Measurement of inclusive and exclusive b−hadron lifetimes at LEP

Seventh Topical Seminar on
The Legacy of LEP and SLC
Siena 2001

- Motivation and Theory
- Methods
- Analyses
- Status
- Conclusion and Outlook

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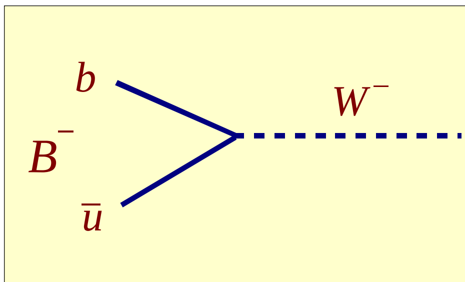
Motivation

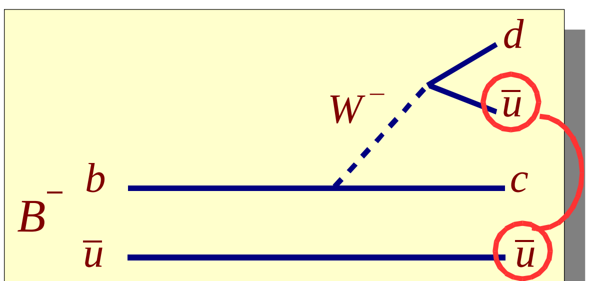
Why measure b−hadron lifetimes ?

- In the so−called ''Spectator−Model'' all b−hadrons have same lifetime
- For a more realistic model one has to consider nonspectator effects such as:

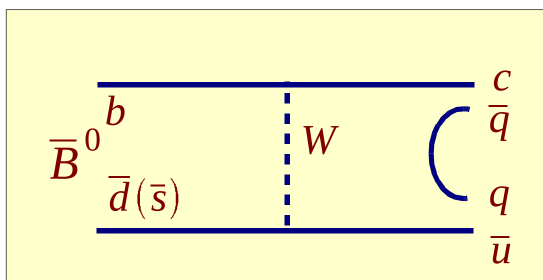
weak annihilation:



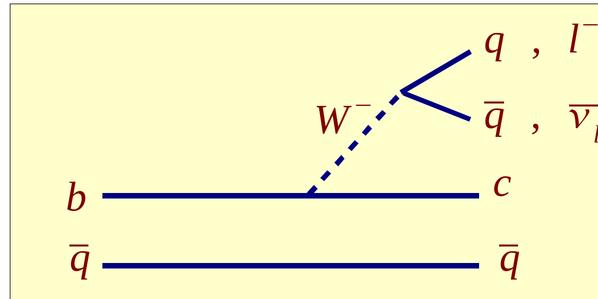
Pauli interference:

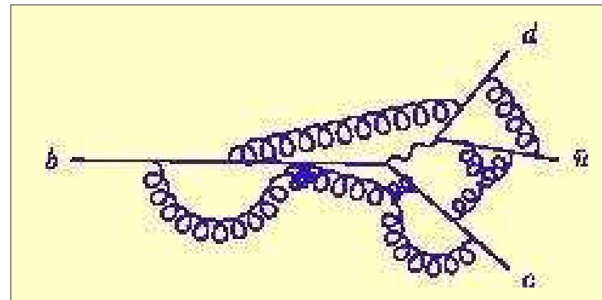


W exchange:



Spectator diagrams:
(with and without QCD−effects)





- Measurements of b hadron lifetimes represent an important test of those nonspectator models
- heavy quark expansion formalism predicts difference between lifetime of b− baryons and mesons to depend on $1/m_b^2$
- meson−meson differences depend on $1/m_b^3$
- the predicted lifetime hierarchy is

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

- b−lifetimes and their ratios allow tests of QCD and B−decay dynamics
- b−lifetimes are used for $|V_{cb}|$ analyses (dominant B−decay width is b−c−transitions) and as input for time−dependent B−decay analyses (oscillations, mixing, CP−asym.)

Methods

- Reconstruction of b−vertex ⇒ decay−length l
- Momenta of associated tracks ⇒ momentum P of b−hadron
- Decay−time t of b−hadron from:

$$t = \frac{m_b l}{pc}$$

exclusive analysis:

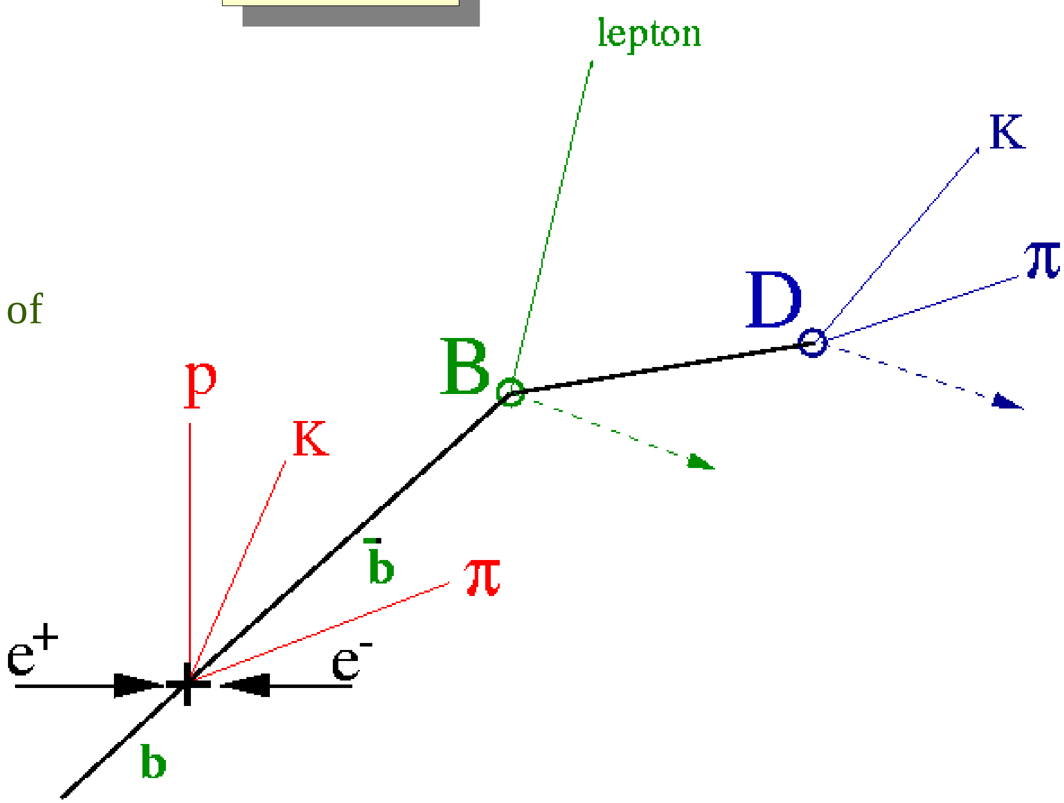
- full reconstruction of b−decay by selecting specific decay channels (statistics limited but very pure samples)

semi−inclusive analysis:

- reconstruction of b−vertex and selection of specific decay channels by exploiting charge correlations with decay−pions

inclusive analysis:

- topological reconstruction of b−vertex regardless of decay channel (error systematics dominated)



ALEPH

exclusive:

The lifetimes of $\bar{B}^0$ and B^- were measured by reconstructing semileptonic decays where the lepton is associated with a D^{*+} or D^0 meson.

