# Highlights of 10 years B Physics at LEP

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**Third International Conference on B Physics and CP Violation**

**3 - 7 December, 1999**
**Taipei, Taiwan**
**臺灣, 臺北**

# Outline

I Introduction

II Discovery or Confirmation of New Particles Containing b Quarks and their Properties

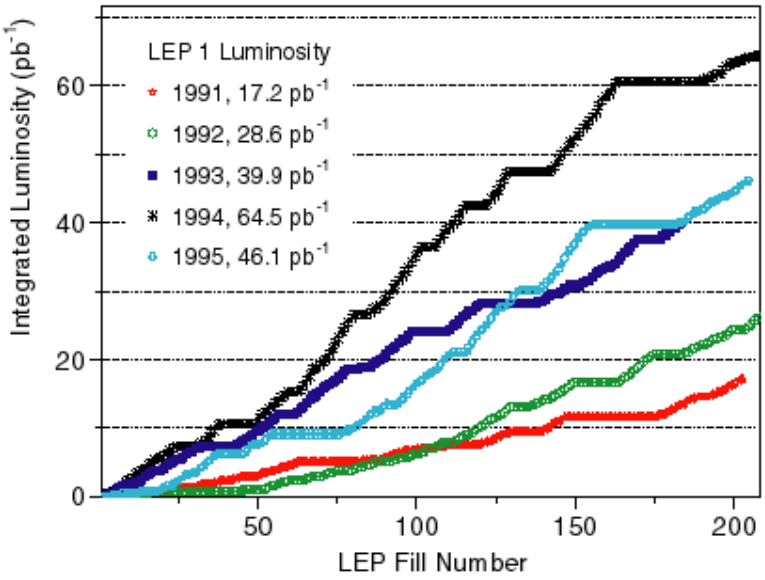
III Measurements Contributing to the CKM Matrix

IV Rare Decays and CP Studies.

*Thanks to : Roger Forty*
*Owen Hayes*

# Introduction

## LEP 1 Luminosity:




***Four experiments: ALEPH, DELPHI, L3, OPAL***

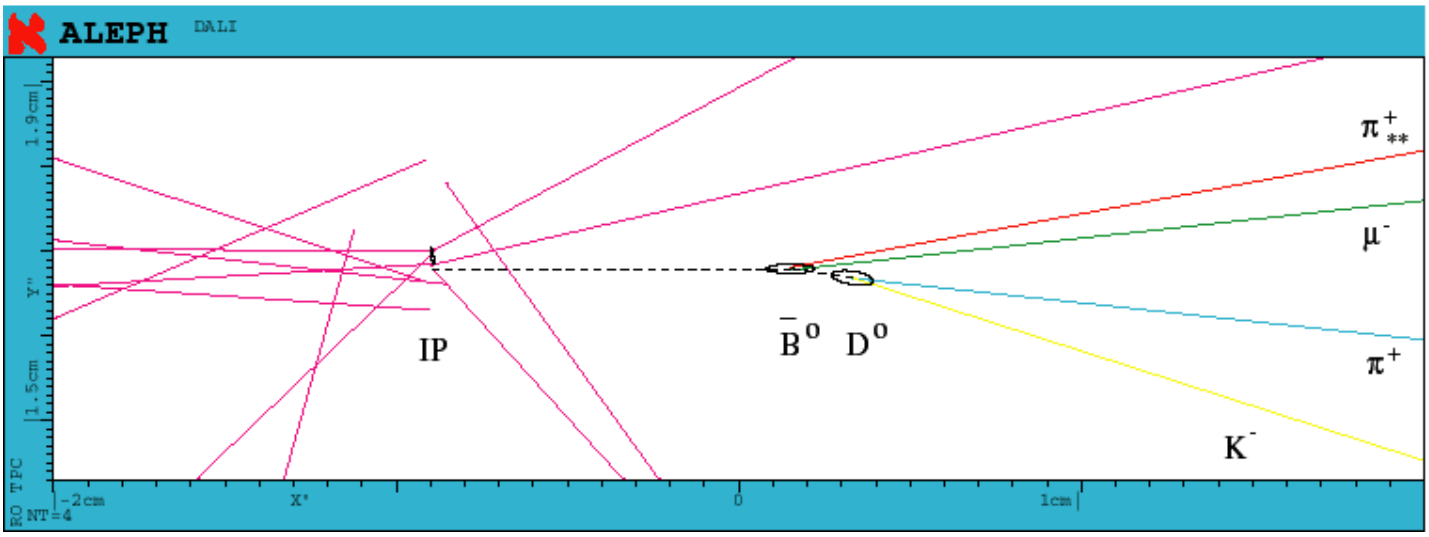
***~ 4 x $10^6$ $Z \rightarrow$ hadrons decays each***

***~ 880,000 $Z \rightarrow b\bar{b}$ decays each***

***Each experiment has precision Silicon Vertex Detector:***

***Point resolution 10-15 $\mu$m in $\Phi$ and Z***

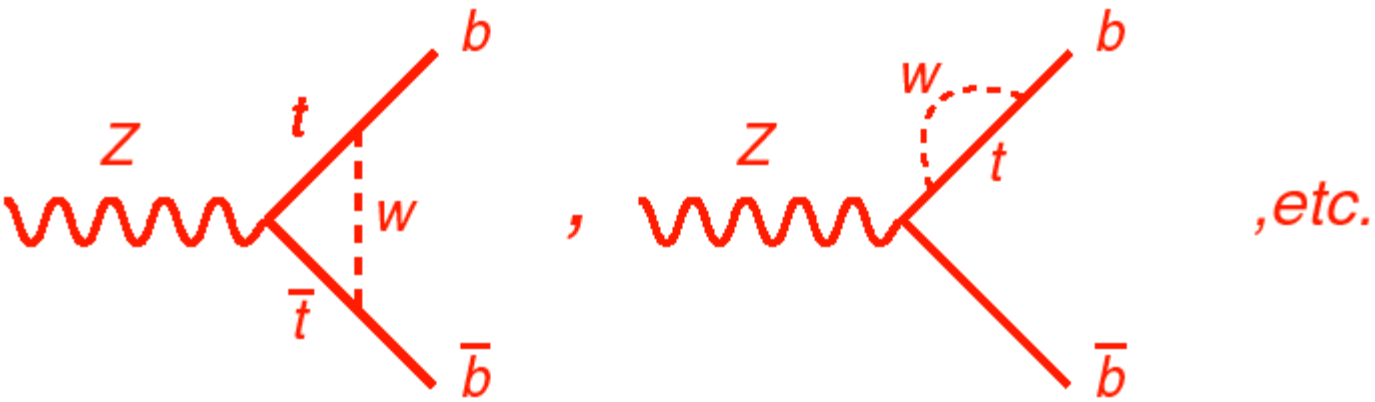
***Average b decay length = 2.5 mm:***



# $R_b$

$$R_b^0 \equiv \frac{\Gamma\left( Z \to b\bar{b} \right)}{\Gamma\left( Z \to hadrons \right)}$$

***Large radiative corrections (coupling to top):***




***sensitive to new physics :***

- $\tilde{t}, \tilde{\chi}^{\pm}$ *(susy)*
- *Z-Z' mixing*
- *b-b' or t-t' mixing*
- *exotic fermions or scalars*
- ⋮

