A Review of B Hadron Lifetimes:

LEP Results and World Averages

presented by

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- General Requirements for B lifetime measurements
- Introduction and Theory
- Lifetime measurements and world averages for the

  average b hadron lifetime, B^0, B^-, B_s, and b baryons

- Status and Prospects

Acknowledgements:

Thanks to the LEP B Lifetime Working Group for compiling the averages.
(See http://wwwcn.cern.ch/~claires/lepblife.html.)

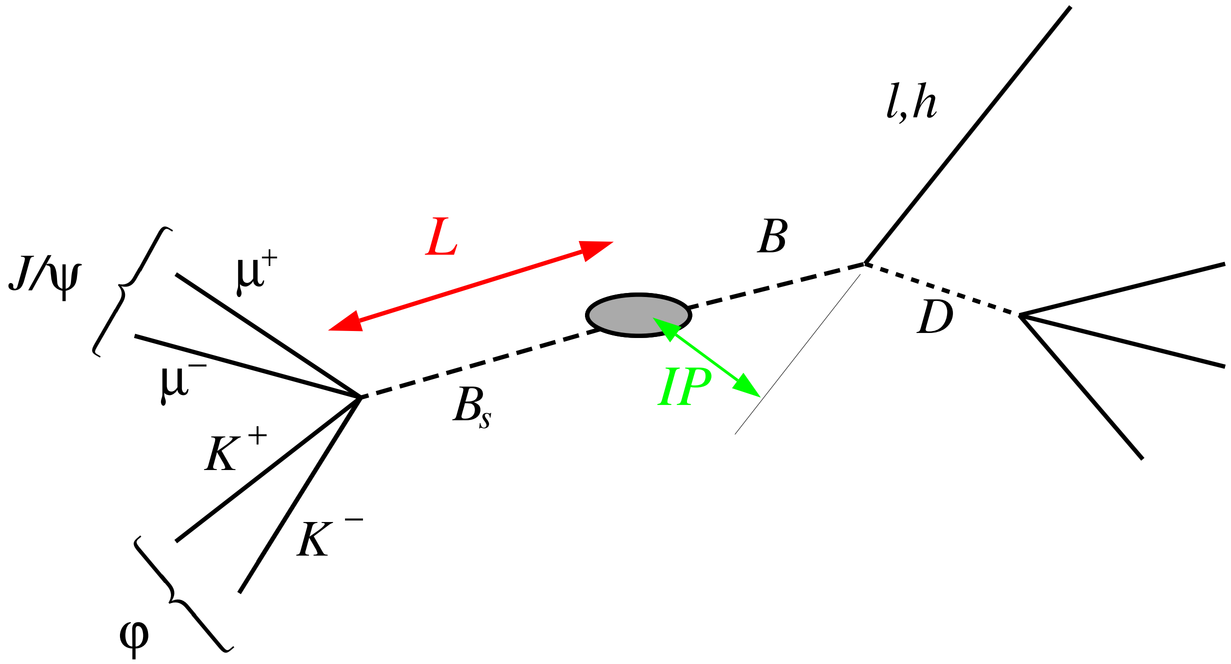
General Requirements

To measure B lifetimes, one typically needs to reconstruct:

B decay length & momentum: $t = \frac{m_B}{c\,p_B} L$

or

Impact Parameter of a track from B decay, e.g. a lepton



B hadrons have a large boost: LEP/SLD: $p_{B\text{av}} \sim 30$ GeV, $\rightarrow \ell_{\text{av}} \sim 3$mm

CDF: softer — depends on trigger

Detector requirements:

- Good vertex reconstruction Si vertex dets. ($\delta\ell \sim 300\mu$m)
- Good invariant mass resolution $\Rightarrow$ large tracking chambers
- Particle identification dE/dx & RICH

Lifetime Measurement Techniques

- **Decay Length (vertex):**

  Form a vertex, measure distance to the e^+e^- interaction point.

  Use boost estimate to get length to time $\Rightarrow$ some model dependence

  Fit to exponential convoluted with a resolution function.

- **Impact Parameter (IP):**

  Measure IP of a track (e.g a high p, p_t lepton).

  $\Rightarrow$ almost independent of the B hadron boost.

  Fit data with a convolution of a “physics function” — estimated from Monte Carlo models — and a resolution function.

Data...

- e^+e^- Clean environment ($Z^0 \to b\bar{b}$ & BR = 22%)
  (LEP 1.7×10^6/expt, SLD 64,000 b decays)

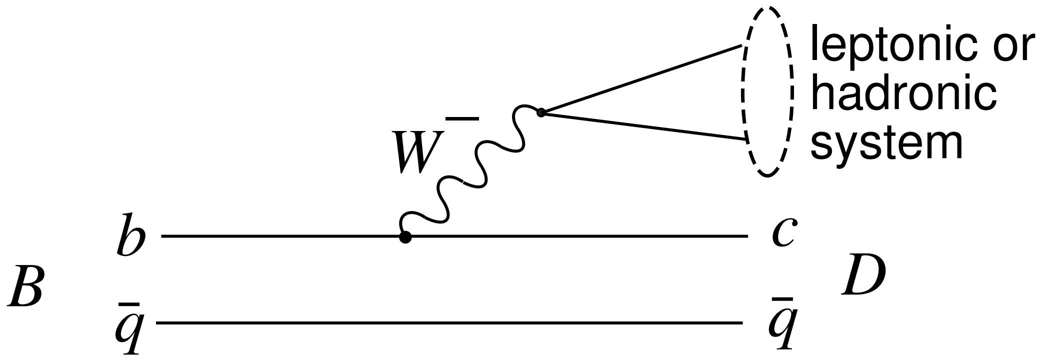
- p$\bar{\text{p}}$ Many b hadrons but high BG — best at clean modes
  (CDF $\sim 10^9$ b decays)

Hadrons produced at LEP/SLC (production fractions)

b hadron type	nominal	PDG 1996 Average
$B^0 + B^-$	0.80	0.756 ± 0.044
B_s	0.12	$0.112^{+0.018}_{-0.019}$
b baryons	0.08	0.132 ± 0.041

Introduction

Spectator Model: b quark decays independently $b \rightarrow cW^{*-}$ ...



$\Rightarrow$ all b hadrons should have equal lifetimes

Non–spectator effects cause lifetime differences:

c.f. the charm sector: $\tau_{D^+} \sim 2\tau_{D_s} \sim 2.5\tau_{D^0} \sim 5\tau_{\Lambda_c}$

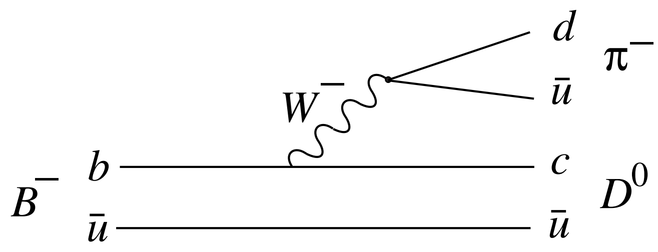
1. Quark Interference
2. Weak Annihilation
3. W Exchange

Non-spectator effects scale inversely with quark mass

$\Rightarrow$ *these effects should be smaller for b hadrons.*

Non-spectator effects

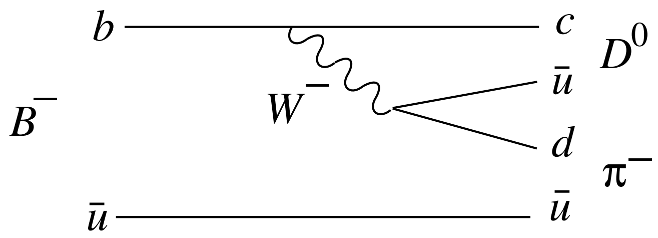
1. Quark Interference



Identical states

$\Rightarrow$ taken altogether, the identical states produce *destructive interference*

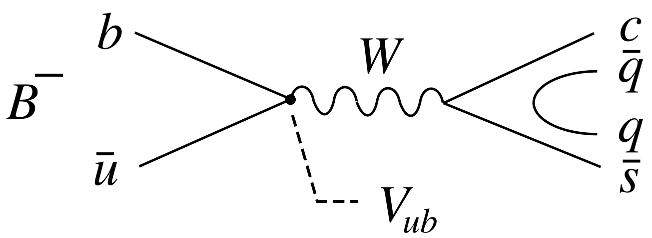
$\Rightarrow$ longer B^- lifetime



For B^0, the similar decay is $B^0 \to D^+\pi^-$ and $B^0 \to \overline{D}^0\pi^0 \Rightarrow$ distinguishable states, no interference.

$\Rightarrow B^-$ lifetime longer than B^0

2. Weak Annihilation

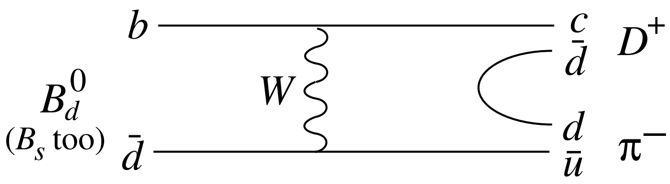


$|V_{ub}|^2$ is small

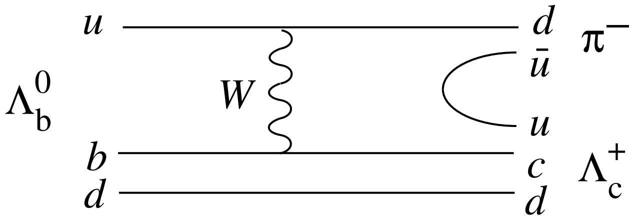
$\Rightarrow$ only important for B_c^-

Non-spectator effects (cont.)