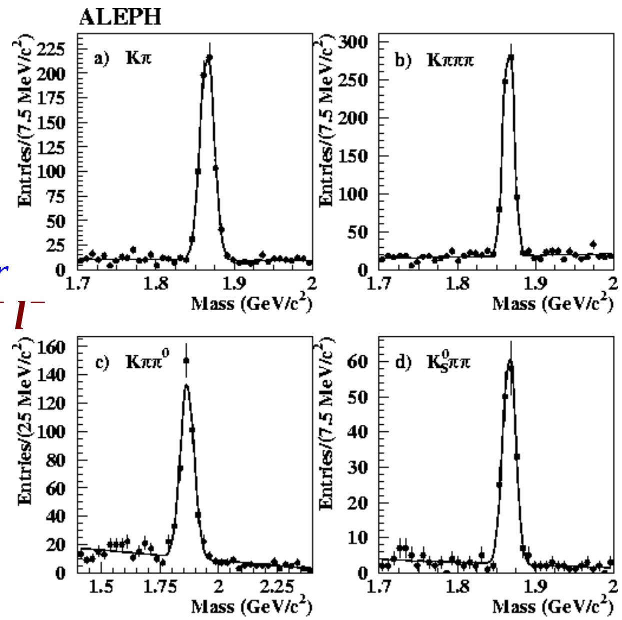
D^0's were identified by one of the following decay channels:

$$D^0 \to K^- \pi^+$$
$$D^0 \to K^- \pi^+ \pi^- \pi^+$$
$$D^0 \to K^- \pi^+ \pi^0$$
$$D^0 \to K^0_S \pi^+ \pi^-$$

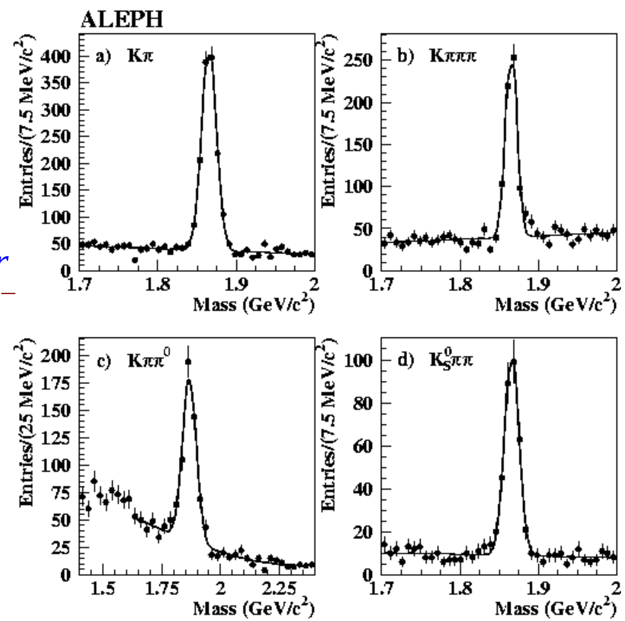
D^{*+} and D^0 were then distinguished by the existance or nonexistence of a slow pion around the nominal mass difference of *145.4 MeV*.

Events within 2σ of the fitted D^0 mass were selected for the B−vertex reonstruction resulting in 1880 $D^{*+} l^-$ and 2856 $D^0 l^-$ candidates with $\bar{B}^0 (B^-)$ purities of *85%(80%)*.

invariant mass of D^0 candidate for the four subsamples in the $D^{*+} l^-$ event selection



invariant mass of D^0 candidate for the four subsamples in the $D^0 l^-$ event selection



Lifetime−fit

For the measurement an unbinned likelihood fit was performed using the following likelihood function:

$$L = \prod_{i=1}^{N_{D^* l}} \left[f^*_-(\tau_{B^-}/\tau_{\bar{B}^0}) F(t_{i,} \sigma_{i,} \tau_{B^-}) + f^*_0(\tau_{B^-}/\tau_{\bar{B}^0}) F(t_{i,} \sigma_{i,} \tau_{\bar{B}^0}) + f^*_{bkg} F^*_{bkg}(t_i) \right]$$

$$\times \prod_{i=1}^{N_{D^0 l}} \left[f^0_-(\tau_{B^-}/\tau_{\bar{B}^0}) F(t_{i,} \sigma_{i,} \tau_{B^-}) + f^0_0(\tau_{B^-}/\tau_{\bar{B}^0}) F(t_{i,} \sigma_{i,} \tau_{\bar{B}^0}) + f^0_{bkg} F^0_{bkg}(t_i) \right]$$

with:

f's fraction of the samples calculated from measured branching ratios

F's exponential distribution convoluted by resolution and energy correction function taking into account missing energy

F_{bkg}***'s*** proper time distributions of background determined from simulated events

Results

unbinned maximum likelihood fit has been applied to data from the years 1991 to 1995

Most relevant systematic error sources:

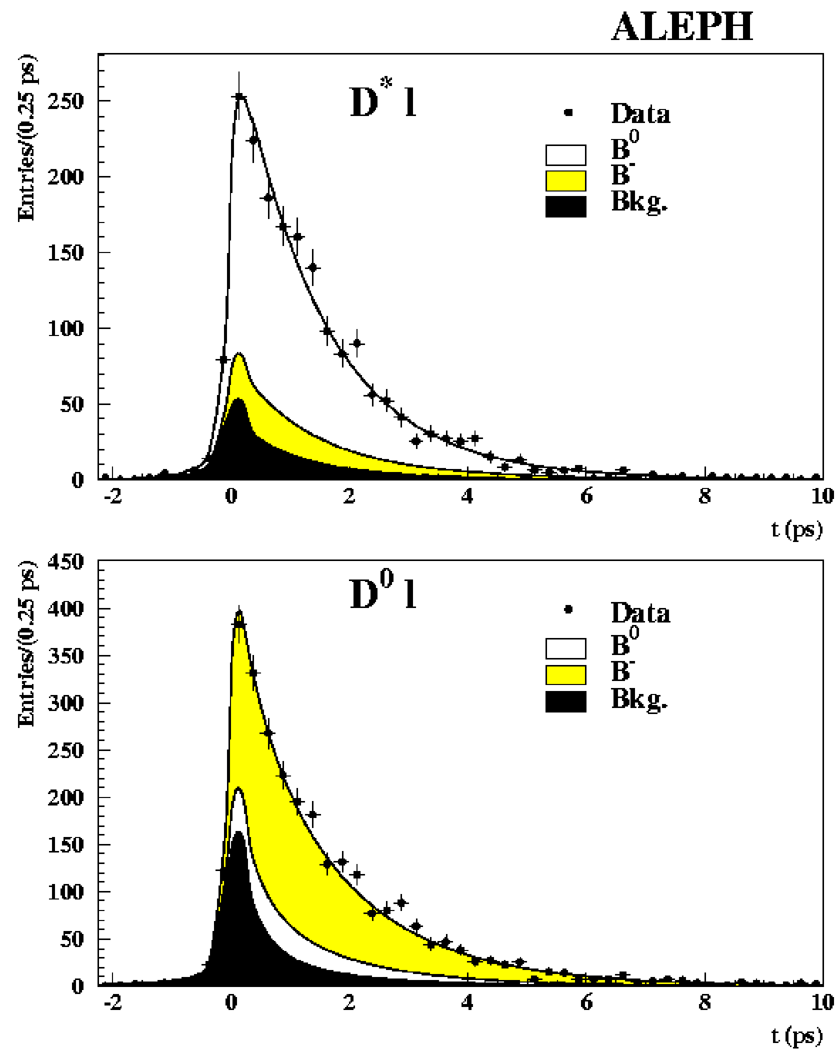
- B momentum reconstruction (missing neutrino)
- Background treatment ($BR(B \to D^{**} l \nu)$)
- decay length resolution

$$\tau_{B^+} = 1.648 \pm 0.049 (stat.) \pm 0.035 (syst.) \; ps$$

$$\tau_{B^0} = 1.518 \pm 0.053 (stat.) \pm 0.034 (syst.) \; ps$$

$$\frac{\tau_{B^+}}{\tau_{B^0}} = 1.085 \pm 0.059 (stat.) \pm 0.018 (syst.)$$

proper time distributions for the two samples with the fit overlaid



OPAL

Semi−inclusive:

Reconstruction of $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$

by combining high p and p_t lepton with oppositely charged pions from the $D^{*+} \to D^0 \pi^+$ decay with small transverse momentum (pion $p_t < 0.3\,GeV$)

Selection of pions relies on small mass difference of only *145 MeV*.