# $R_b$ Controversy

*As of March 1996 (Moriond),*

*$R_b$ value $3\sigma$ different from SM prediction*

*Prompted development of hemisphere method:*

*$N_t$ = number of singly-tagged hemispheres*

*$N_{tt}$ = number of doubly-tagged hemispheres*

$$\epsilon_b \cong \frac{2N_{tt}}{N_t}$$

$$R_b \cong \frac{N_t^2}{4N_{tt}N_{hadrons}}$$

$\epsilon_b$ **measured in data**

*Coupled with lifetime, mass, and multivariate tags*

$\Rightarrow$ *Systematic errors better understood using these techniques.*

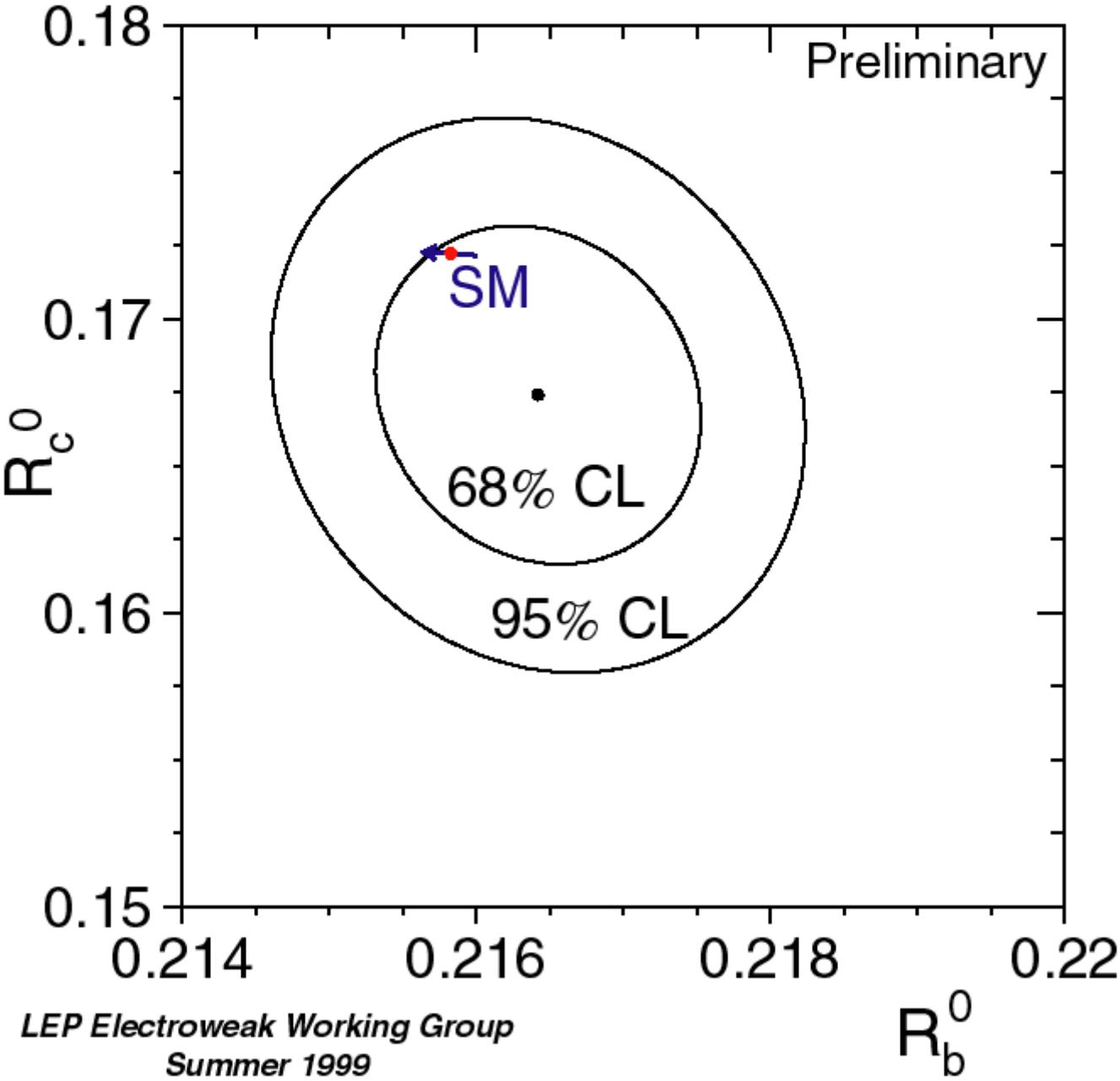
# $R_b$ Latest Results

**Combined LEP and SLD electroweak fit:**

$R_b = 0.21642 \pm 0.00073$

**SM Prediction ( $m_t = 173.8 \pm 5.2$ GeV)**

$R_b^{SM} = 0.21584 \pm 0.00018$



## Outline II

# Discovery or Confirmation of New Particles Containing b Quarks and their Properties

- Discovery of $\Lambda_b$
- Discovery of $B_s$
- $B^*, B^{**}$
- $B_c$

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- B hadron lifetimes

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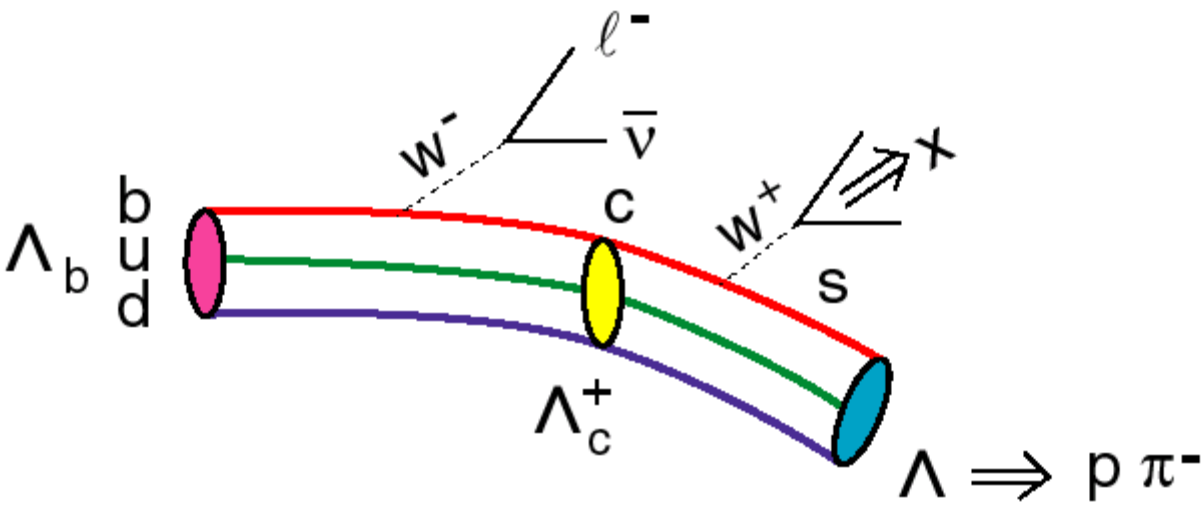
# Discovery of b - Baryons
# $\Lambda_b$ (bud)

***Consider semileptonic decay of $\Lambda_b$***

$$\Lambda_b \rightarrow \Lambda_c^+ \ell^- \bar{\nu} X$$
$$\hookrightarrow \Lambda X$$