3. W Exchange



Helicity suppressed



Not helicity suppressed
$\Rightarrow$ lower Λ_b lifetime

Expected hierarchy:

$$\boxed{\tau_{\Lambda_b} < \tau_{B^0} \sim \tau_{B_s} < \tau_{B^-}}$$

But what about the size of these lifetime differences?

Individual B lifetimes - Theory

Heavy Quark Expansion gives size of differences …

- Baryon–meson differences given by $\mathcal{O}(1/m_b^2)$ terms
- Meson–meson differences smaller $\mathcal{O}(1/m_b^3)$ — but what size is the coefficient of these terms?

Standard predictions: I.I. Bigi (hep-ph 9507364)

$$\begin{aligned}\tau_{B^-}/\tau_{B^0} &= 1 + 0.05\left(\frac{f_B}{200\,\mathrm{MeV}}\right)^2 \text{, i.e. } 1+\mathcal{O}(10\%)\\ \tau_{B_s}/\tau_{B^0} &= 1 \pm \mathcal{O}(0.01)\\ \tau_{\Lambda_b}/\tau_{B^0} &= \sim 0.9\end{aligned}$$

$$\boxed{\tau_{\Lambda_b} < \tau_{B^0} = \tau_{B_s} < \tau_{B^-}}$$

…however: M. Neubert, C.T. Sachrajda (CERN-TH/96-19) question some assumptions used above, and find:

$$\begin{aligned}\tau_{B^-}/\tau_{B^0} &= 1 \pm \mathcal{O}(1/m_b^3) \text{, but could be 0.8–1.2 !}\\ \tau_{B_s}/\tau_{B^0} &= 1 \pm \mathcal{O}(0.01)\\ \tau_{\Lambda_b}/\tau_{B^0} &= 0.98 \pm \mathcal{O}(1/m_b^3)\end{aligned}$$

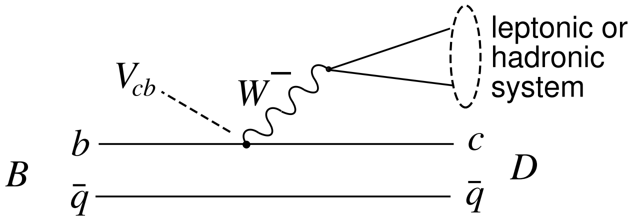
$\tau_{\Lambda_b} < \tau_{B^0} = \tau_{B_s}$ but no useful prediction for τ_{B^-}

Perhaps experiments can help…

Differences between lifetimes are expected to be small
$\Rightarrow$ precise measurements are required.

Average B lifetime

Why measure average B lifetime?



$$\Gamma = \frac{1}{\tau_B} \propto G_F^2 m_b^5 \mid V_{cb} \mid^2$$

but V_{cb} better measured using

$$\overline{B}_d^0 \rightarrow D^{*+} l^- \overline{v}$$

Most useful for checking consistency of individual-hadron lifetime results.

What *is* the "average B lifetime"?

τ_B depends on mixture of b hadrons in the sample — different analyses select different compositions…

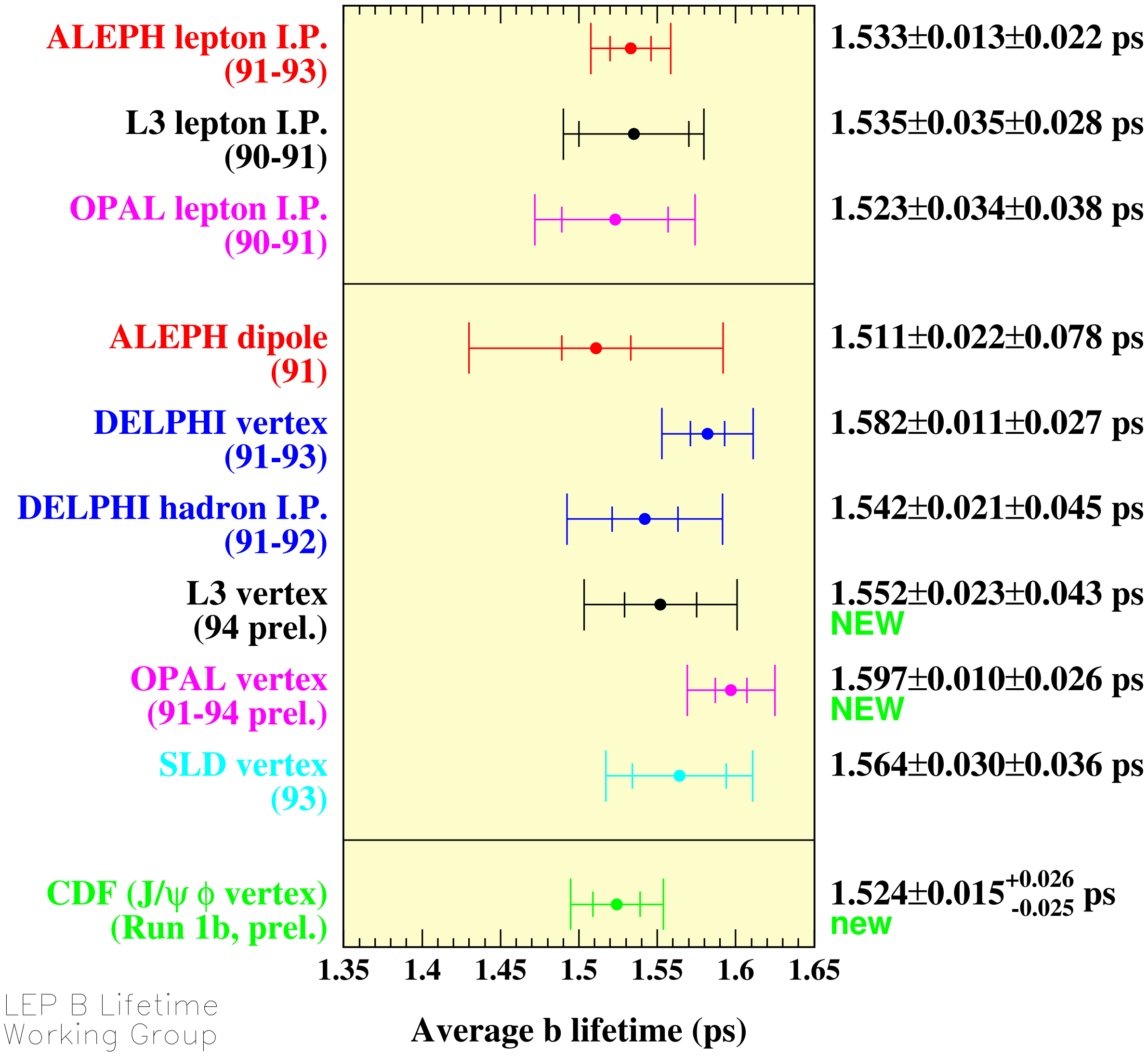
$\Rightarrow$It is not trivial to compare results of different analyses!

e.g. at what mixture should measurements be compared?

Experimental techniques

- Impact parameters: using leptons (ALEPH,L3,OPAL) & hadrons (DELPHI)
- Inclusive displaced vertex reconstruction: DELPHI, L3, OPAL, SLD (ALEPH uses dipole method – need not know e^+e^- interaction point)
- $J/\psi \rightarrow l^+l^-$ vertex: CDF

Average B lifetime - World Average



- No average is shown because the the different biases in the b hadron composition among techniques.
- Results are systematics limited: decay models, b fragmentation, …

More interesting to measure individual B hadron lifetimes:

$$B^0, B^-, B_s, \Lambda_b, \ldots$$

Individual B lifetimes - Techniques

- **Full reconstruction** e.g. $B_s \to J/\psi\phi$

  Good vertex determination

  Good boost determination - no missing particles

  Very little dependence on MC simulations

  Poor statistics (e.g. ALEPH 121 B^0 from 3M Z^0)

  Good at CDF — very large B sample

- **Reconstruct charm hadrons** e.g. $B \to Dl(X\nu)$

  More statistics limited by BR($b \to lX$)

  Good vertex determination

  Missing $\nu(X)$ degrades boost determination

  More MC dependence than above, but still small

  Good at LEP and CDF

- **More Inclusive** e.g. topological analyses, $\Lambda_b \to \Lambda l X$

  Large statistics

  Worse vertex resolution, but see DELPHI topological vertex

  Can be heavily MC dependent

  Assumptions necessary to extract individual hadron lifetimes

  Good at SLD (very good vertexing) and LEP

B^-/B^0 Lifetimes

$B \to D^{(*)} l \nu (X)$ — ALEPH, DELPHI, OPAL & CDF

The basic idea…

$D^{(*)+} l^-$ correlations $\Rightarrow B^0$

$$B^0 \to D^{*+} l^- \nu$$
$$\hookrightarrow D^0 \pi^+$$
$$\hookrightarrow K^- \pi^+$$
$$K^- \pi^+ \pi^- \pi^+$$

$$B^0 \to D^+ l^- \nu$$
$$\hookrightarrow K^- \pi^+ \pi^+$$

$D^0 l^-$ correlations $\Rightarrow B^-$

$$B^- \to D^0 l^- \nu$$
$$\hookrightarrow K^- \pi^+$$

$\Rightarrow$ be sure D^0 not from $D^{*+} \to D^0 \pi^-$

But: each final state is a mixture of B^- and B^0 because of D^{**} decays, e.g.

