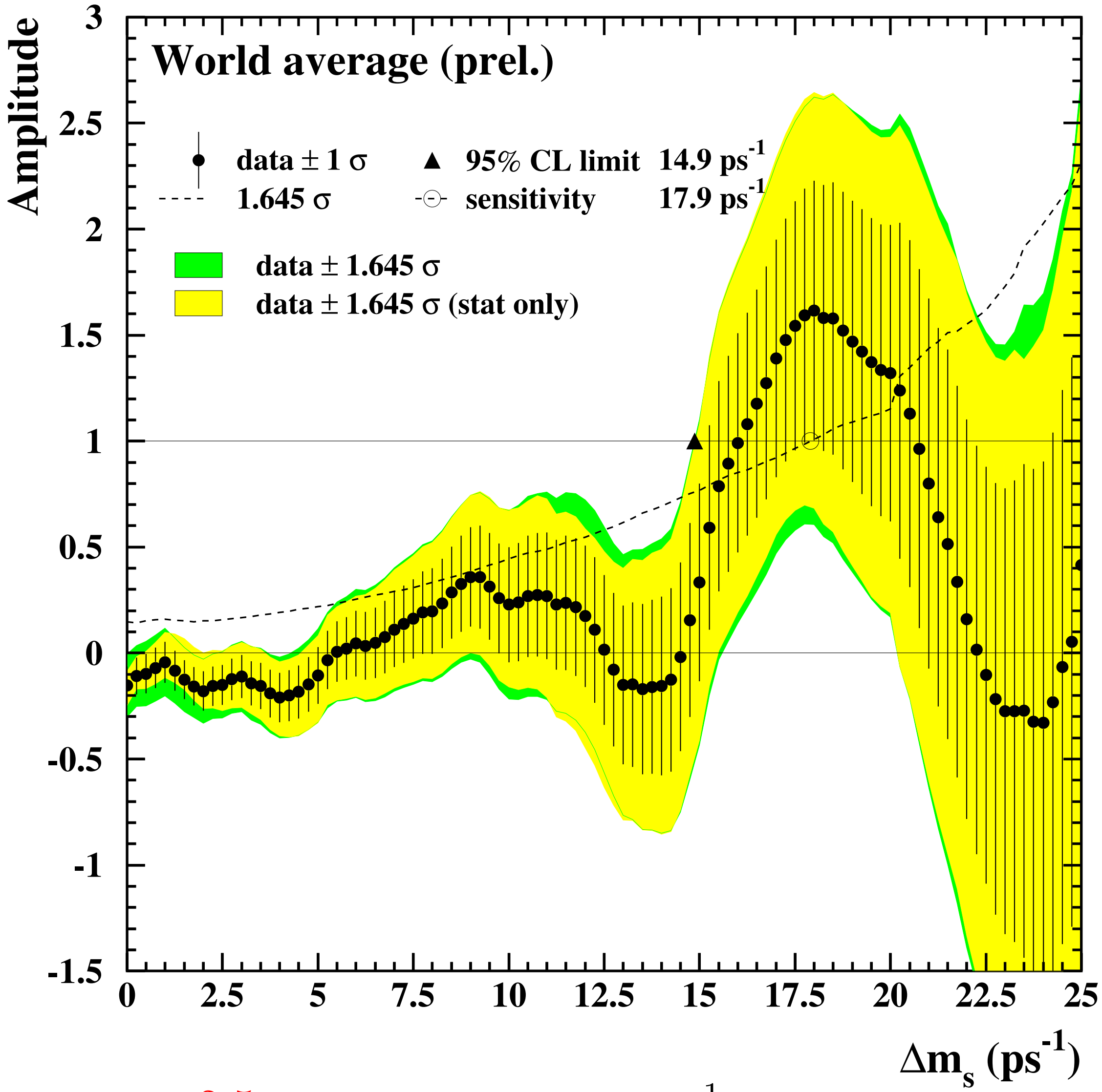
Biggest LEP contributions from inclusive lepton and $\mathrm{D_s}$-lepton analyses.

Limit results from many different analyses combined. . .

Limit on Δm_s

LEP alone: sensitivity 14.4 ps^{-1}, limit 11.5 ps^{-1}.

World average: sensitivity 17.9 ps^{-1}, limit 14.9 ps^{-1}.



There is a $\sim 2.5\sigma$ 'signal' at about 17.5 ps^{-1}.

Probability of such a 'signal' at any Δm_s from a background fluctuation is around 2.5 %.

Suggestive, but not yet a measurement of the B_s oscillation frequency. . .

Conclusions

LEP b-physics program has been a great success!

Five years after end of datataking, results are still being improved—intensive effort of many people over many years.

- b hadron lifetimes measured to precisions of 1–4 %.
- Meson lifetimes in good agreement with theoretical expectation.
- Λ_{b} lifetime is still an ongoing puzzle.
- Precision measurement of B^0 oscillation frequency Δm_{d}
- No sign of CP violation in inclusive decays.
- 'Holy grail' of $\mathrm{B_s}$ oscillation frequency has not been acheived—looks to be just out of reach, but not for lack of trying!

LEP b-physics analysis program is (almost) over, now we wait to see what the next generation of experiments will find.