$$BR(\Lambda_c \rightarrow \Lambda + ..) = (35 \pm 11)\% \quad PDG99$$



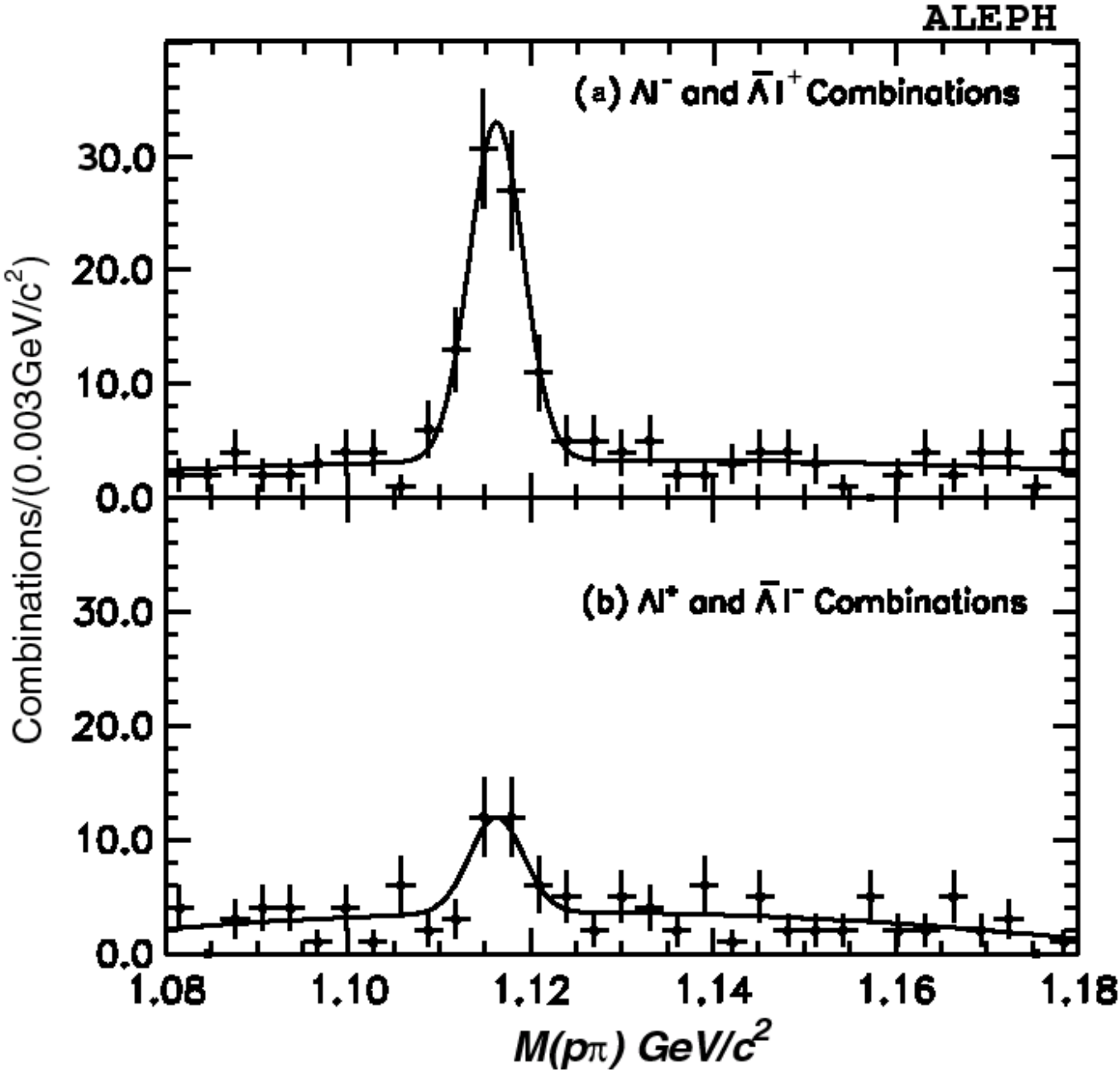

***Look for***

$\Lambda \ell^-$ (or $\bar{\Lambda} \ell^+$) **RIGHT SIGN COMBINATION**

$\Lambda \ell^+$ (or $\bar{\Lambda} \ell^-$) **WRONG SIGN COMBINATION**

# First Evidence: $\Lambda_b$

***In 1991, ALEPH presented:*** [PL **B 278** (1992)209]




***73±11 Right Sign***

***20±7 Wrong Sign - (1.5±2) background***

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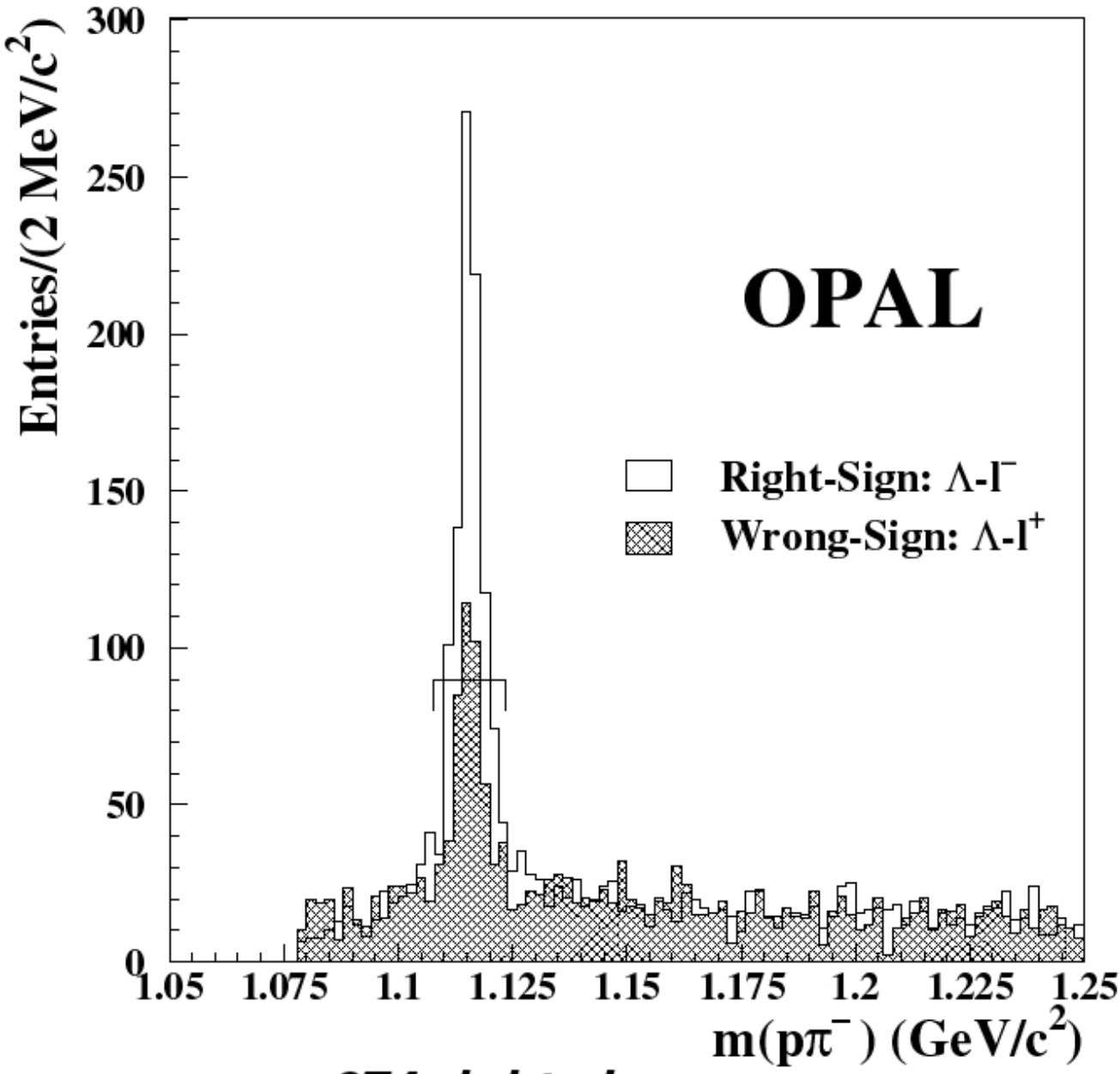
***(54.5±13.0 stat ± 8.2 syst) events due to $\Lambda_b$ signal***

## Current: $\Lambda_b$

[OPAL, ZP **C69** (1996) 195]




874 right sign
- 384 wrong sign

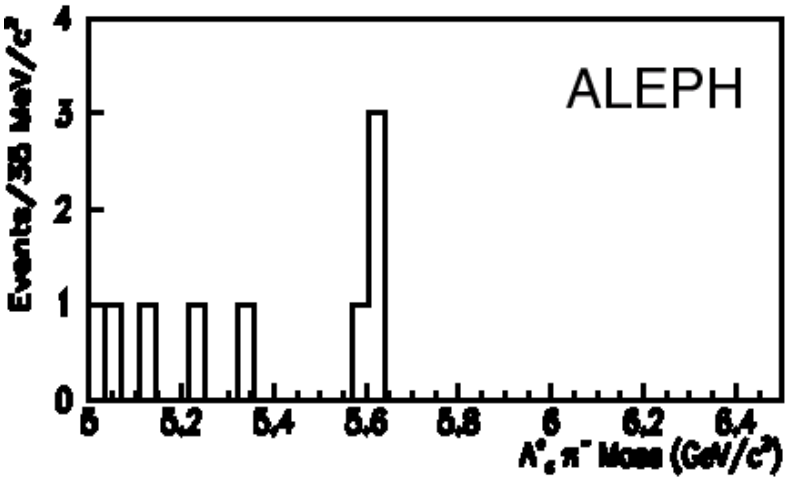
490 events due to $\Lambda_b$ signal

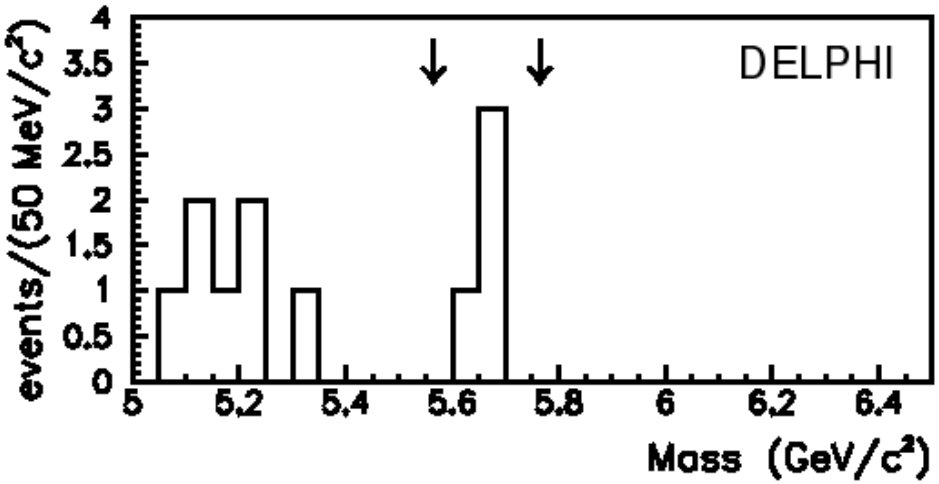
**LEP Average Production Rate:**

$$f(b \to \Lambda_b) \times Br(\Lambda_b \to \Lambda \ell^- \bar{\nu} X) = (3.04 \pm 0.25) \times 10^{-3}$$