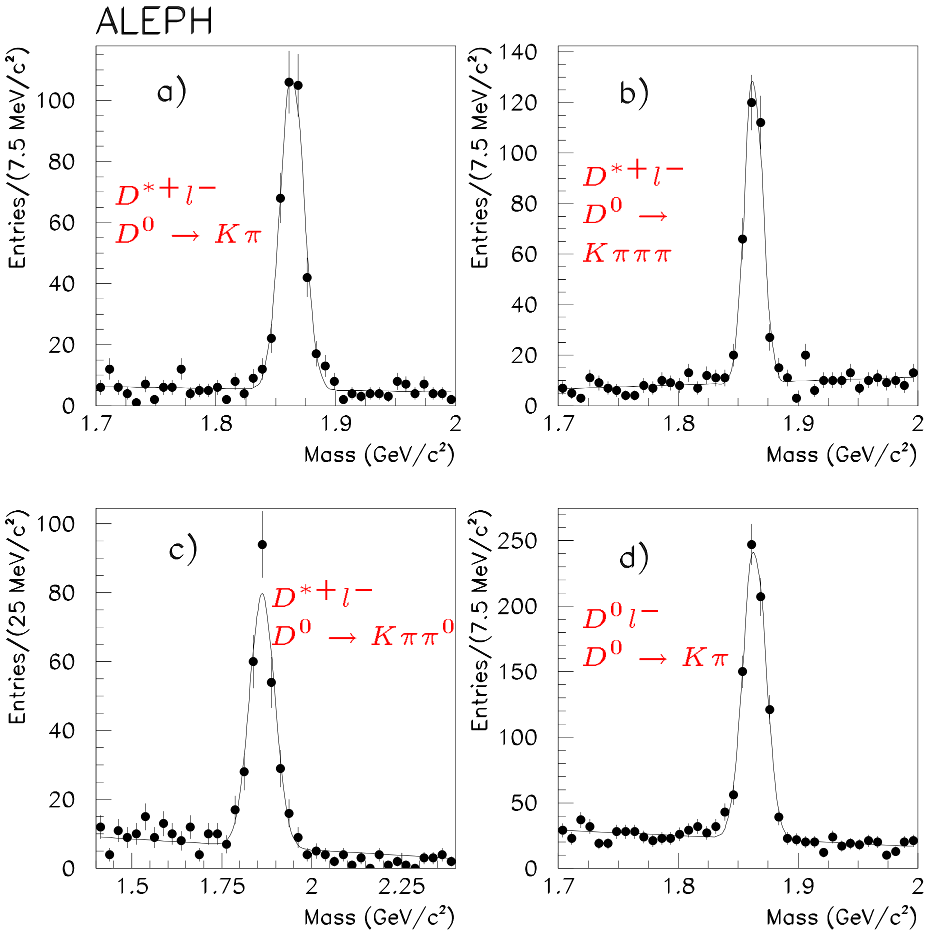
$$B^- \to D^{**0} l^- \nu$$
$$\hookrightarrow D^{*+} \pi^-$$

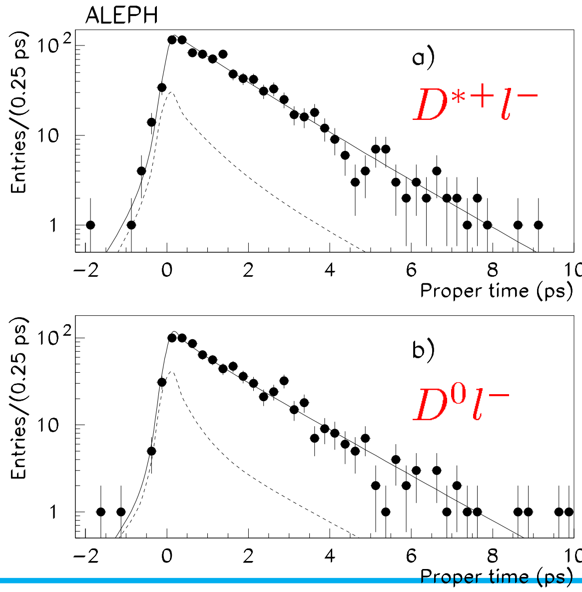
$\Rightarrow$ Now $D^{*+} l^-$ combination is from a B^-!

Use external measurements to extract the separate B^0 and B^- lifetimes (e.g. the fraction $B \to D^{**} l \nu = 36 \pm 12\%$ – CLEO).

$B \to D^{(*)} l \nu (X)$ Analysis

Invariant mass of D^0 candidates





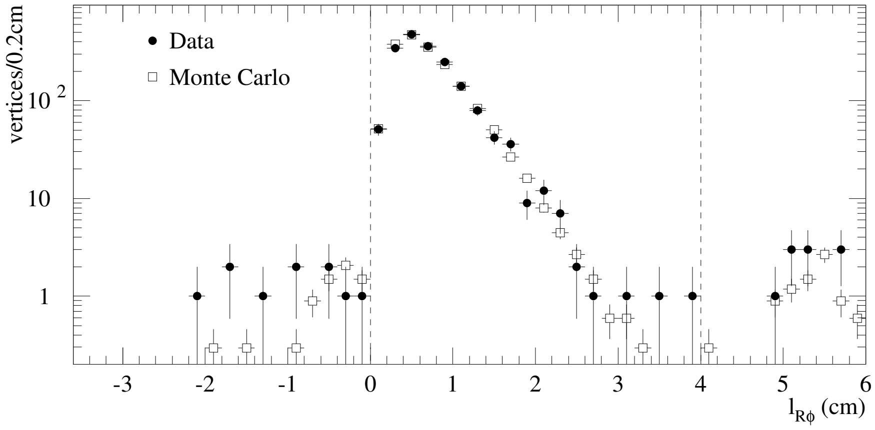
Proper time distributions

$$\tau(B^0) = 1.61 \pm 0.07^{+0.043}_{-0.041} \text{ ps}$$

$$\tau(B^-) = 1.58 \pm 0.09^{+0.044}_{-0.042} \text{ ps}$$

Topological vertexing — DELPHI

Inclusively reconstruct secondary vertices well separated from primary
$\Rightarrow < 1\%$ non-B hadron background.

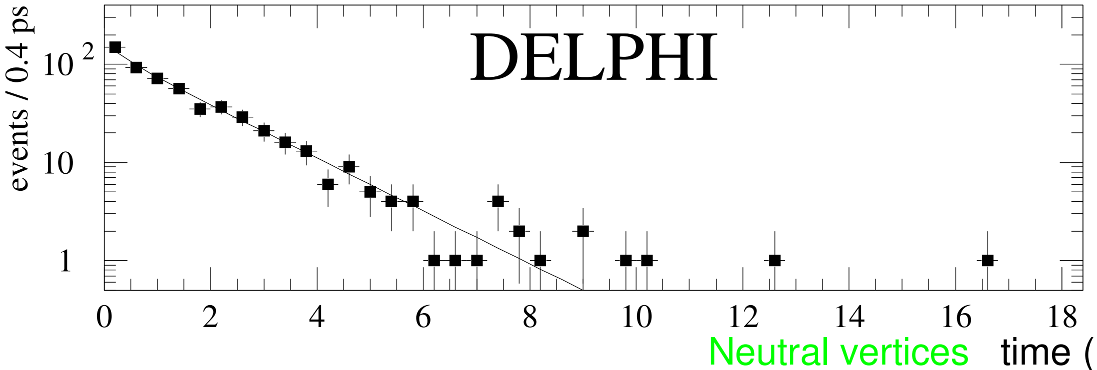


- Determine minimum possible decay length to form the vertex

  Find $\ell_{excess} = \ell - \ell_{min}$

  Estimate boost from visible p and m of vertex

- Use vertex change $\Rightarrow$ fit t_{excess} for charged and neutral B lifetimes.



Neutral vertices

- Assume B_s and Λ_b content to get $\tau(B^-)$ and $\tau(B^0)$

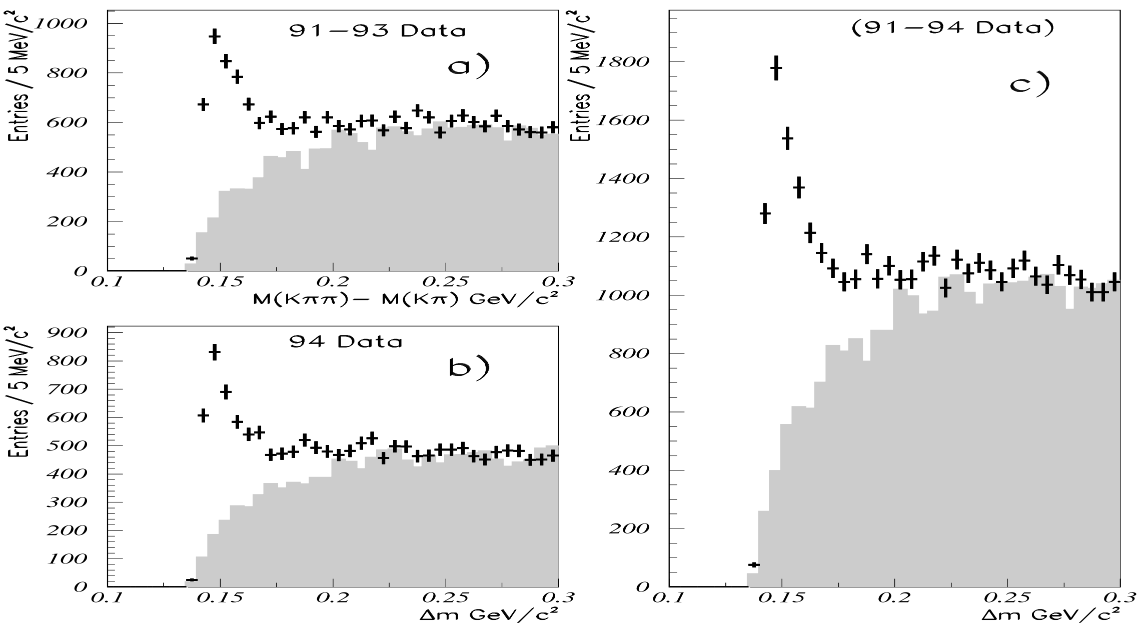
  $\tau(B^-) = 1.72 \pm 0.08 \pm 0.06 \quad \tau(B^0) = 1.63 \pm 0.14 \pm 0.13$