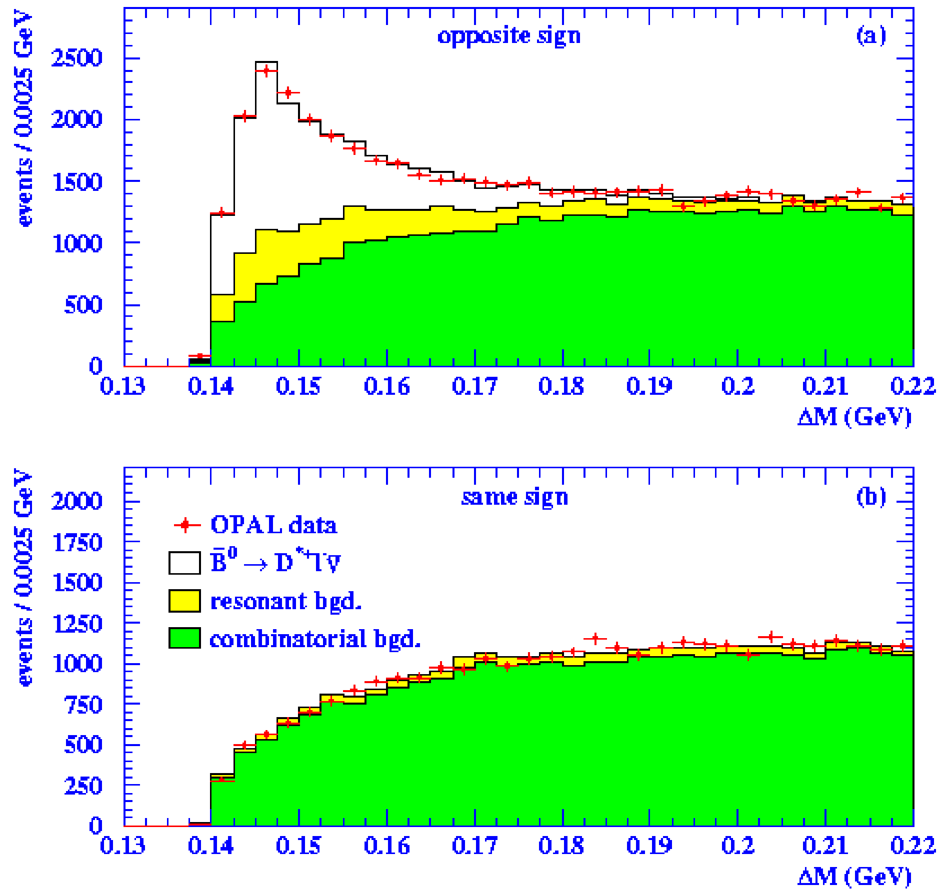
For final selection mass difference

$$\Delta M = \sqrt{E^2_{D^*} - |p_{D^*}|^2} - m_{D^0}$$

was calculated for same and opposite sign events.

D^0's were reconstructed inclusively.

ΔM for opposite and same sign lepton−pion combinations



Sample composition:

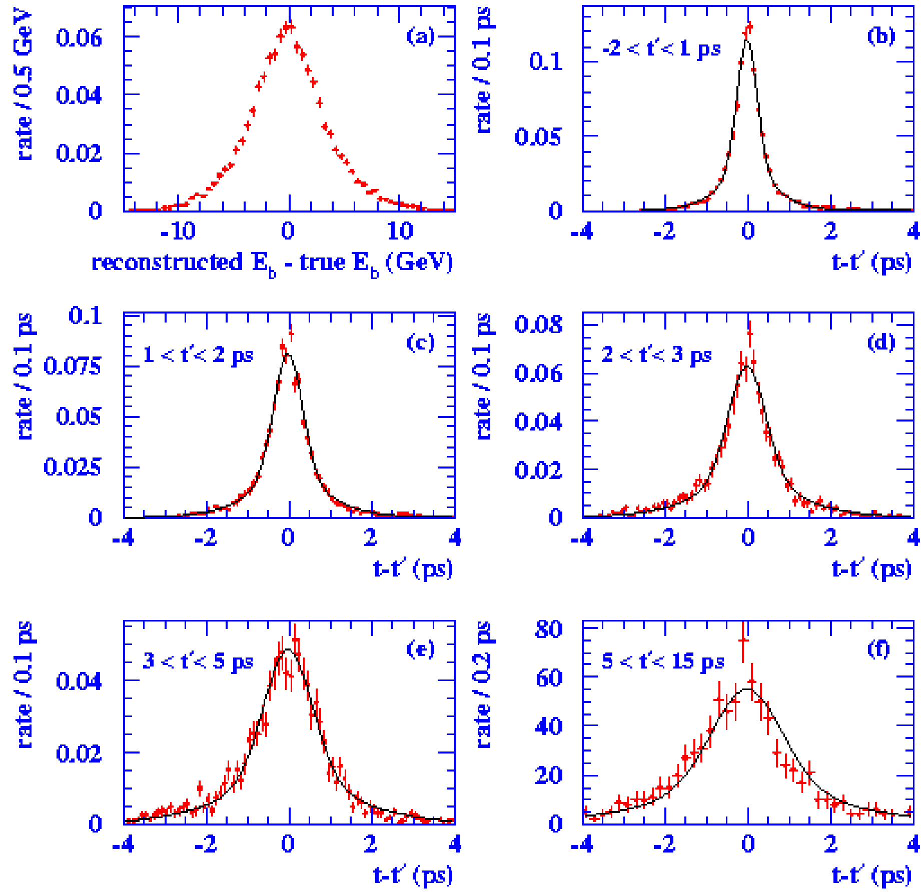
36% of opposite sign events with *ΔM<0.17 GeV* are signal

15% are resonant background consisting of $B^- \to D^{*+} \pi^- l^- \bar{\nu}$, $\bar{B}^0 \to D^{*+} \pi^0 l^- \bar{\nu}$ and $\bar{B}_s \to D^{*+} K^0 l^- \bar{\nu}$

49% combinatorial background, made up by events with fake slow pions , fake leptons or both

Resolutions and fit

reconstructed B−hadron energy resolution and time resolution in various ranges of true proper time t' for MC signal events



The four resolution functions (one for the signal and three for different background sources) were calculated.

τ_{B^0} has been extracted by maximising the following log−likelihood−function:

$$\ln L = \sum_{i=1}^{M^a} \ln L_i^a + \sum_{j=1}^{M^b} \ln L_j^b - N^a - N^b$$

were $\ln L_i^a$ and $\ln L_j^b$ are the individual event log−likelihoods taken over all the observed M^a opposite sign and M^b same sign events in the data sample.

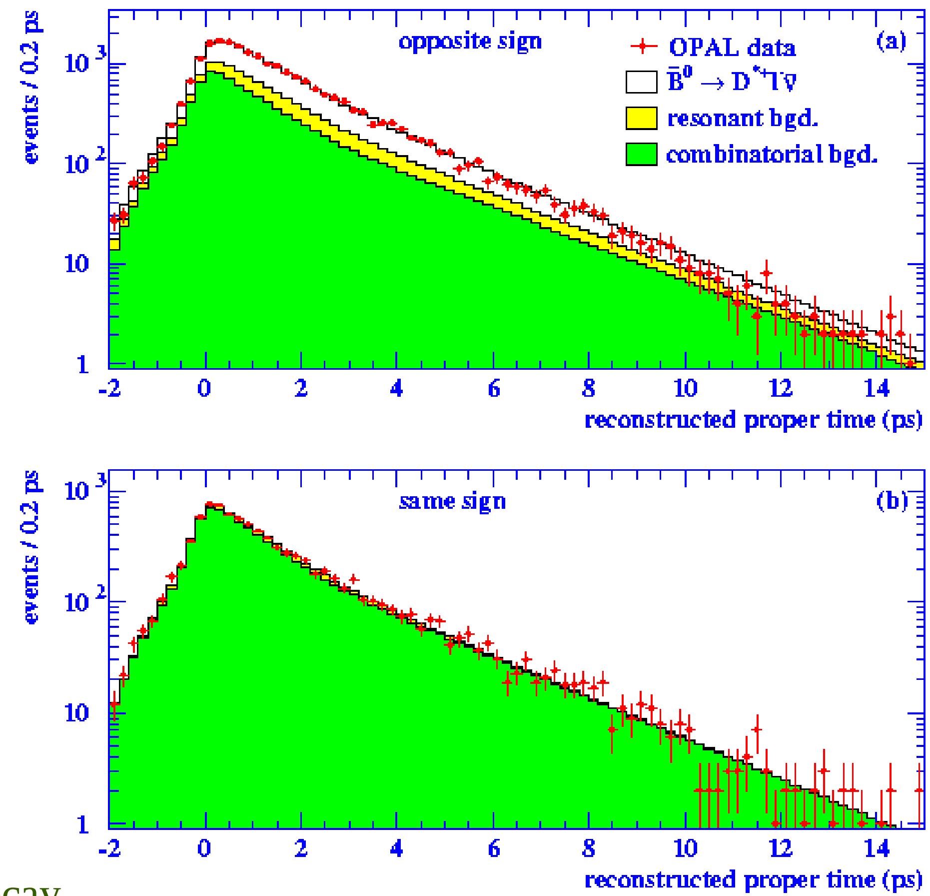
Result

Analysis was applied on data from the years 1991 to 1995

Most dominant systematic errors were:

- B^+ Lifetime
- $BR(b \rightarrow D^{*+} D_s^{(*)-})$
- Tracking resolution
- Details of the fitting method
- Other opposite sign background involving a genuine lepton and slow pion from D^{*+} decay

Fit result for opposite and same sign lepton−pion combinations with ΔM<0.17 GeV



$$\tau_{B^0} = 1.541 \pm 0.028(stat.) \pm 0.023(syst.)\ ps$$

DELPHI

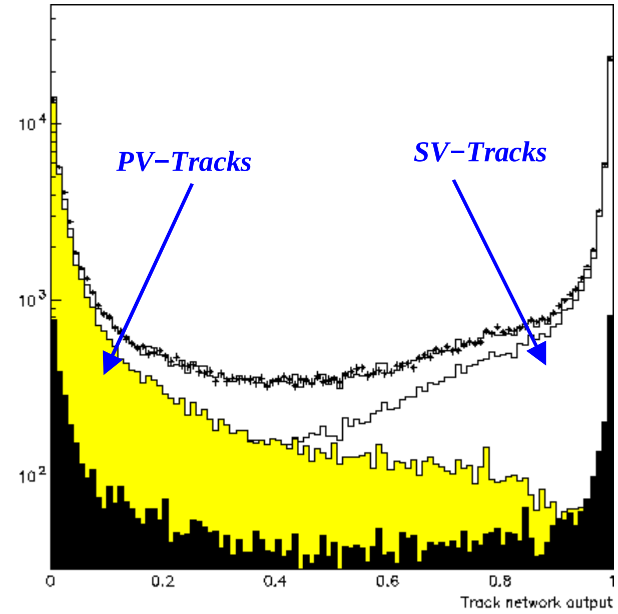
Inclusive Analysis (PRELIMINARY!):

Reconstruction using neural networks:

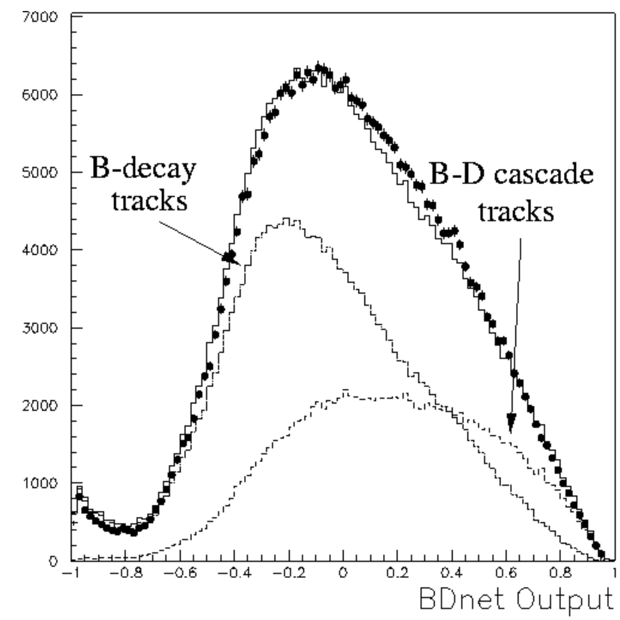
For track classification neural network techniques were used. Some important input variables were:

- ***Impact parameter−based probabilities that the track belonged to the primary (PV) or secondary (SV) vertex***
- ***Track rapidity***
- ***momentum of tracks in the b−rest frame***
- ***Particle identification information***

Separation of tracks from primary (PV) and secondary vertex (SV)



Separation of tracks from b−vertex and B−D cascade vertex

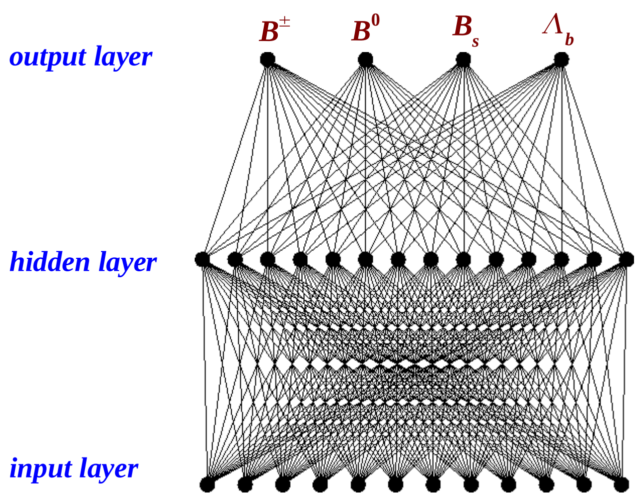


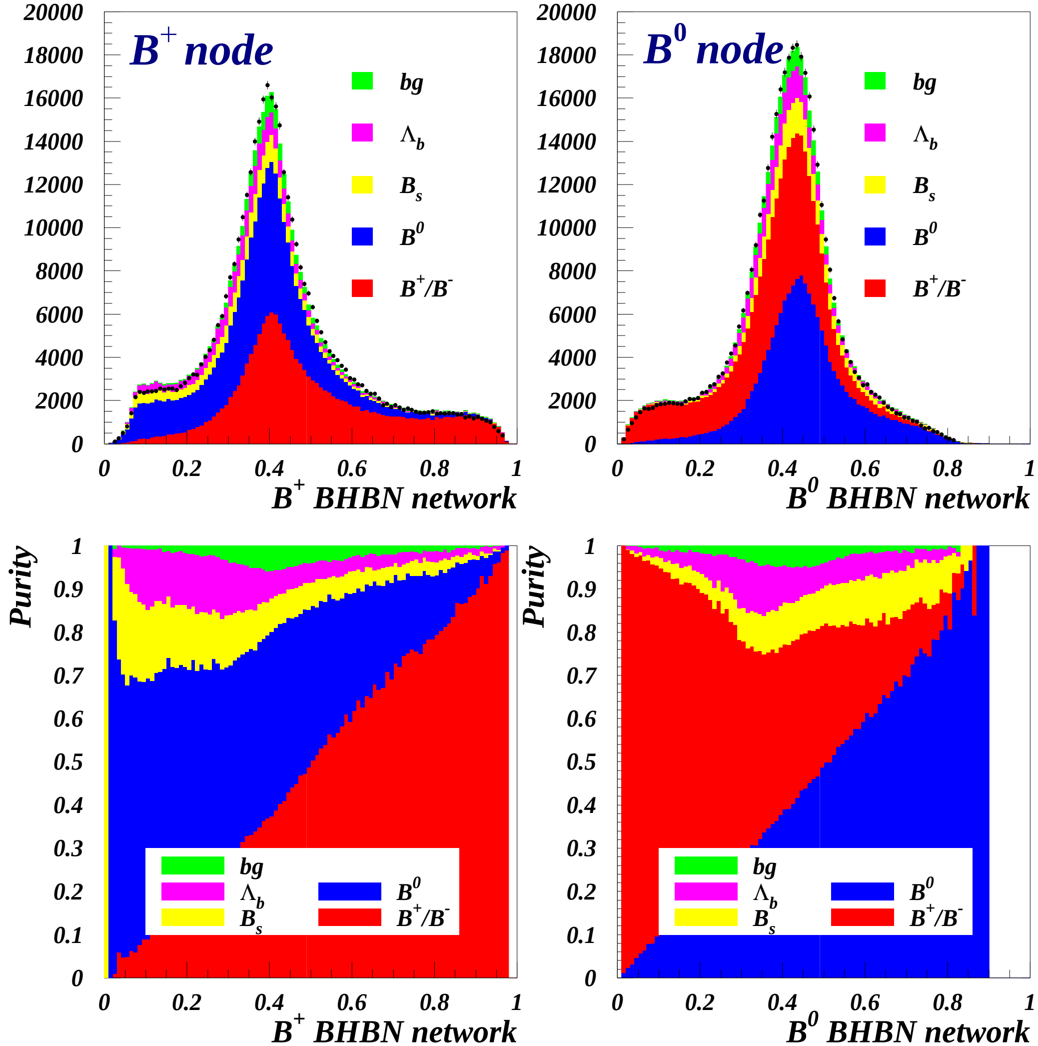
Separation and enhancement of B−Hadron−Species:

⇒ neural network

some input variables:

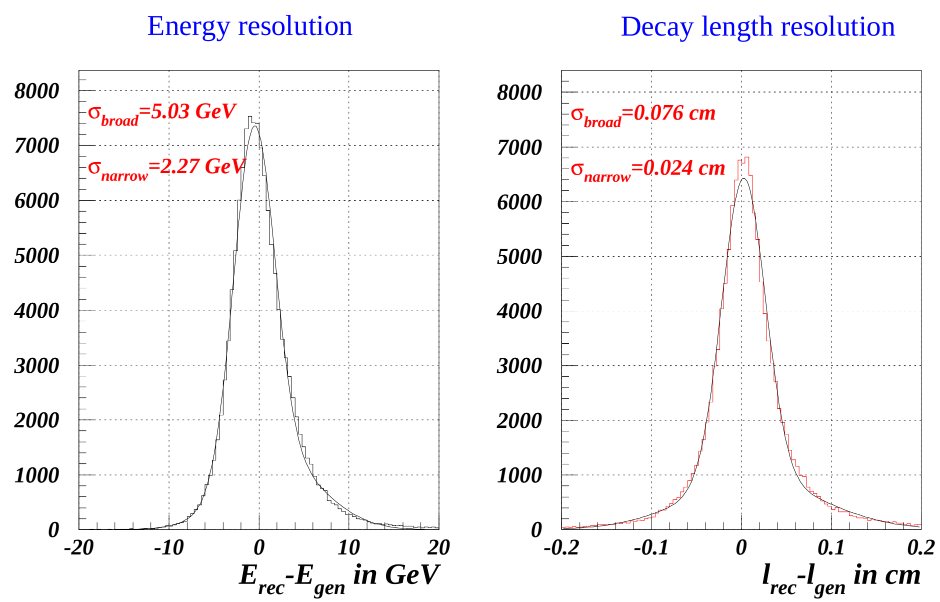
- ***Vertex charge***
- ***Error on vertex charge***
- ***Number of charged pions per hemisphere***
- ***Reconstructed energy of the hemisphere***
- ***Probability that identified kaon/pion stems from fragmentation or B−decay***
- ***Quality variables (e.g. hemisphere quality)***





Event selection:

- Enhancement in b−events attained by a cut on DELPHI impact parameter based b−tag
- $\cos(\vartheta_{thrust})<0.65$
- Cuts on B−species neural network for $B^+(B^0)$ enhancement
- For each event one of four different decay−length algorithms were chosen. Choice was dictated by optimising the resolution and minimising any bias while still retaining the best possible efficiency.



$\Rightarrow$ 2 data samples with 38988(11573) events in $B^+(B^0)$ sample respectively with good purity (~70%) and good resolution (~240 μm)

- same procedure for MC events
- <u>in addition:</u> reweighting of MC−events to compensate known discrepancies between data and MC (e.g. hemisphere quality)

Lifetime fit:

- Reweighting of MC lifetime distributions by:

$$w_i = \frac{\tau_{gen}}{\tau_{new}} \exp\left(t_i \frac{\tau_{gen} - \tau_{new}}{\tau_{gen}\tau_{new}}\right)$$

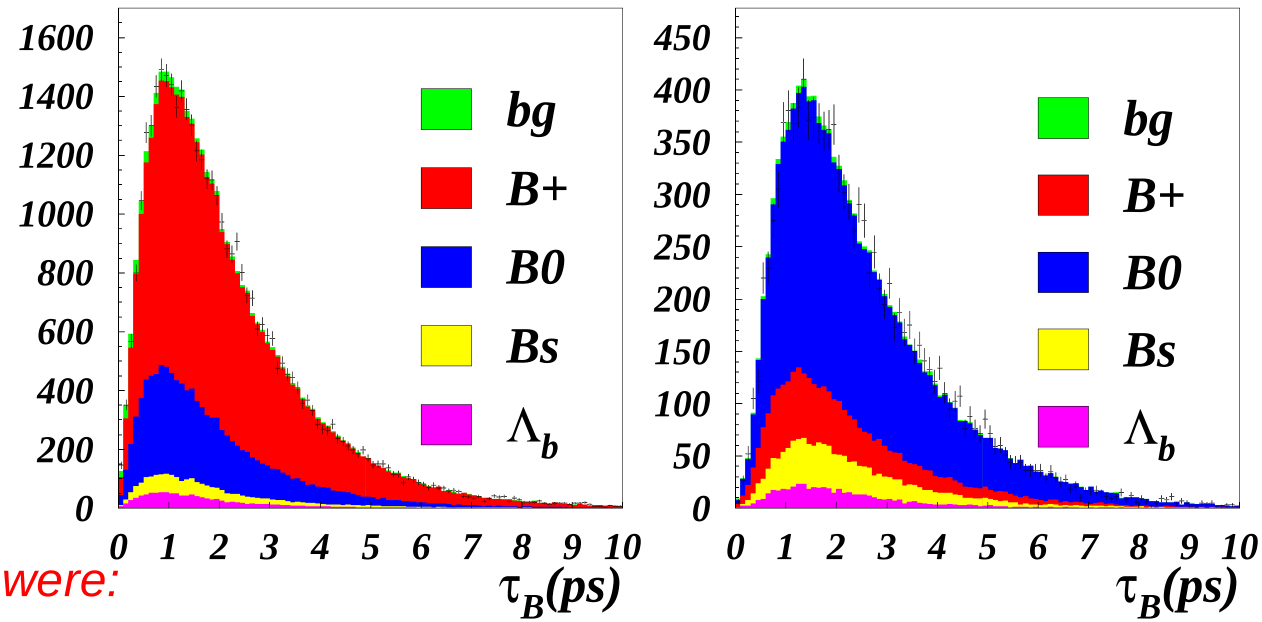
- Minimisation of the following χ^2 function:

$$\chi^2 = \sum_{B^{\pm},B^0} \left[\sum_{i=1}^{n_{bins}} \frac{\left(W_i^{MC} - N_i^{DATA}\right)^2}{\left(\sigma_i^{MC}\right)^2 + \left(\sigma_i^{DATA}\right)^2}\right]$$

Results

Analysis was applied on data from 1994 and 1995 separately and the result combined afterwards

Fit result from 1994 sample



most significant systematics were:

- Physics modelling:
  - $\Rightarrow BR(B_s \to D_s X)$ and B_s lifetime (only for B^0)
  - $\Rightarrow BR(B \to \text{wrong} - \text{sign} \quad \text{charm})$
  - $\Rightarrow D$ topological BR's
- Cuts and details of b enhancement and b−hadron species net
- Resolution, hemisphere quality and acceptance