(Owen Hayes)

# $\Lambda_b$ Mass

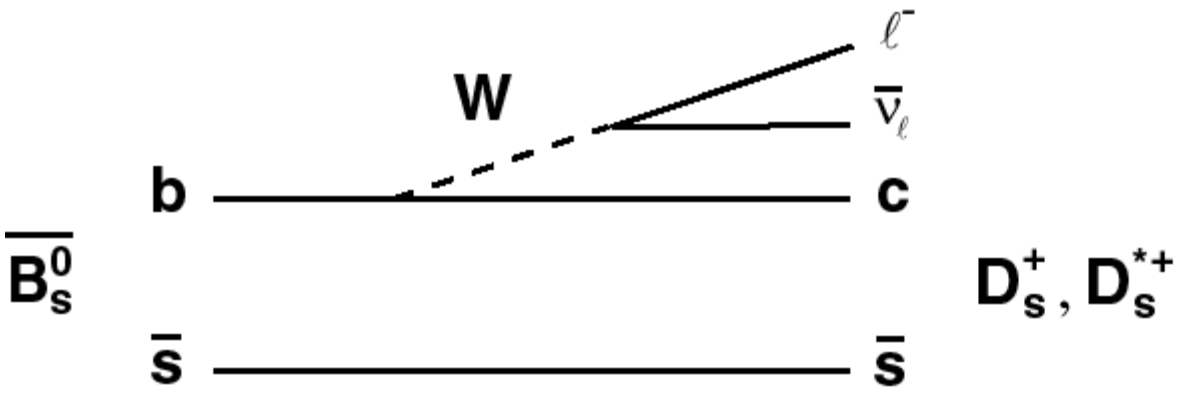



| experiment | channels | peak (events) | background (events) | mass(MeV) |
|---|---|---|---|---|
| ALEPH | $\Lambda_b \to (\Lambda 3\pi)\pi^-$<br>$\to (pK^-\pi^+)\pi^-$<br>$\to (pK^0)\pi^-$ | 4 | 0.38±0.06 | 5614±21±4<br>[PL **B380** (1996)442] |
| DELPHI | $\Lambda_b \to (pK^-\pi^+)\pi^-$<br>$\to (pK^-\pi^+)a_1^-$ | 4 | 0.6±0.2 | 5668±16±8<br>[PL **B374** (1996)351] |
| CDF | $\Lambda_b \to J/\psi\Lambda$ | 38 | 18.1±1.6 | 5621±4±3<br>[PR **D55** (1997)1142] |

**World Average: $M(\Lambda_b)$ = (5624±9) MeV** **PDG '99**

# Discovery of Strange b - Mesons $B_s\,(\bar{b}s)$




$$\bar{B}_s^0 \longrightarrow D_s^+ \ell^- \bar{\nu} \quad (x)$$

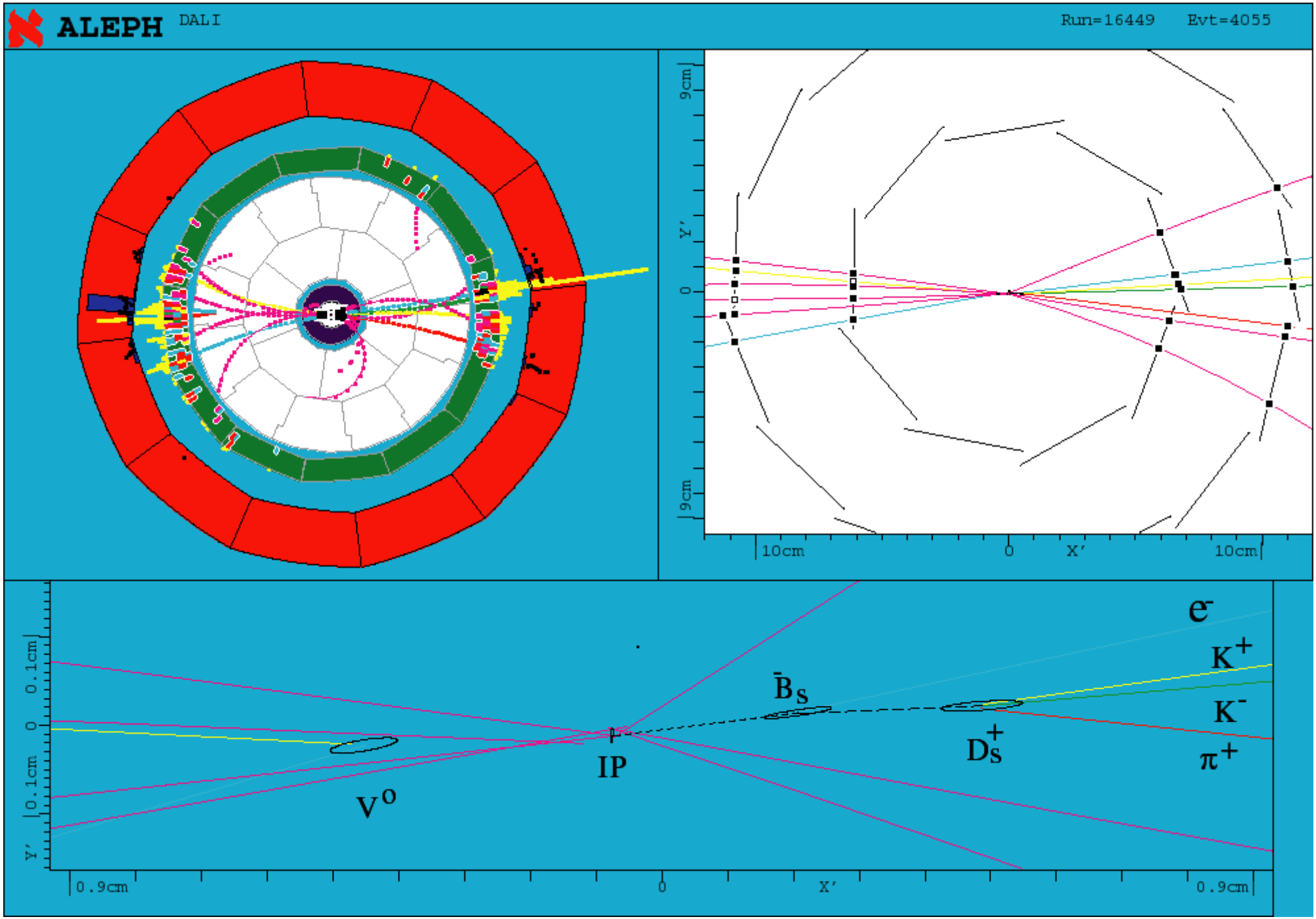
$$D_s^+ \longrightarrow \phi\ \pi^+ \qquad (3.6 \pm 0.9)\ \% \quad \text{PDG99}$$

$$\phi \longrightarrow K^+ K^-$$

$$D_s^+ \longrightarrow \bar{K}^*(892)\, K^+ \qquad (3.3 \pm 0.9)\ \% \quad \text{PDG99}$$