- Inclusive vertex reconstruction also done by SLD

B^0 lifetime from $\pi_s^+ l^-$ corrl. — DELPHI

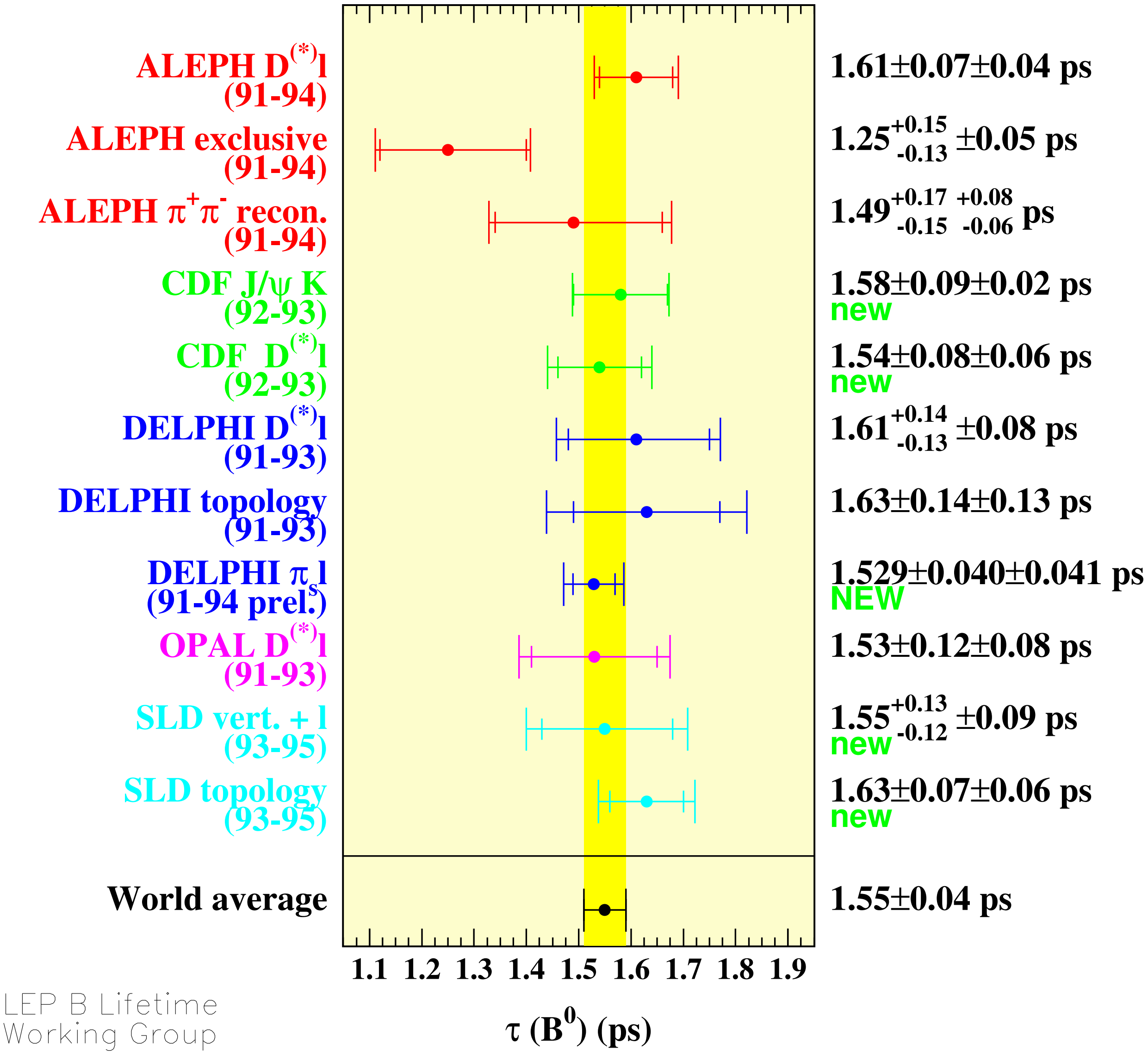
$$\overline{B^0} \rightarrow D^{*+} X l^- \overline{\nu_l}$$
$$\hookrightarrow D^0 \pi_s^+ \qquad \pi_s^+ = \text{"slow pion"}$$

- In events with high p, p_t lepton inclusively reconstruct D candidate by clustering tracks in a jet up to 2.2 GeV
- Look for right sign π ($\pi^+ l^-$) and form invariant mass with and without π.
- Peak due to D^*.
- Find 3520 ± 150 signal cands in $0.14 < \Delta m < 0.016$ ($\sim 30\%$ background)



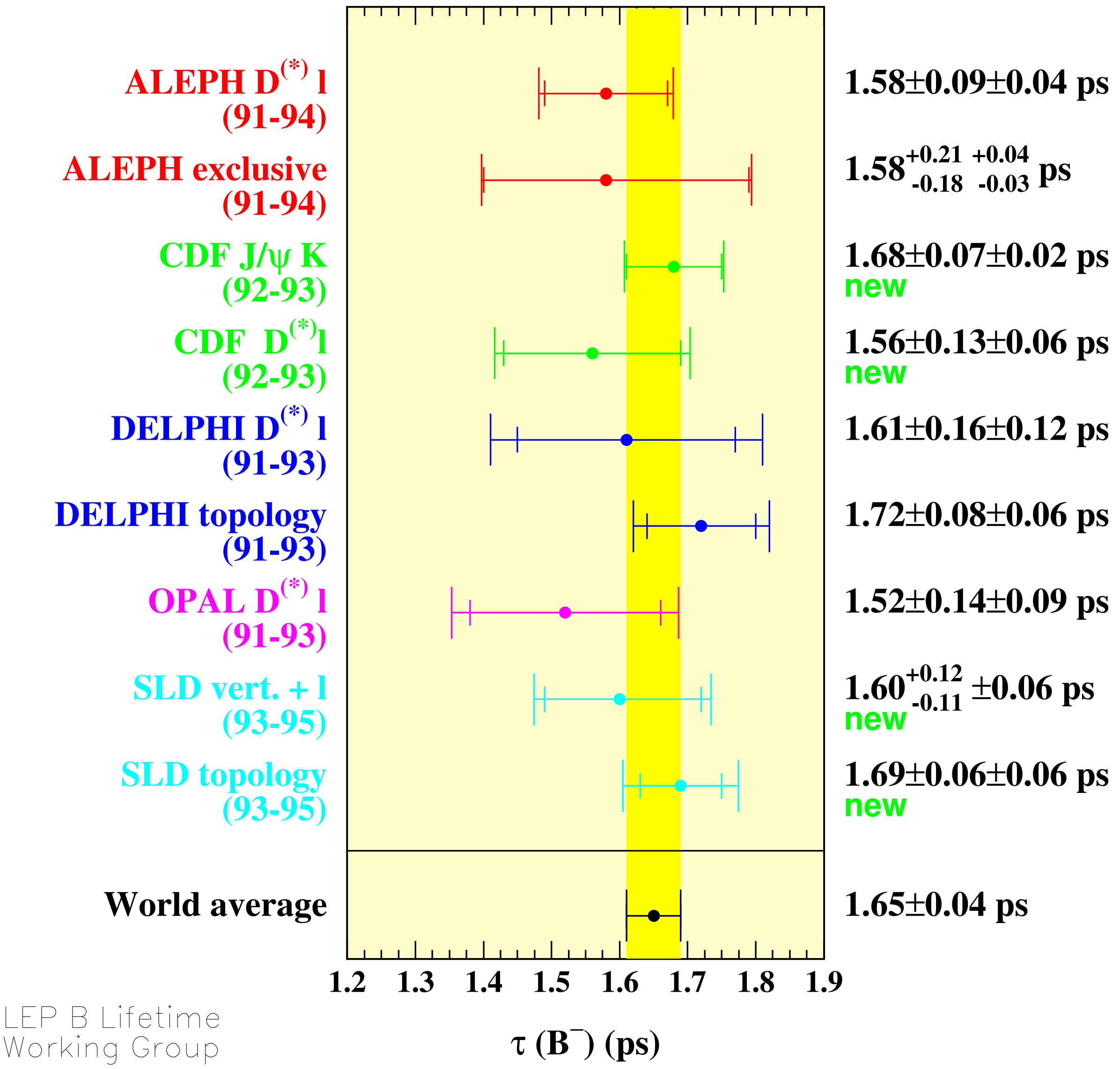
- DELPHI measures $\tau_{B^0} = 1.529 \pm 0.040 \pm 0.041$ ps (preliminary)