Result of B^+ and B^0 lifetime fit (combined):

$$\tau_{B^+} = 1.631 \pm 0.012(stat.) \pm 0.021(syst.) \; ps$$

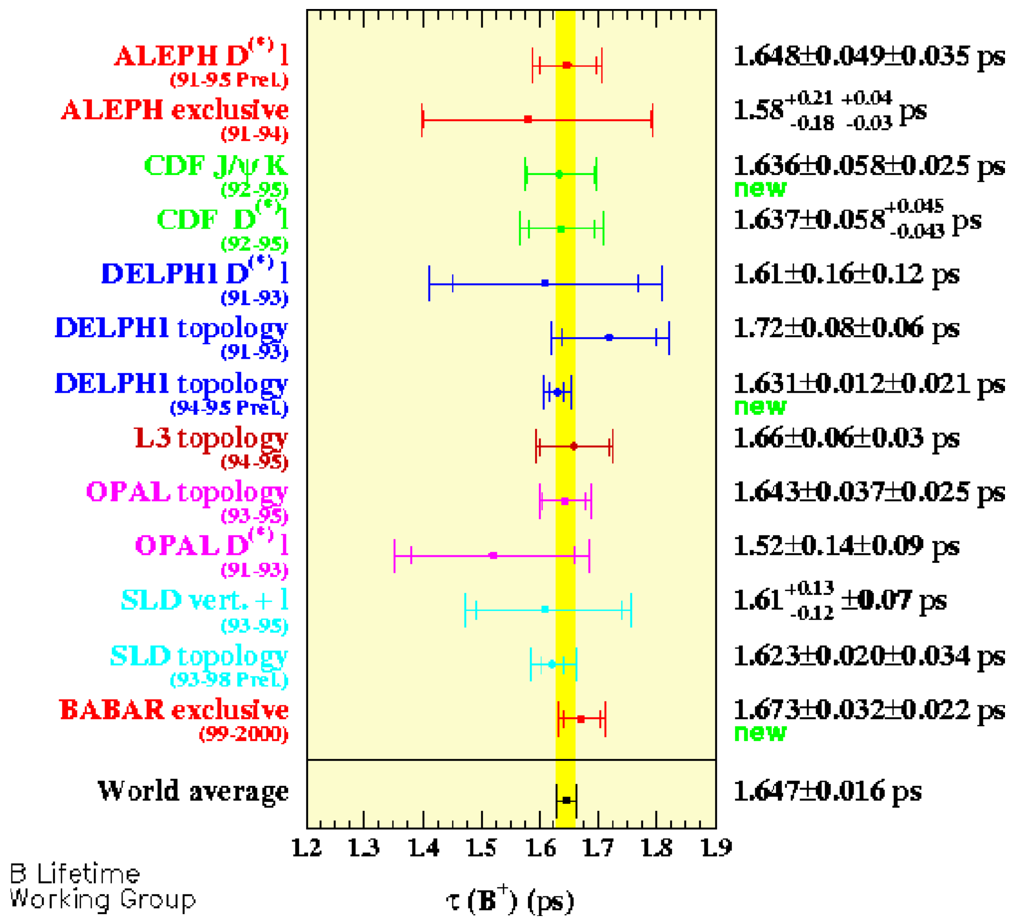
$$\tau_{B^0} = 1.546 \pm 0.018(stat.) \pm 0.035(syst.) \; ps$$

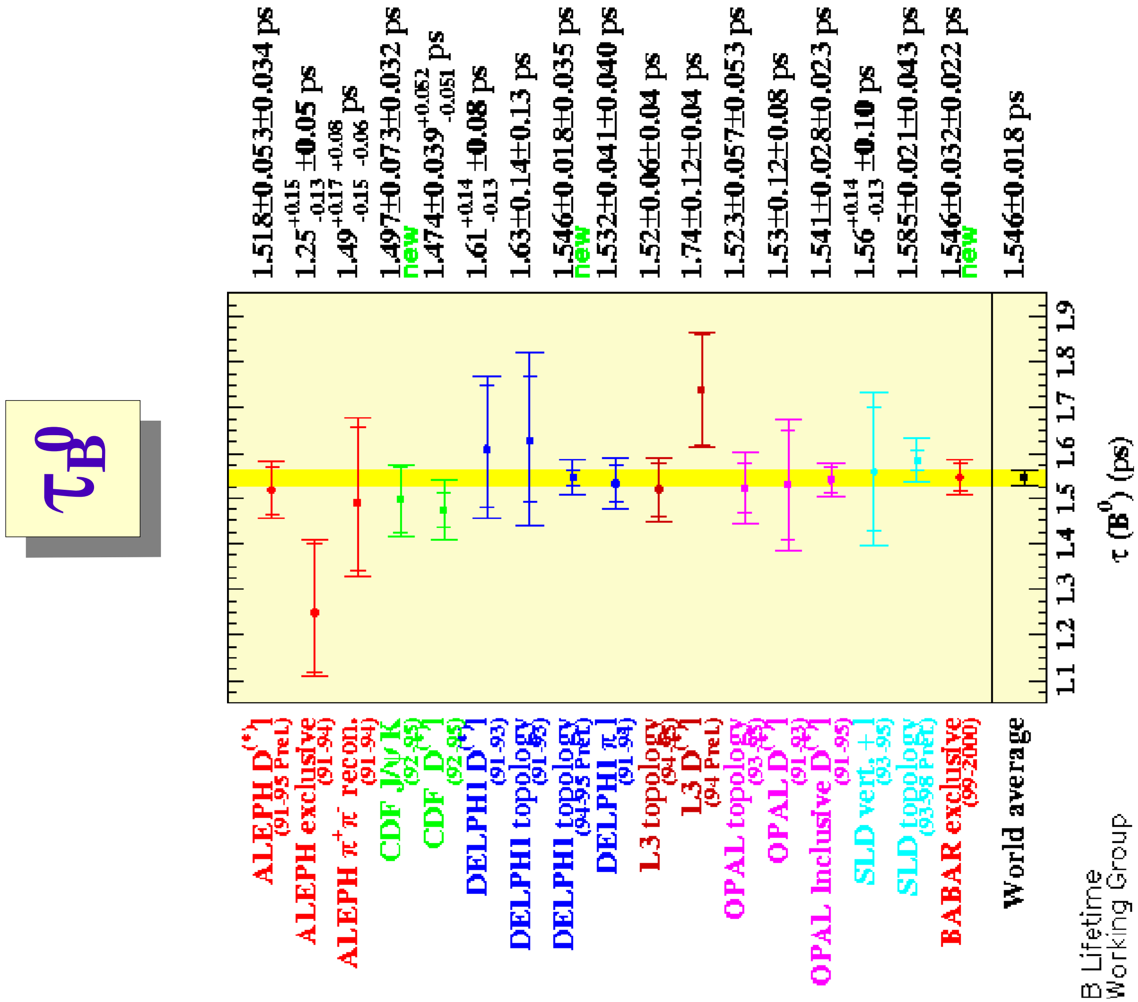
$$\frac{\tau_{B^+}}{\tau_{B^0}} = 1.054 \pm 0.017(stat.) \pm 0.027(syst.)$$

Status

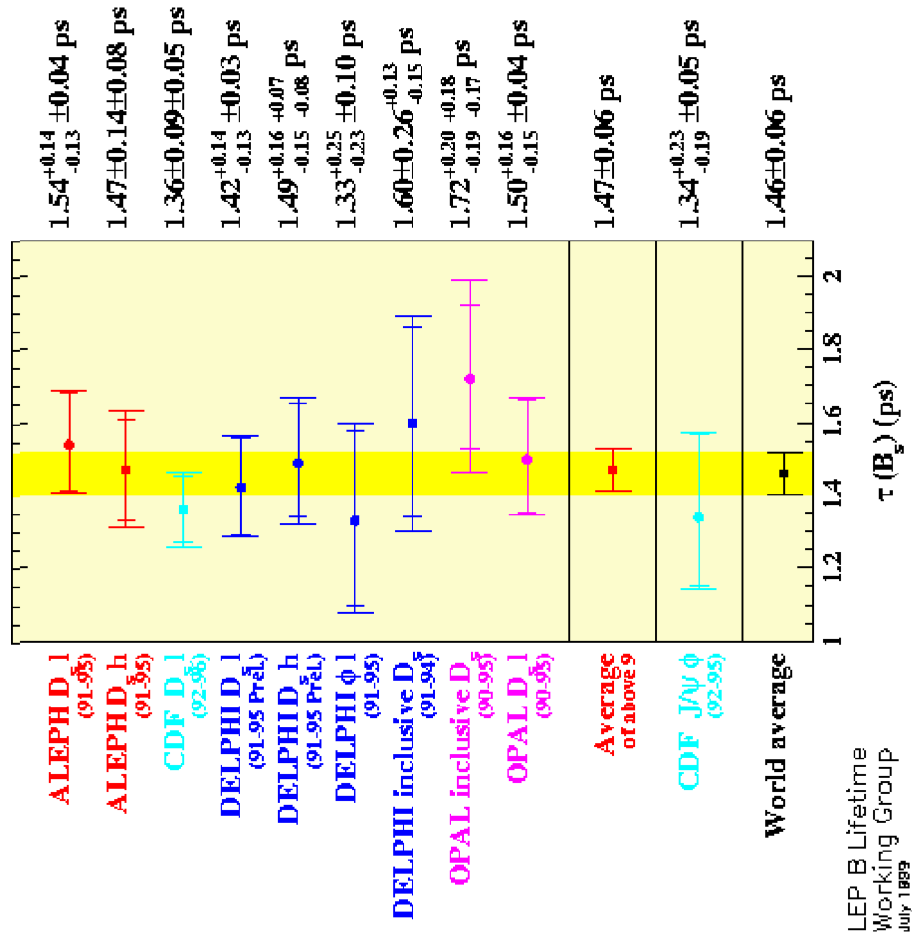
World average b lifetimes from LEP working group