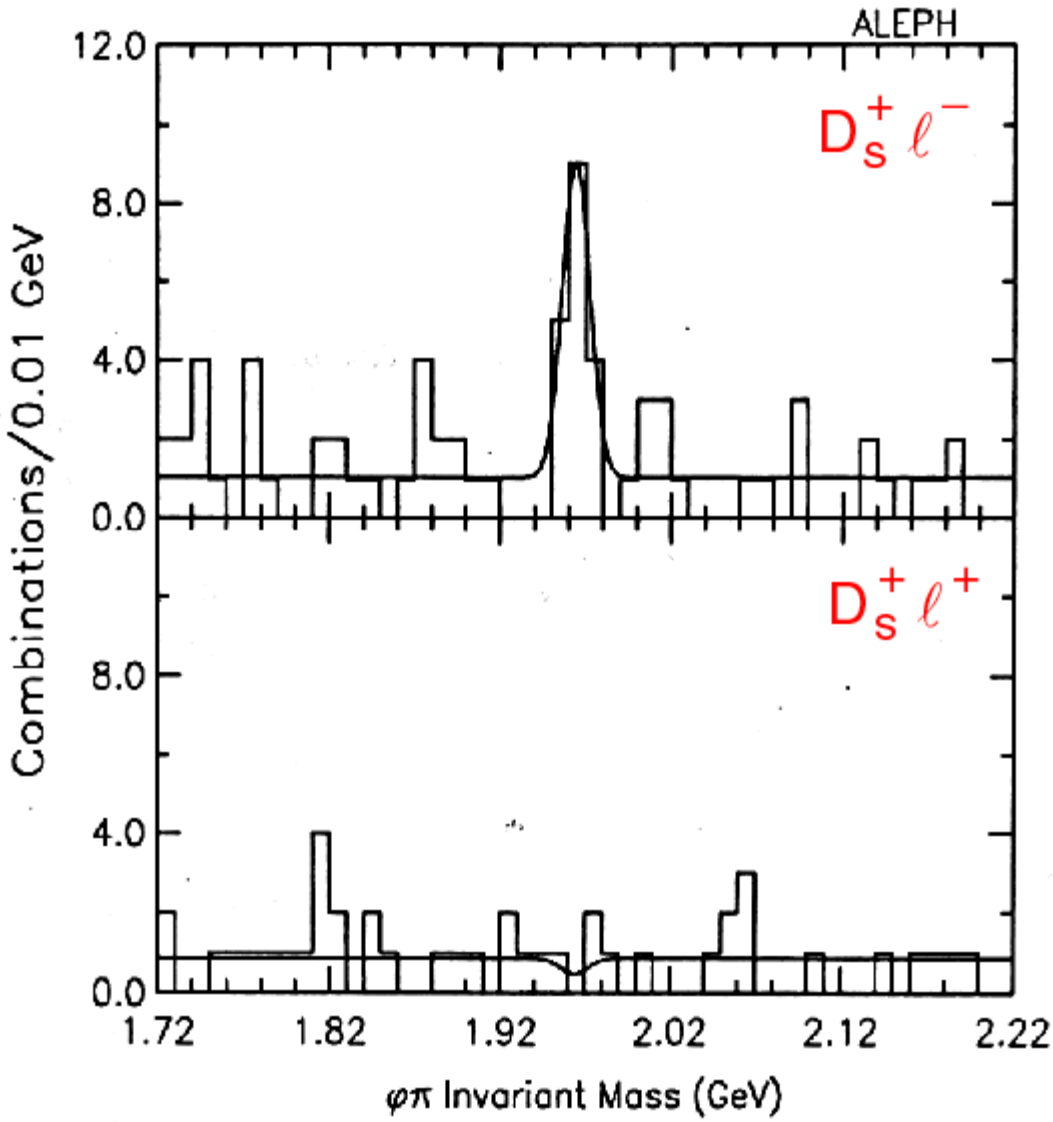
STUDY $D_s^+ \ell^-$ RIGHT SIGN COMBINATION

$D_s^+ \ell^+$ WRONG SIGN COMBINATION


ALEPH
DALI
Run=16449 Evt=4055
9cm
Y'
0
9cm
10cm
0
X'
10cm
e-
K+
K-
π+
B̄s
Ds+
IP
V0
0.1cm
0
0.1cm
Y'
0.9cm
0
X'
0.9cm

# First Evidence

***First observed by ALEPH, DELPHI, OPAL in 1992***




$B_s^0 \to (\phi\pi^+)\ell^-\bar{\nu}_\ell X$: $(13.7\ ^{+4.4}_{-4.8})$ events

$B_s^0 \to (\bar{K}^{*0}K^+)\ell^-\bar{\nu}_\ell X$: $(13.1\ ^{+5.5}_{-5.8})$ events

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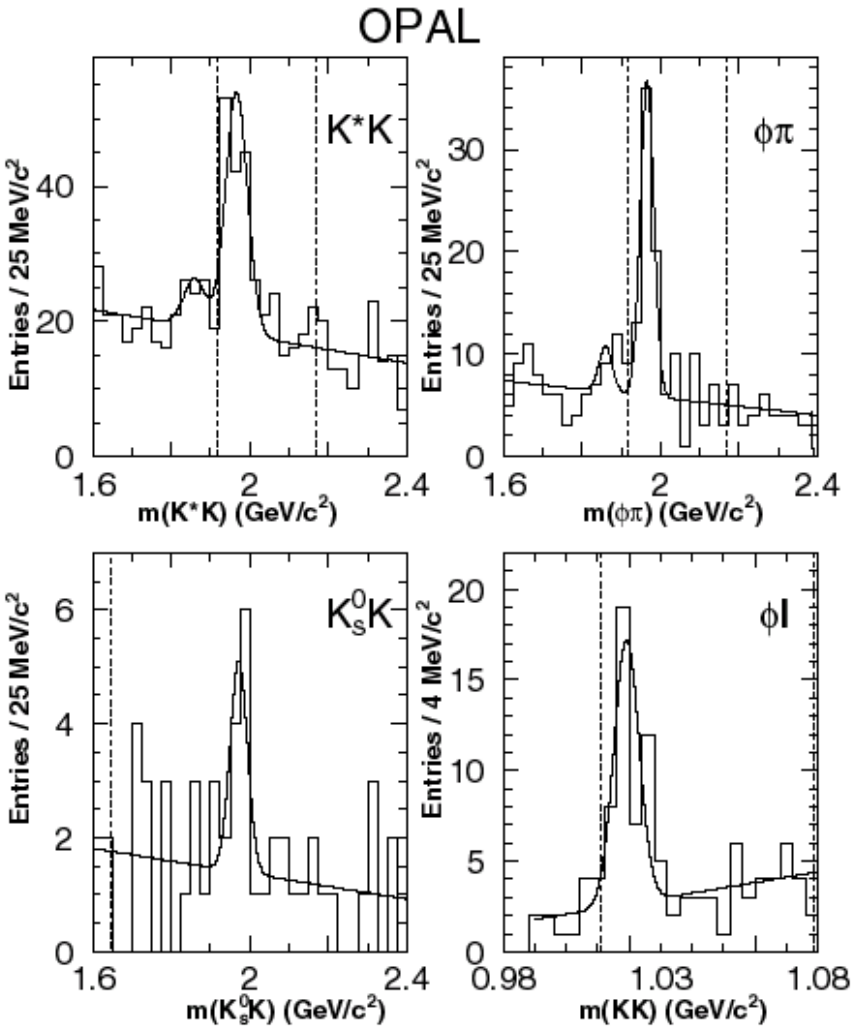
| | |
|---|---|
| *DELPHI* | *[PL **B289** (1992) 199]* |
| *ALEPH* | *[PL **B294** (1992) 145]* |
| *OPAL* | *[PL **B295** (1992) 357]* |