World Average – B^0 lifetime



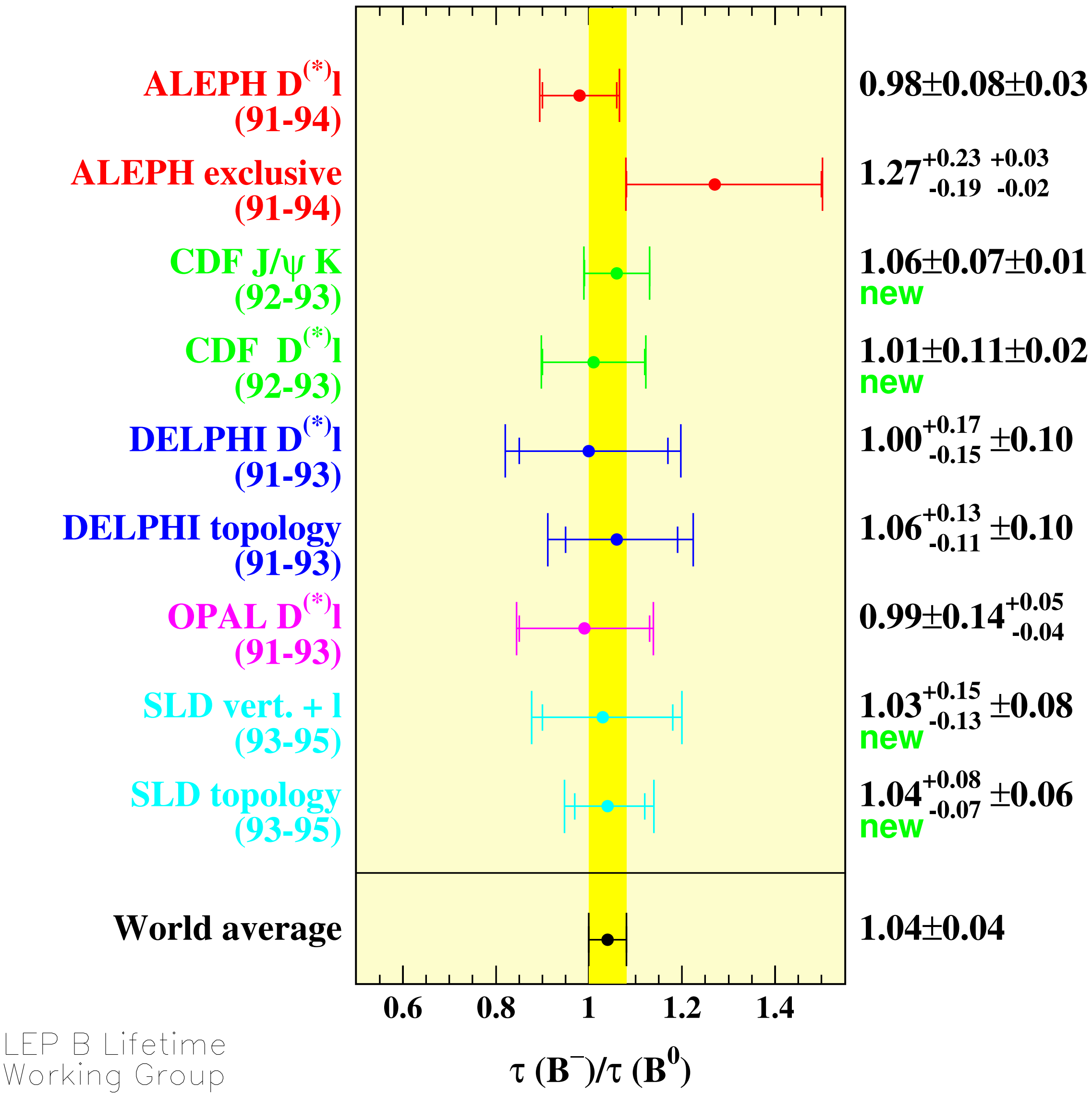
- SLD impressive – only 150,000 Z^0
- Error on world average is $\sim$ 2.5%

World Average – B^- lifetime



- Error on world average is $\sim$ 2.5%

World Average – B^- / B^0 lifetime ratio



- N.B. World average does not include DELPHI's π_s-l analysis (τ_{B^0} only) Average uses each expt's measurement of the lifetime ratio (proper treatment of correlated errors, etc.)

Ratio of averages: $\langle\tau_{B^-}\rangle \;/\; \langle\tau_{B^0}\rangle = 1.06$ (uncertainty $\approx \pm 0.04$)

B_s lifetime

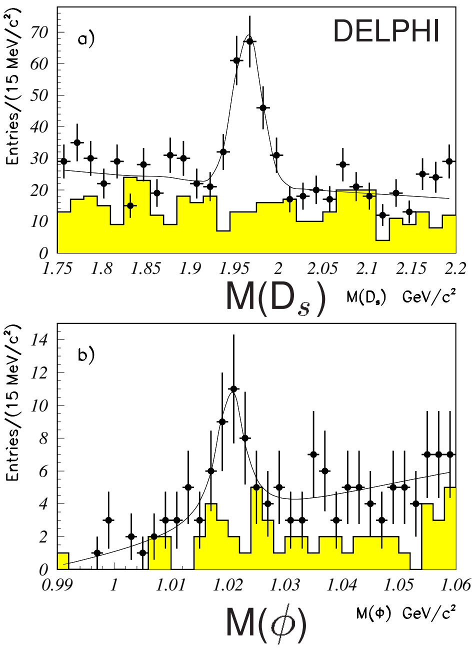
$B_s \to D_s l\nu(X)$ — ALEPH,OPAL,DELPHI & CDF

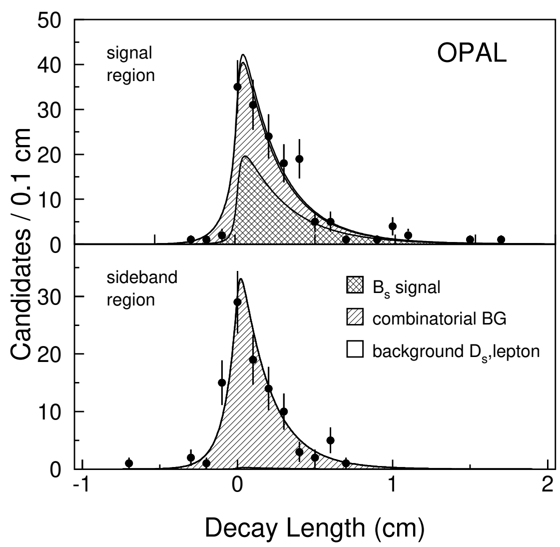
D_s reconstructed in 7 channels ALEPH DELPHI

D_s^- channel (ALEPH)	Events	Purity
$\phi\pi^-$	61	78%
$K^{*0}K^-$	102	63%
$K_s^0K^-$, $\phi 3\pi$, $K^{*0}K^{*-}$	70	56%
$\phi e^-\nu$, $\phi\mu^-\nu$	44	68%

N.B. DELPHI does $f^0\pi^+$ instead of $\phi 3\pi$; OPAL uses only $\phi\pi^-$ and $K^{*0}K^-$.

- ALEPH 181 signal using 7 channels — CDF has $\phi\pi$ 254!

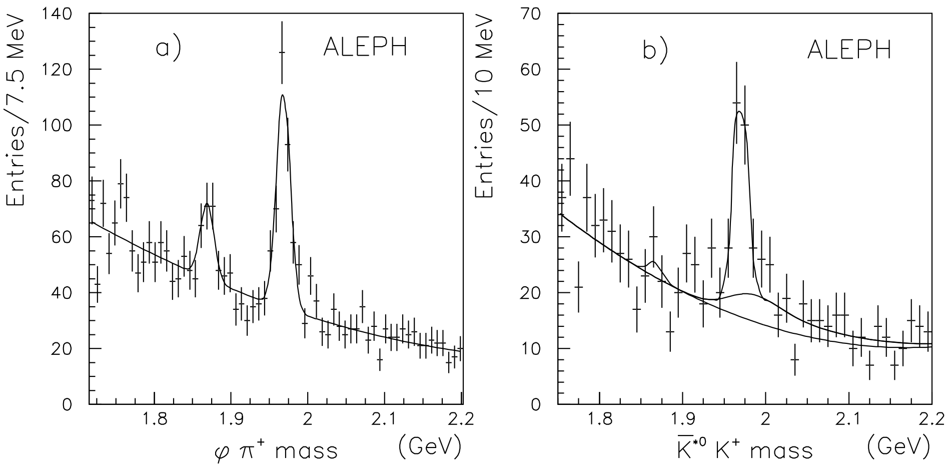


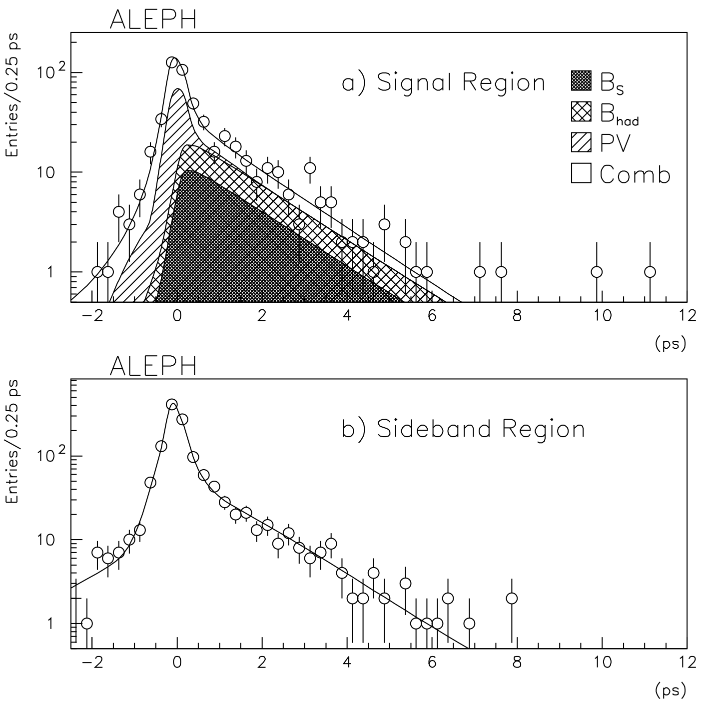


B_s Lifetime via Inclusive Techniques

- Inclusive D_s — DELPHI
- D_s–hadron — ALEPH & DELPHI
- ϕ–lepton — DELPHI

Example: ALEPH D_s–hadron analysis...