τ_{B^+}

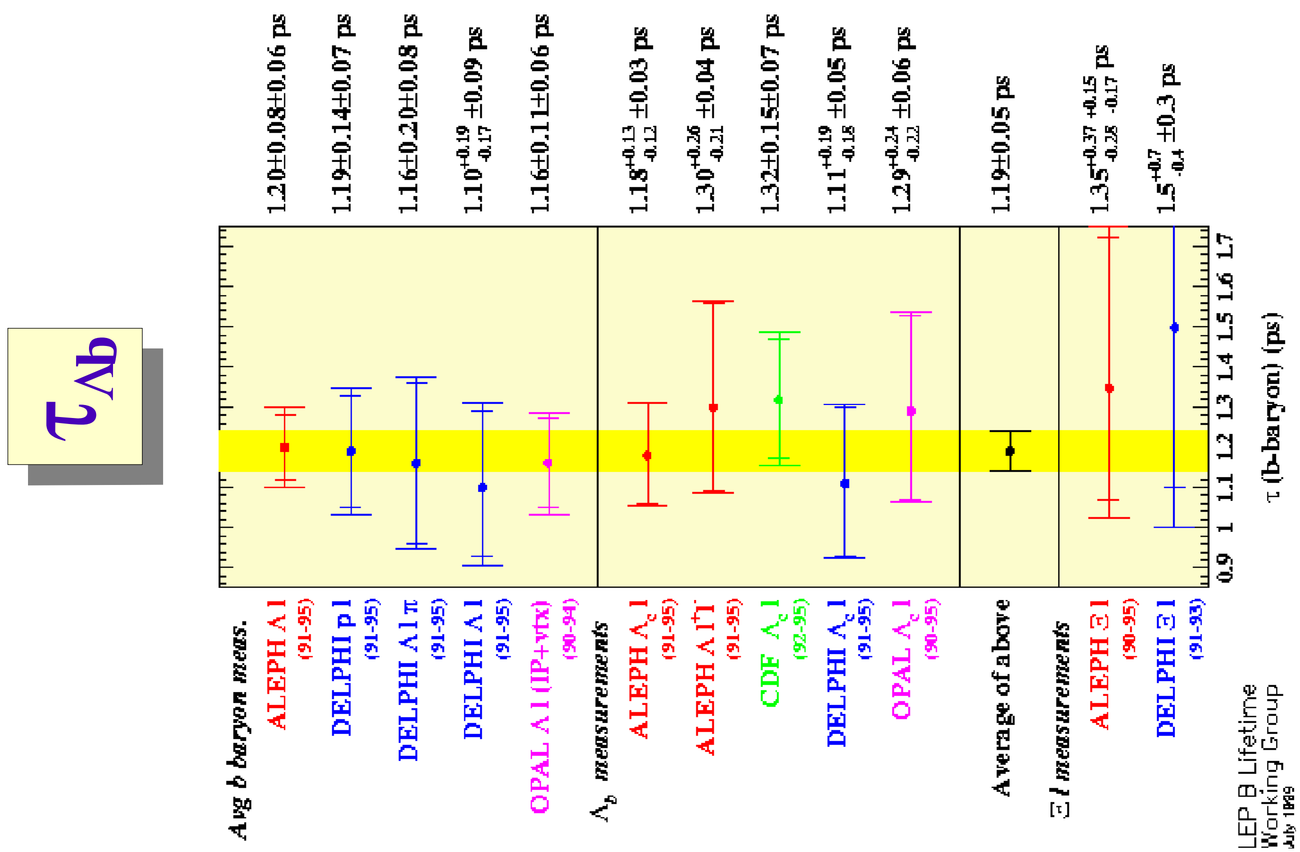



τ_{B^0}
ALEPH D(*) l (91-95 Prel.) 1.518±0.053±0.034 ps
ALEPH exclusive (91-94) 1.25 +0.15 -0.13 ±0.05 ps
ALEPH π+π- recon. (91-94) 1.49 +0.17 -0.15 +0.08 -0.06 ps
CDF J/ψ K (92-95) 1.497±0.073±0.032 ps new
CDF D(*) l (92-95) 1.474±0.039 +0.052 -0.051 ps
DELPHI D(*) l (91-93) 1.61 +0.14 -0.13 ±0.08 ps
DELPHI topology (91-93) 1.63±0.14±0.13 ps
DELPHI topology (94-95 Prel.) 1.546±0.018±0.035 ps new
DELPHI π+ l (91-94) 1.532±0.041±0.040 ps
L3 topology (94-95) 1.52±0.06±0.04 ps
L3 D(*) l (94 Prel.) 1.74±0.12±0.04 ps
OPAL topology (93-95) 1.523±0.057±0.053 ps
OPAL D(*) l (91-93) 1.53±0.12±0.08 ps
OPAL Inclusive D(*) l (91-95) 1.541±0.028±0.023 ps
SLD vert. + l (93-95) 1.56 +0.14 -0.13 ±0.10 ps
SLD topology (93-98 Prel.) 1.585±0.021±0.043 ps
BABAR exclusive (99-2000) 1.546±0.032±0.022 ps new
World average 1.546±0.018 ps
1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9
τ (B0) (ps)
B Lifetime Working Group