## Current: $B_s$

**OPAL Observe:** *[PL **B426** (1998) 161]*



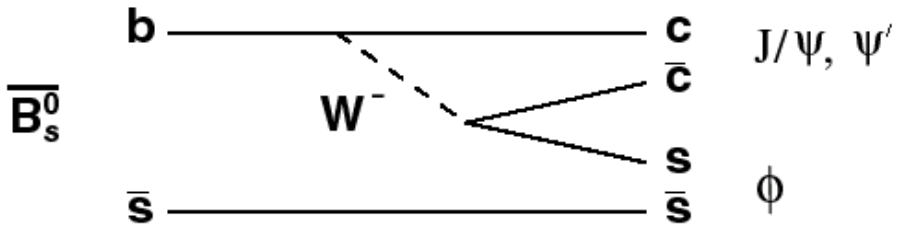

**4 Channels:** $D_s \rightarrow \phi\pi$, $K^*K$, $K^-K^0_s$, $\phi\ell\nu$ } **199±26 signal events**

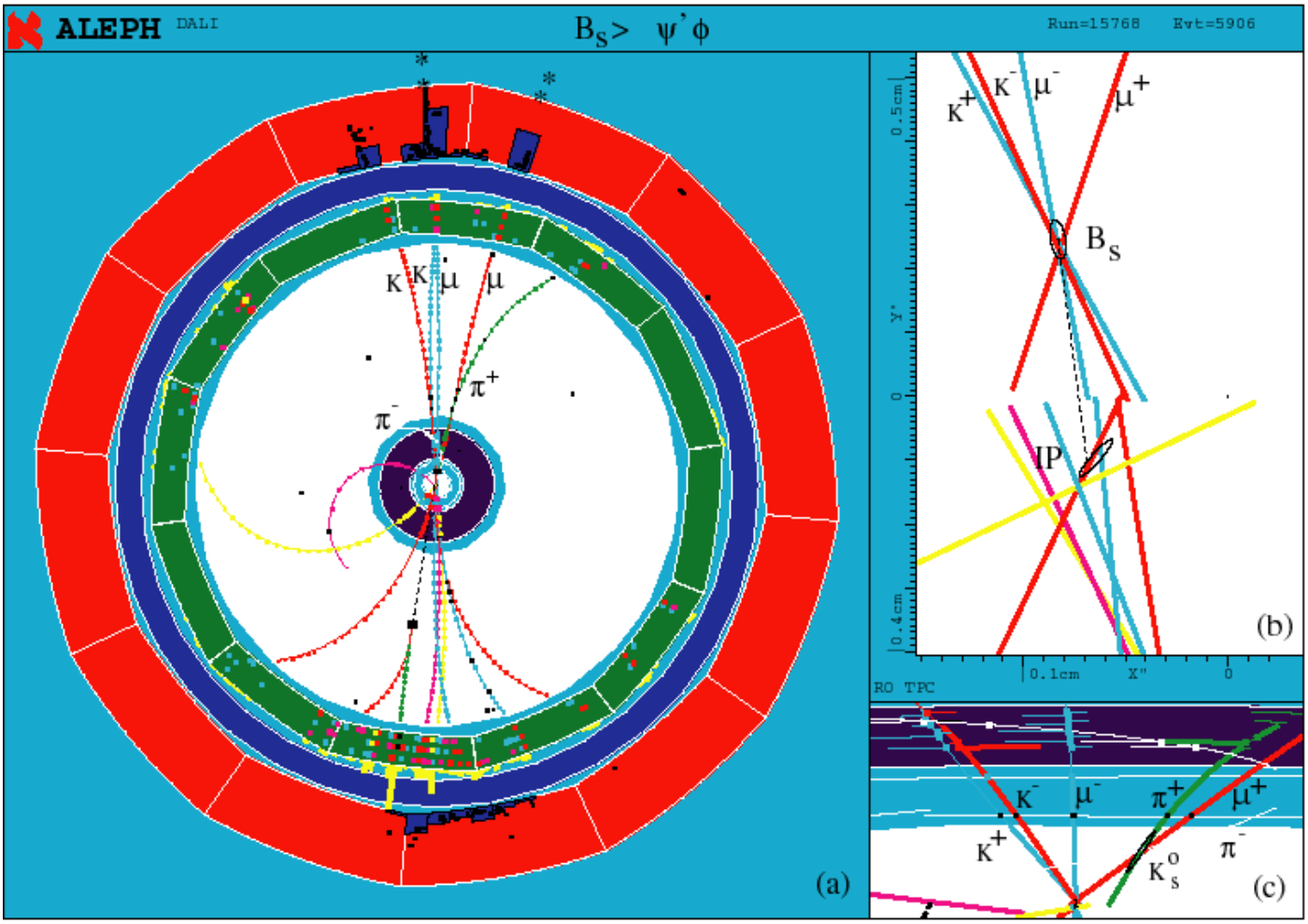
**LEP Average production rate:**

$$f\,(b \rightarrow \overline{B}^0_s) \times Br\,(\overline{B}^0_s \rightarrow D^+_s \ell^- \overline{\nu}_\ell X) = (7.2 \pm 2.1) \times 10^{-3}$$

*(Owen Hayes )*

# $B_s^0$ Meson Mass Reconstruction



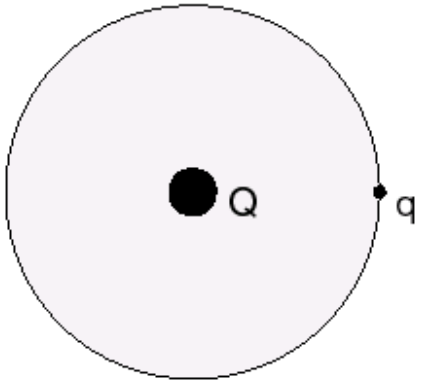




| Experiment | N Events | Mass(MeV) | |
|---|---|---|---|
| ALEPH | 2 | 5368.6±5.8 | [PL **B311** (1993)425] |
| DELPHI | 3 | 5374 ±16 | [PL **B324** (1994)500] |
| OPAL | 1 | 5359 ±20 | [PL **B337** (1994)196] |
| CDF | 32 | 5369.9±2.6 | [PL **D53** (1996)3496] |

World Average: $M(B_s^0) = (5369.3 \pm 2.0)$ MeV PDG '99

# Excited B Mesons ($B^*$, $B^{**}$)

## Heavy Quark Symmetry




as $m_Q \to \infty$

$$\left\{ \begin{array}{l} \vec{S}_Q \\ \vec{j}_q = \vec{S}_q + \vec{L} \end{array} \right\}$$

become independent

predicted states: $(\vec{J} = \vec{S}_Q + \vec{j}_q)$

| | $L$ | $j_q$ | $J^P$ | state | main decay mode | |
|---|---|---|---|---|---|---|
| $B^* \to$ | 0 | $\frac{1}{2}$ | $0^-$<br>$1^-$ | B<br>$B^*$ | weak<br>$B\gamma$ | |
| " $B^{**}$ " | 1 | $\frac{1}{2}$ | $0^+$<br>$1^+$ | $B_0^*$<br>$B_1$ | $B\pi$<br>$B^*\pi$ | S-wave, broad |
| | 1 | $\frac{3}{2}$ | $1^+$<br>$2^+$ | $B_1$<br>$B_2^*$ | $B^*\pi$<br>$B^{(*)}\pi$ | D-wave, narrow |

**Average of LEP measurements** (ALEPH, DELPHI,L3,OPAL)

$m(B^*) - m(B) = (45.73 \pm 0.49)\ MeV / c^2$

$$\frac{N(B^*)}{N(B)} = 0.75 \pm 0.04$$

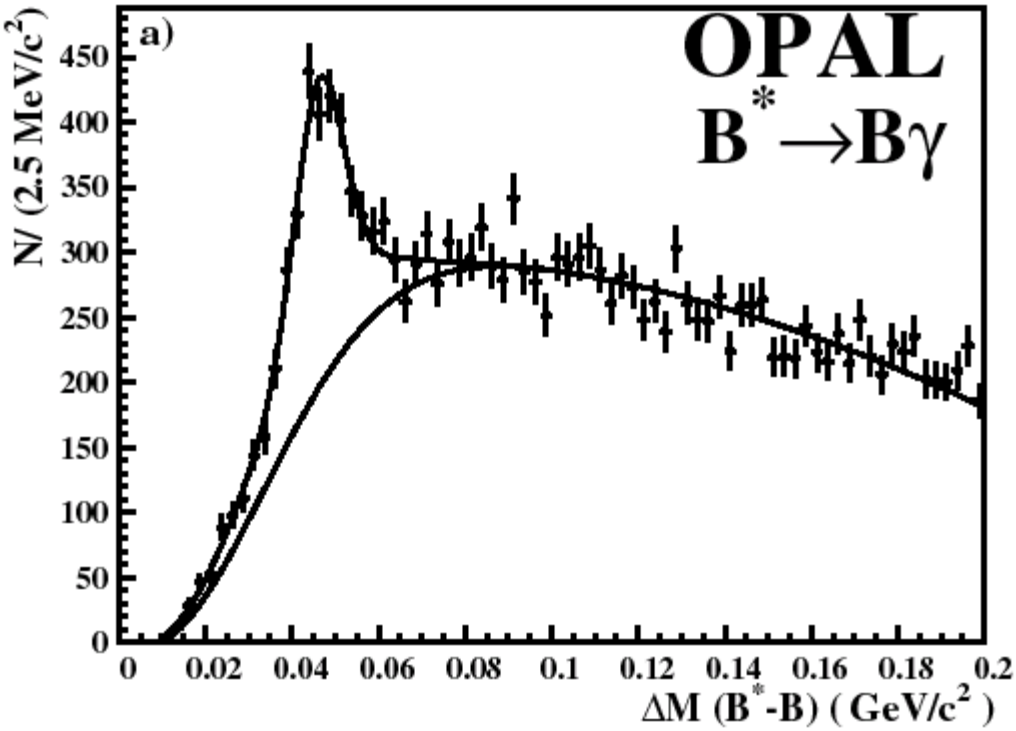
B(J=0) 1 Spin State ($J_Z$=0)
$B^*$(J=1) 3 Spin States ($J_Z$ = -1,0,1)
Expect $B^*/(B+B^*)=3/(1+3)$