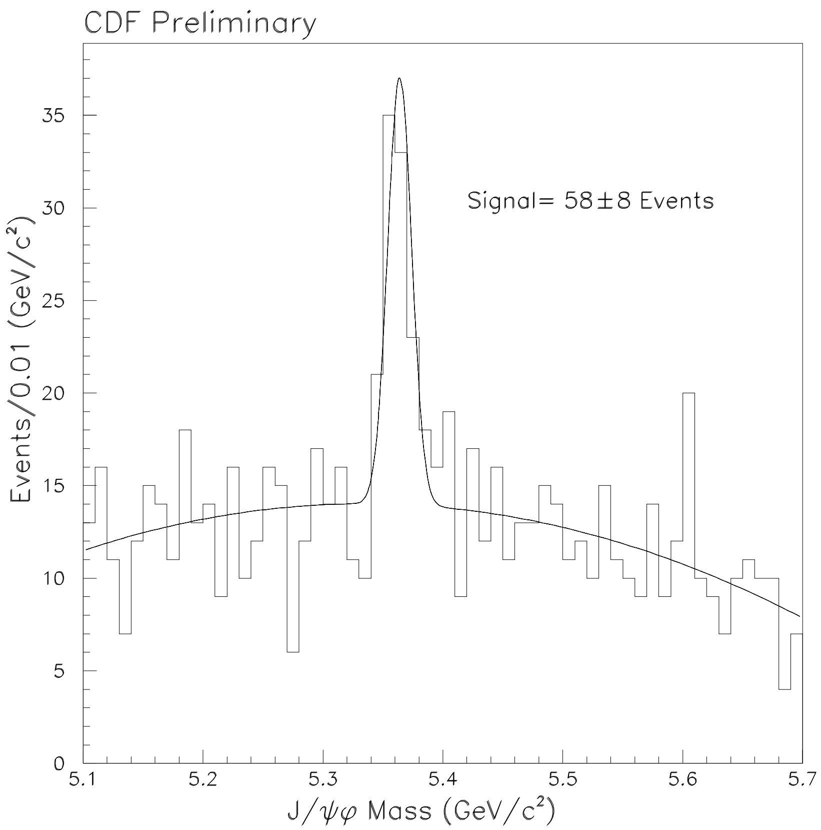


B_s Lifetime via Exclusive Techniques

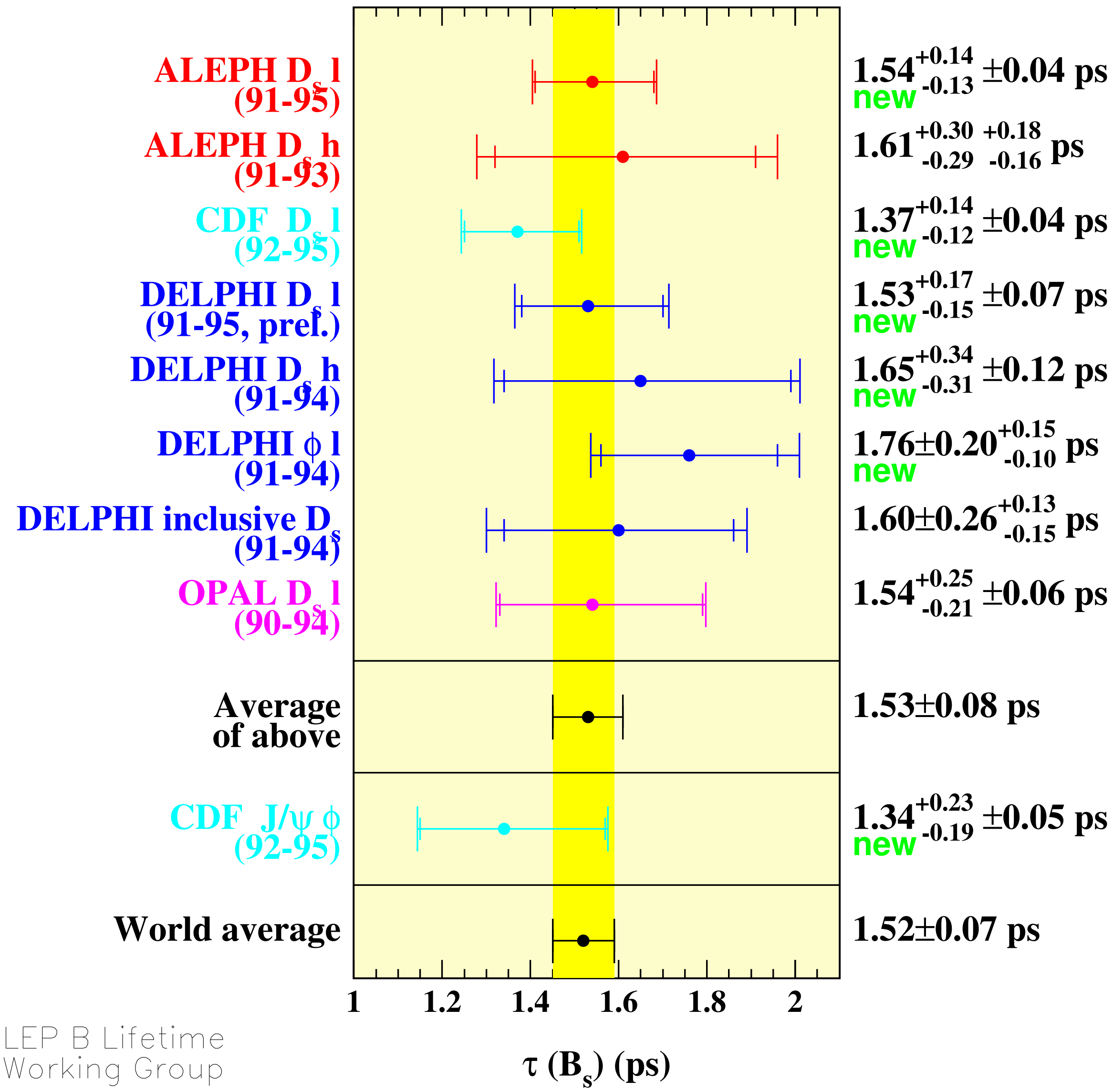
- $B_s \to J/\Psi\ \phi$ — CDF   Promising, but lacking statistics.

  Useful for looking for lifetime differences between CP eigenstates — up to 30% difference in lifetimes of CP eigenstates is possible.

  I.I. Bigi (hep-ph 9507364)



World Average – B_s lifetime



- Average shown with and without $J/\psi\phi$ channel. This has different CP eigenstate composition.

B-baryon lifetime measurements

A mixture of B-baryon states is produced at LEP: Λ_b^0, Σ_b, Ξ_b, Ω_b

Only ground state baryons Λ_b^0, Ξ_b^0, Ξ_b^-, Ω_b^- should decay weakly.

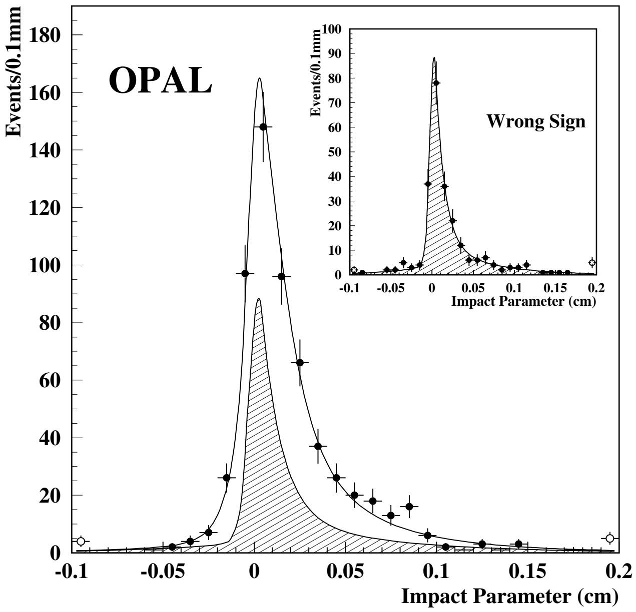
Average b baryon lifetime — ALEPH, DELPHI & OPAL

- One can measure the average b baryon lifetime by observing properly correlated b baryon decay products: e.g. Λl^-

$$\Lambda_b^0/\Xi_b^0/\Xi_b^-/\Omega_b^- \rightarrow \Lambda\, l^-\, \overline{\nu_l} X$$
$$\hookrightarrow p\pi^-$$

- Techniques: the average b baryon lifetime can be measured using:

  Λ-lepton using lepton impact parameter (ALEPH, DELPHI, OPAL)
  Λ-lepton vertex (OPAL)
  Λ-lepton-π vertex (DELPHI)
  proton-muon vertex (DELPHI)