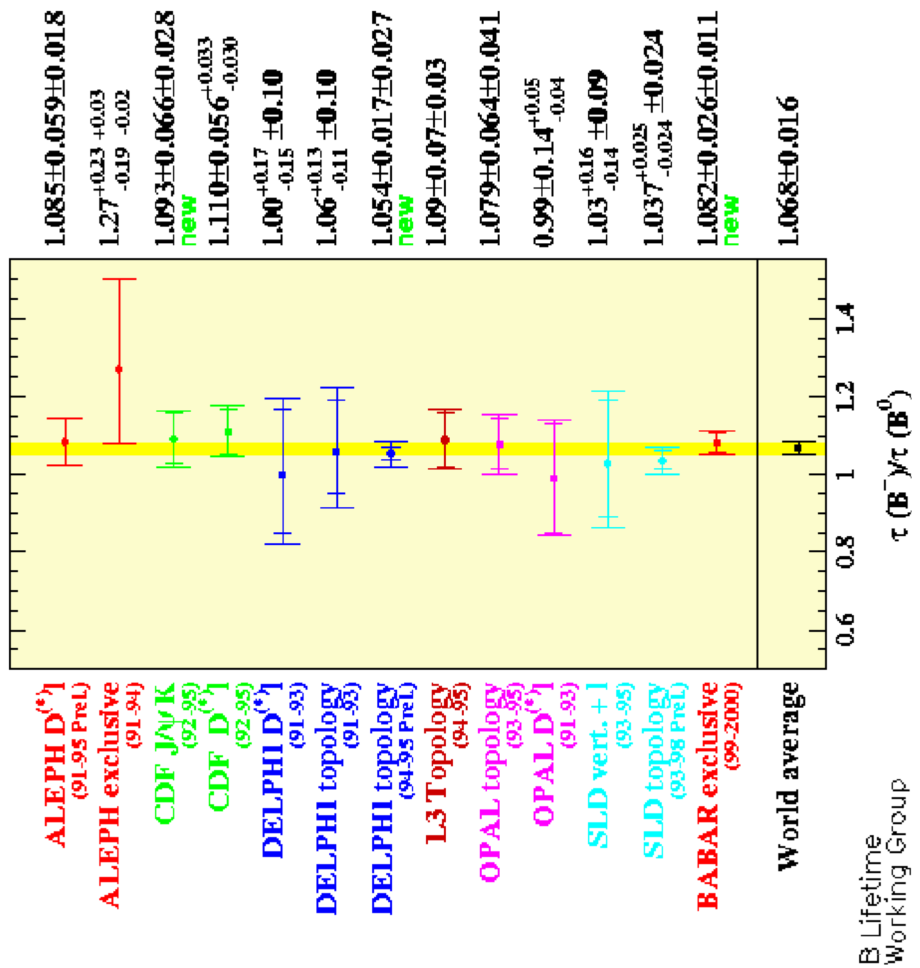
τ_{B_s}



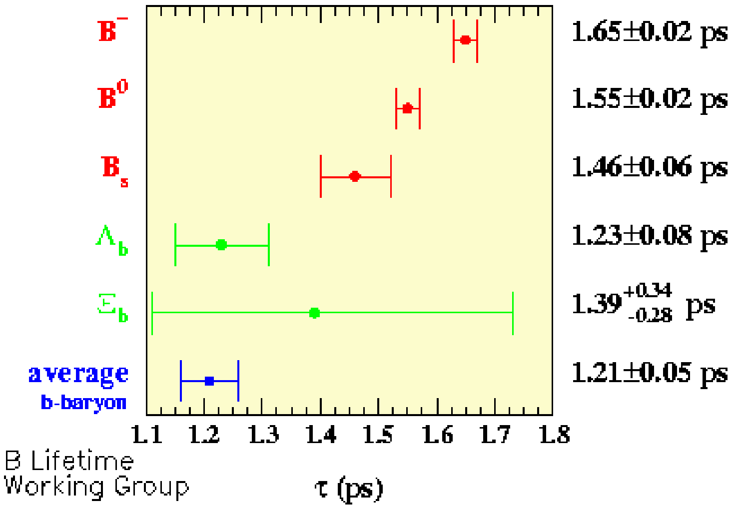
ALEPH D_s l (91-95)
ALEPH D_s h (91-95)
CDF D_s l (92-96)
DELPHI D_s l (91-95 Prel.)
DELPHI D_s h (91-95 Prel.)
DELPHI φ l (91-95)
DELPHI inclusive D_s (91-94)
OPAL inclusive D_s (90-95)
OPAL D_s l (90-95)
Average of above 9
CDF J/ψ φ (92-95)
World average
$1.54^{+0.14}_{-0.13} \pm 0.04$ ps
$1.47 \pm 0.14 \pm 0.08$ ps
$1.36 \pm 0.09 \pm 0.05$ ps
$1.42^{+0.14}_{-0.13} \pm 0.03$ ps
$1.49^{+0.16}_{-0.15}{}^{+0.07}_{-0.08}$ ps
$1.33^{+0.25}_{-0.23} \pm 0.10$ ps
$1.60 \pm 0.26^{+0.13}_{-0.15}$ ps
$1.72^{+0.20}_{-0.19}{}^{+0.18}_{-0.17}$ ps
$1.50^{+0.16}_{-0.15} \pm 0.04$ ps
1.47 ± 0.06 ps
$1.34^{+0.23}_{-0.19} \pm 0.05$ ps
1.46 ± 0.06 ps
1
1.2
1.4
1.6
1.8
2
$\tau(B_s)$ (ps)
LEP B Lifetime Working Group
July 1999


$\tau_{\Lambda b}$
Avg b baryon meas.
ALEPH Λ l (91-95) 1.20±0.08±0.06 ps
DELPHI p l (91-95) 1.19±0.14±0.07 ps
DELPHI Λ l π (91-95) 1.16±0.20±0.08 ps
DELPHI Λ l (91-95) $1.10^{+0.19}_{-0.17}$ ±0.09 ps
OPAL Λ l (IP+vtx) (90-94) 1.16±0.11±0.06 ps
Λ_b measurements
ALEPH Λ_c l (91-95) $1.18^{+0.13}_{-0.12}$ ±0.03 ps
ALEPH Λ l⁺l⁻ (91-95) $1.30^{+0.26}_{-0.21}$ ±0.04 ps
CDF Λ_c l (92-95) 1.32±0.15±0.07 ps
DELPHI Λ_c l (91-95) $1.11^{+0.19}_{-0.18}$ ±0.05 ps
OPAL Λ_c l (90-95) $1.29^{+0.24}_{-0.22}$ ±0.06 ps
Average of above 1.19±0.05 ps
Ξ l measurements
ALEPH Ξ l (90-95) $1.35^{+0.37}_{-0.28}$ $^{+0.15}_{-0.17}$ ps
DELPHI Ξ l (91-93) $1.5^{+0.7}_{-0.4}$ ±0.3 ps
0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7
τ (b-baryon) (ps)
LEP B Lifetime Working Group July 1999

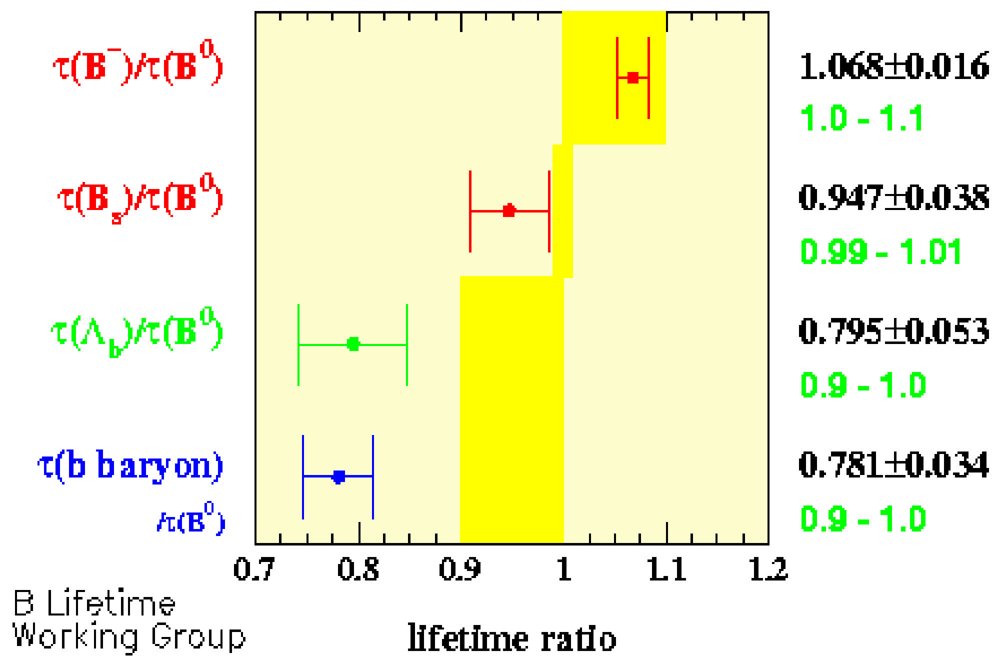
$$\frac{\tau_{B^+}}{\tau_{B^0}}$$



Conclusion and Outlook



measured lifetime ratios with theoretical predictions



- predicted B hadron lifetime hierarchy confirmed through all analyes
- $\tau_{B^+} > \tau_{B^0}$ established
- B−baryon lifetime measurement and theoretical prediction still different
- For τ_{B_s} situation still not totally clear

LEP measurements were more precise than planned due to:

- Si−vertex−detector
- Development of new techniques

Future:

- For the lifetimes of B^+ and B^0 mesons the b−factories BELLE and BABAR will soon deliver the most precise measurements.
- From Tevatron improved exclusive measurements of *b−baryons* and B_s meson lifetimes are expected
- For B_s and *b−baryons* LEP still has the chance to remain competitive with inclusive analyses