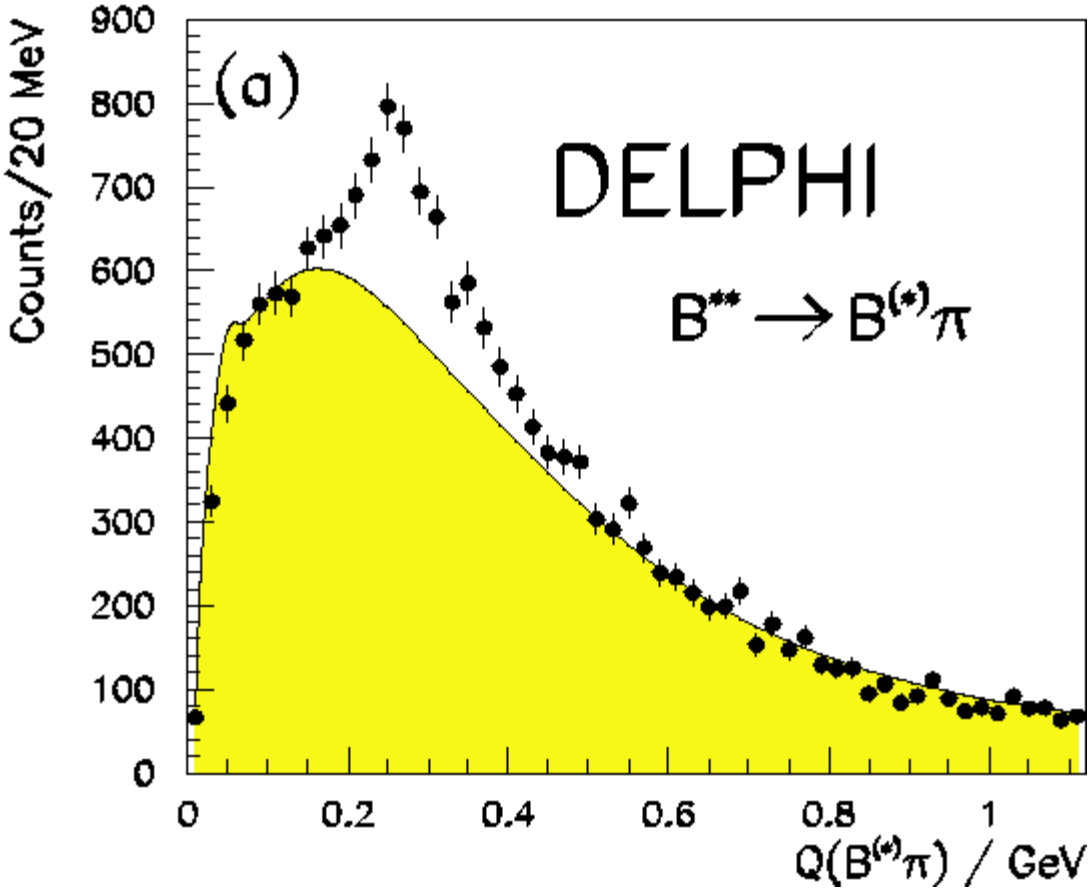
$m(B^{**}) - m(B) = (417 \pm 9)\ MeV / c^2$

$$\frac{N(B^{**})}{N(B)} = 0.29 \pm 0.03$$

$\Rightarrow$ individual contributions ($B^*$,$B_1$,$B_2^*$) not conclusive

# B*, B**


a)
OPAL
B* → Bγ
N/ (2.5 MeV/c²)
ΔM (B*-B) ( GeV/c² )


(a)
DELPHI
B** → B(*)π
Counts/20 MeV
Q(B(*)π) / GeV

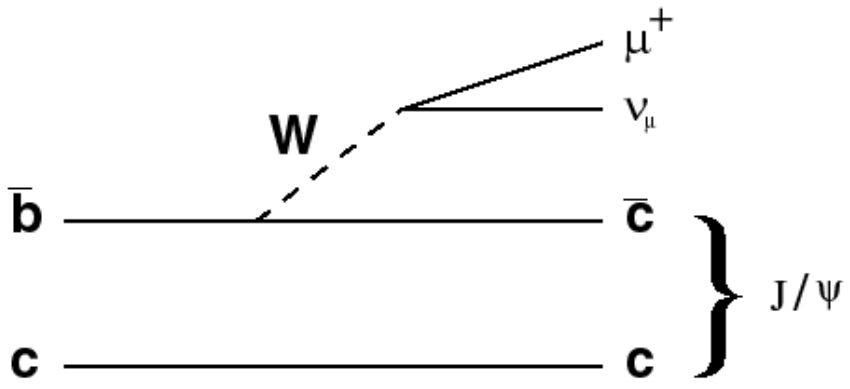
# $B_c^+$

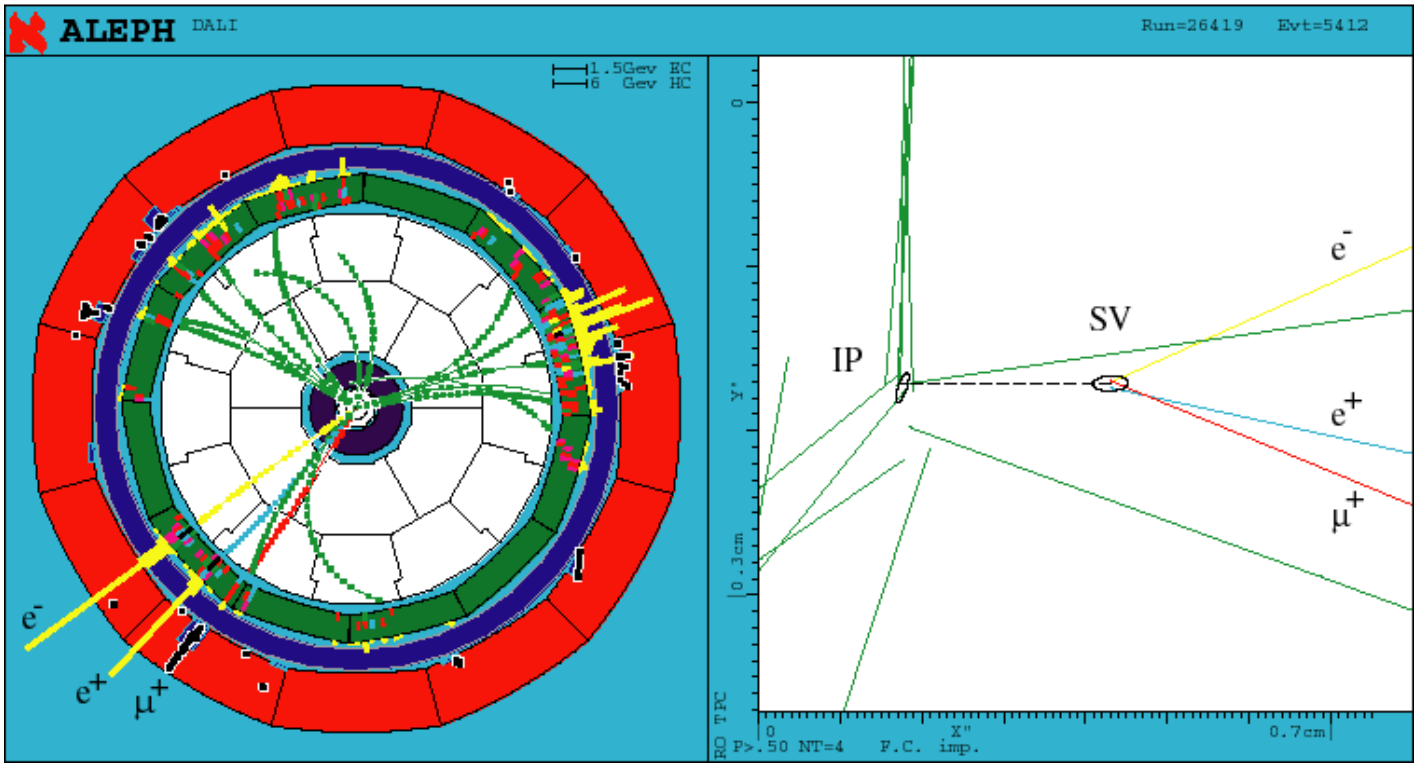
**ALEPH, DELPHI, OPAL Product Br Limits ~$10^{-4}$**

**CDF $20.4^{+6.2}_{-5.5}$ events ($B_c^{\pm} \to J/\Psi\ \ell^{\pm}\nu$)** [PRL **81**(1998)2432]

**ALEPH: 1 Candidate:** $B_c^+ \to J/\Psi(e^+e^-)\mu^+\nu_\mu$

[PL **B 402**(1997)213]