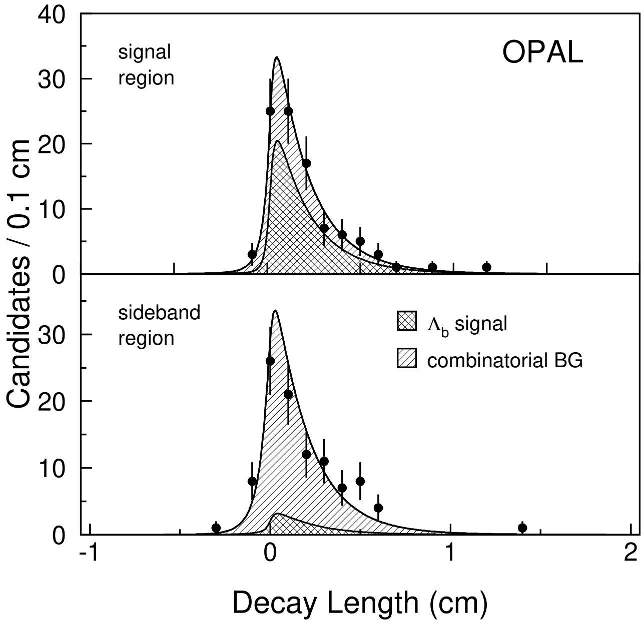
OPAL lepton IP:

$\tau_{b\ baryon} =$
$1.21^{+0.15}_{-0.13} \pm 0.10$ ps

Λ_b^0 Lifetime

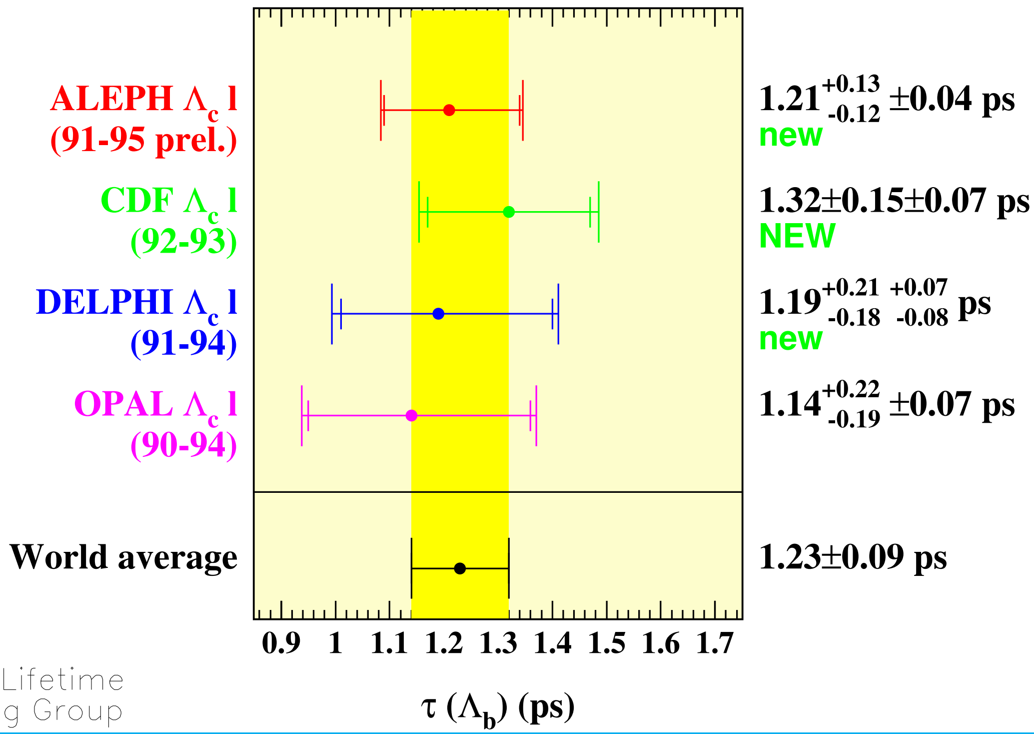
Exclusive reconstruction of Λ_c^+ provides tag of specific Λ_b^0 (bdu).

$\Lambda_c^+ \rightarrow pK^-\pi^+, pK^0, \Lambda\pi^+\pi^+\pi^-$ (lower statistics than Λl).



OPAL $\Lambda_c^+ l^-$:

$$\tau_{\Lambda_b^0} = 1.14^{+0.22}_{-0.19} \pm 0.07 \,\text{ps}$$



Strange B-baryon (Ξ_b) lifetime

Ξ_b (bsu or bsd) was first reported by DELPHI, now also seen by ALEPH.

However, discovery was anticipated by Francis Bacon (1561-1626):

There is no excellent beauty that hath not some strangeness in the proportion. *Essays - 43. On Beauty*

Idea similar to Λ_b reconstruction: correlated $\Xi^- l^-$ pairs...

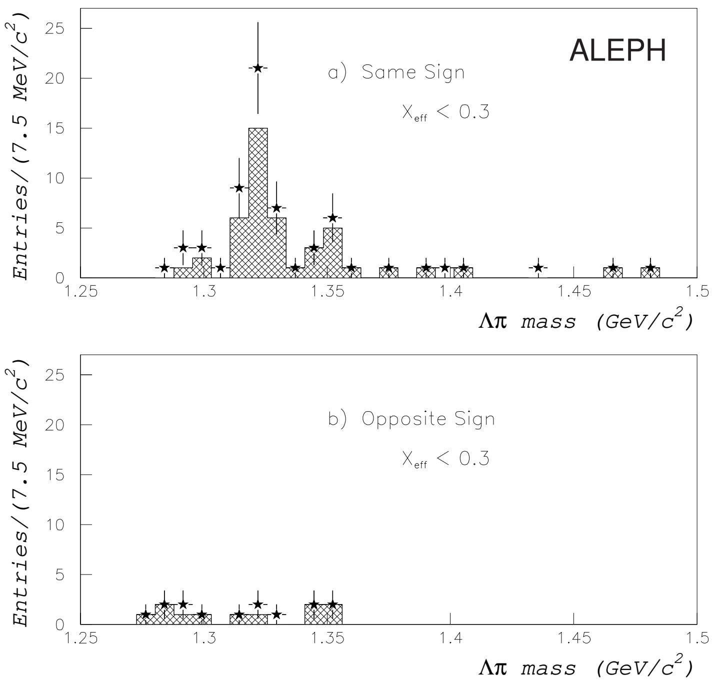
$$\Xi_b \to \Xi^- l^- \overline{\nu_l} X$$

N.B. same sign!

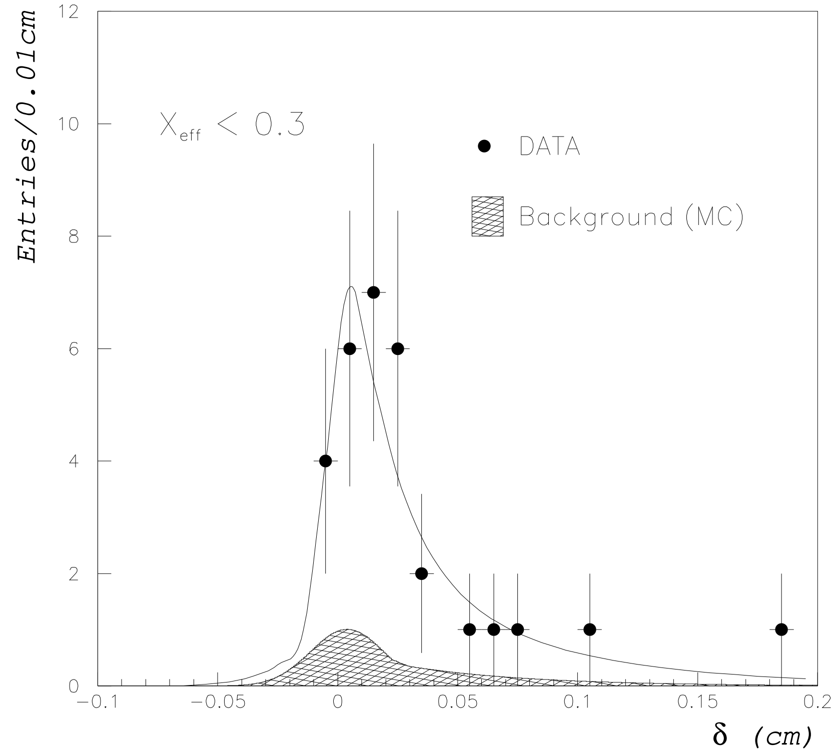
$$\hookrightarrow \Lambda\pi^-$$

$$\hookrightarrow p\pi^-$$

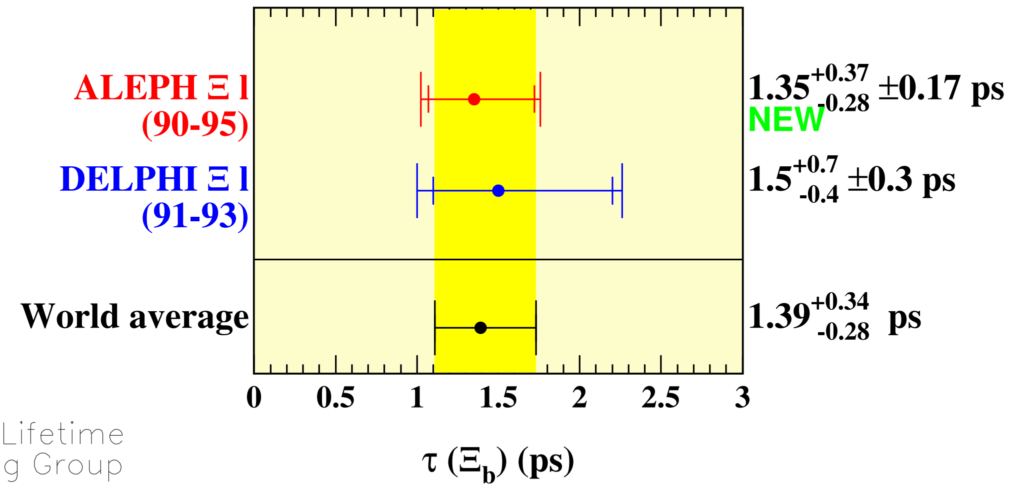
DELPHI have 10 candidates (91-93), and ALEPH have 44 (91-95 prel.)



ALEPH uses the lepton impact parameter to extract the lifetime…

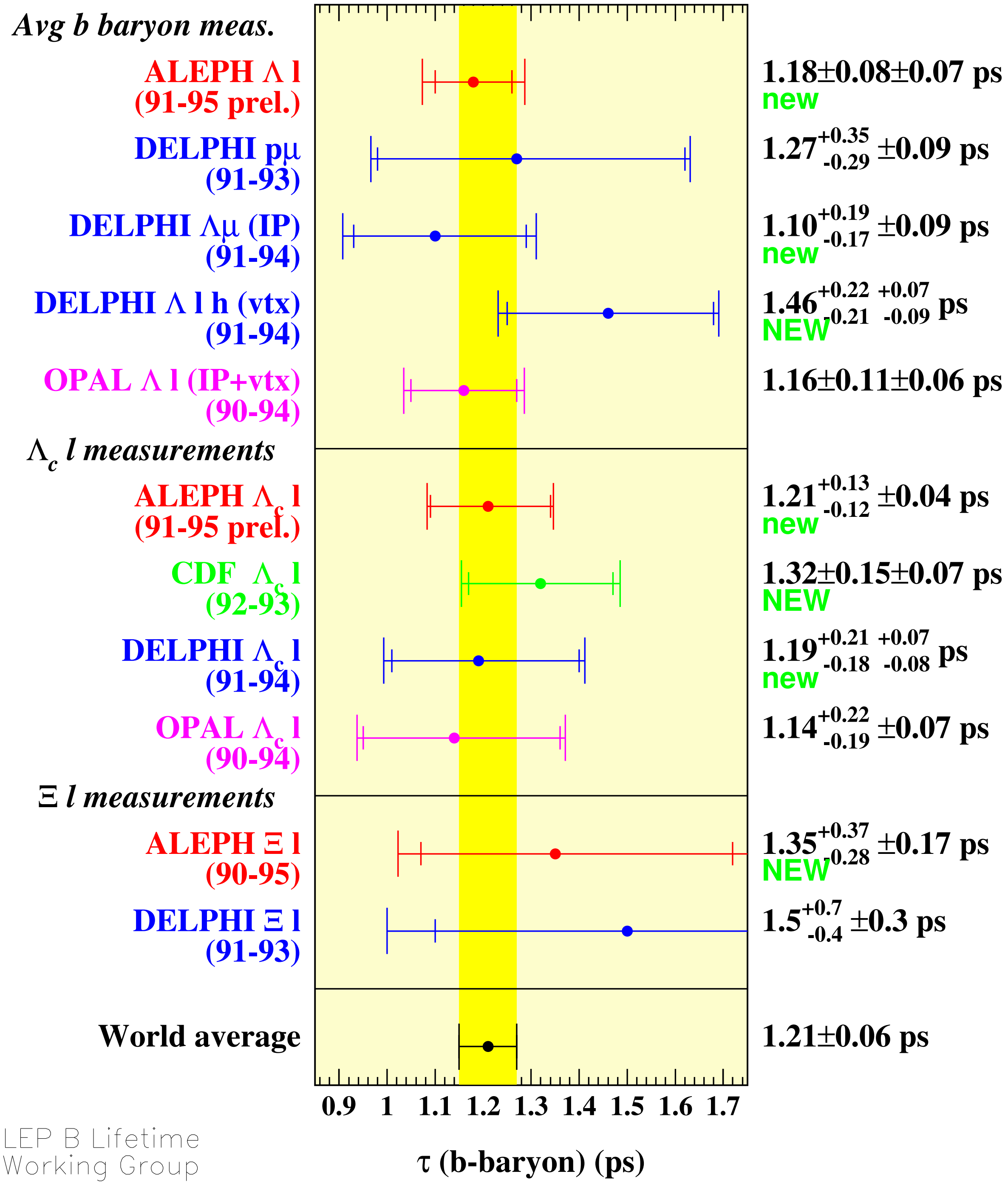


World Average (Ξ_b) lifetime



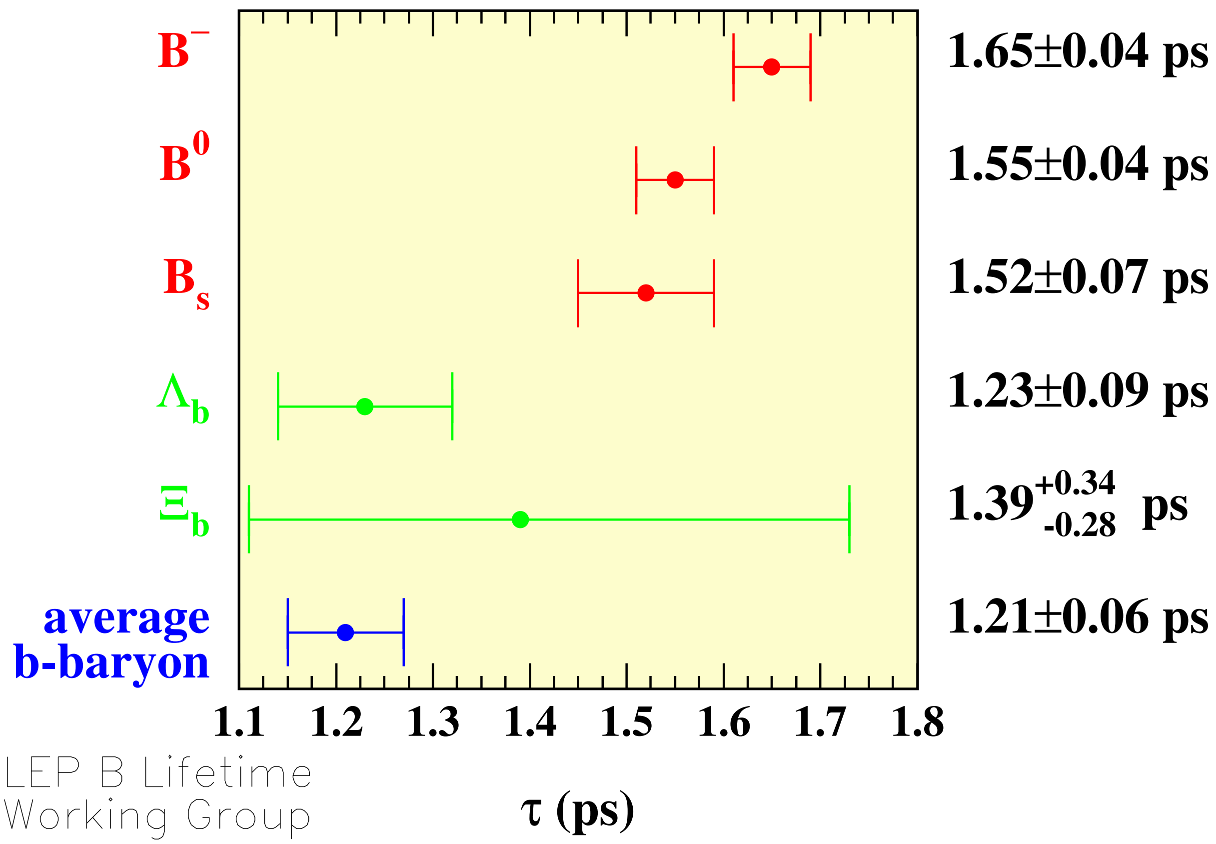
τ_{Ξ_b} is consistent with both Λ_b and B meson lifetimes …

World Average - B-baryon lifetimes



- No evidence for difference between average b-baryon and Λ_b^0.

World Averages Summary



- $\tau_{B^-}/\tau_{B^0} = 1.04 \pm 0.04 \iff$ theory: $1 + \mathcal{O}(10\%)$ ...?

  Ratio is > 1 at 1σ, can start to place constraints on the coefficients in the heavy quark expansion.

- $\tau_{B_s}/\tau_{B^0} = 0.98 \pm 0.05 \iff$ theory: $1 + \mathcal{O}(1\%)$

  Measurements are not precise enough to test the prediction.

- $\tau_{\Lambda_b}/\tau_{B^0} = 0.79 \pm 0.06 \iff$ theory: 0.9 to 0.99

  $\tau_{\text{b-baryon}}/\tau_{B^0} = 0.78 \pm 0.04$

  Ratio is interesting but not conclusive

Conclusions

- Large number of measurements of each B hadron lifetime
- Errors on averages

  $\sim 2.5\%$ for B^0 and B^-,

  $\sim 5\%$ for B_s and average b baryon, and

  $\sim 7\%$ for Λ_b^0
- Most (not all) of LEP, CDF and SLD data already analysed.

  SLD will be getting more data.

  CDF will have to wait for the Tevatron upgrade
- Wider use of new methods and more difficult decay channels should give further improvement.