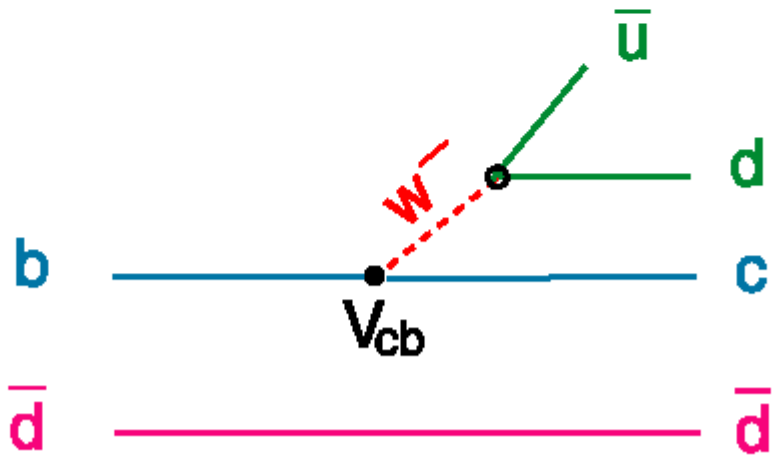


# Lifetimes of b Hadrons

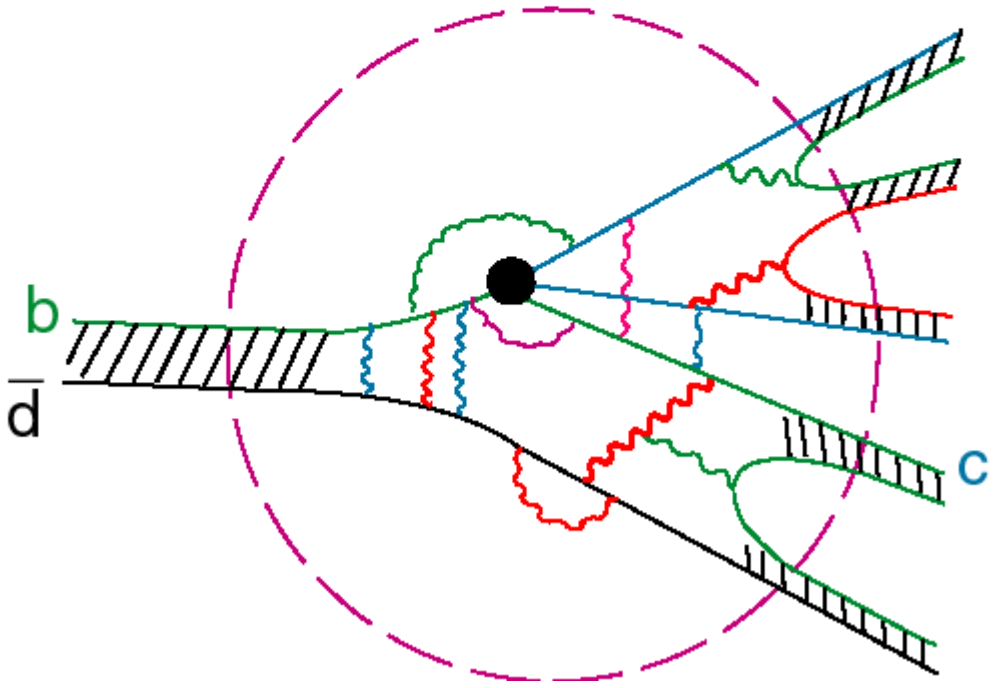
## The Decay of a b Hadron

### (a) The Simple Picture




*Spectator Model* $\Rightarrow$ *Equality of lifetime for all species*

### (b) Reality is more complex



# Lifetimes of b Hadrons :

- b quark heavy
- Spectator picture expected to dominate
- $\frac{\text{Non-spectator decay}}{\text{Spectator}} \propto \frac{f_B^2}{m_b^2}$

$\Rightarrow$ Lifetimes of b hadrons $\approx$ equal

- Bigi et al : (Using charm data as input)
- $\frac{\tau_{B^+}}{\tau_{B^o}} \approx 1.0 \pm 0.05 \left( \frac{f_B}{200\ MeV} \right)^2$
- $\frac{\tau_{B_s}}{\tau_{B^o}} \approx 1.0$
- $\frac{\tau_{\Lambda_b}}{\tau_{B^o}} \approx 0.9$

$f_B$ = decay constant, to be measured in $B \to \tau\nu$

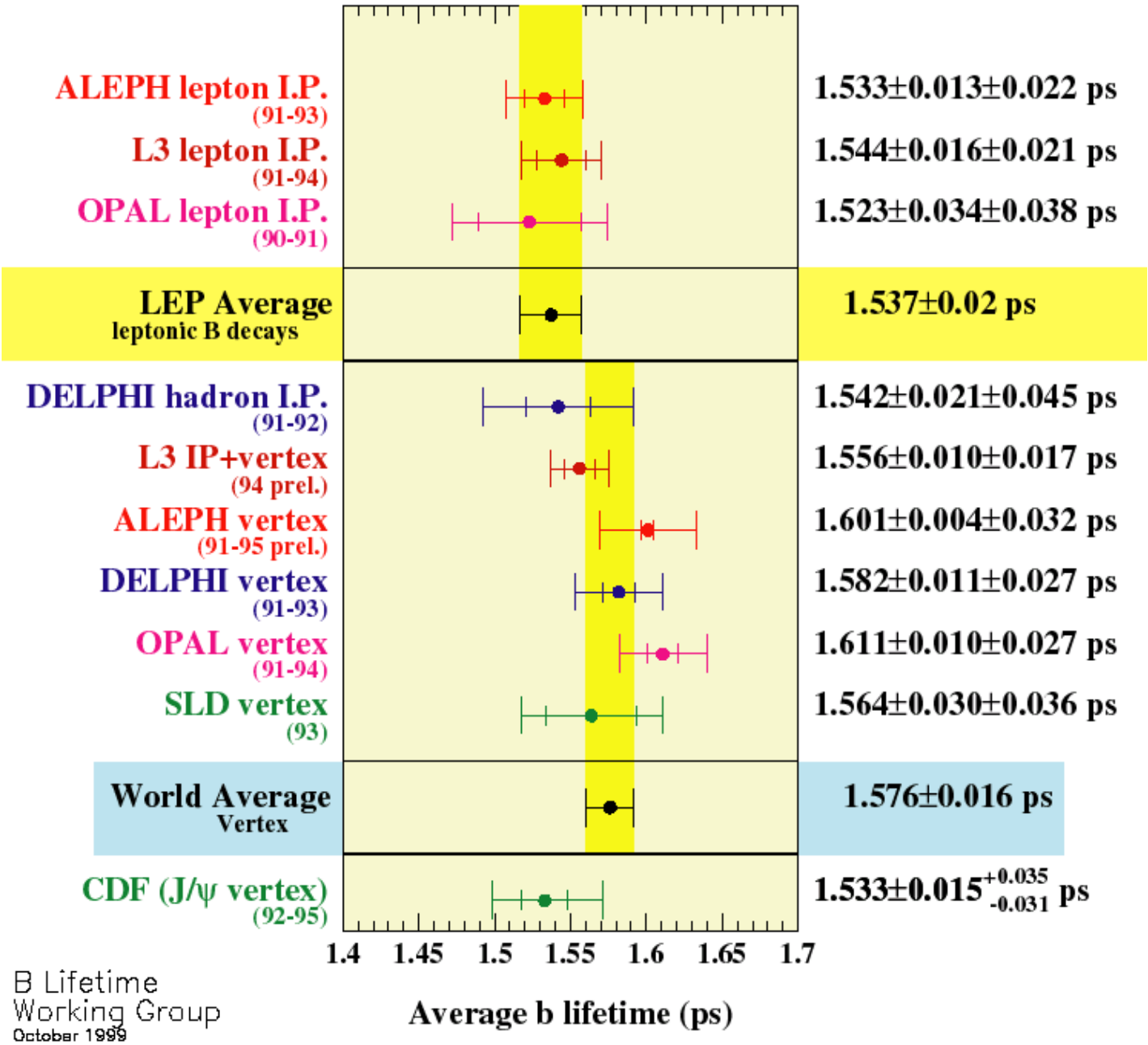
$f_B \sim 200$ MeV (theoretical estimate)

# Average B Hadron Lifetime

## Pioneered by experiments at PEP/SLAC

| | |
|---|---|
| MAC | PRL 51 (1983) 1022 |
| MARK II | PRL 51 (1983) 1316 |

**Methods:** (1) Lepton impact parameter
(2) Secondary vertex

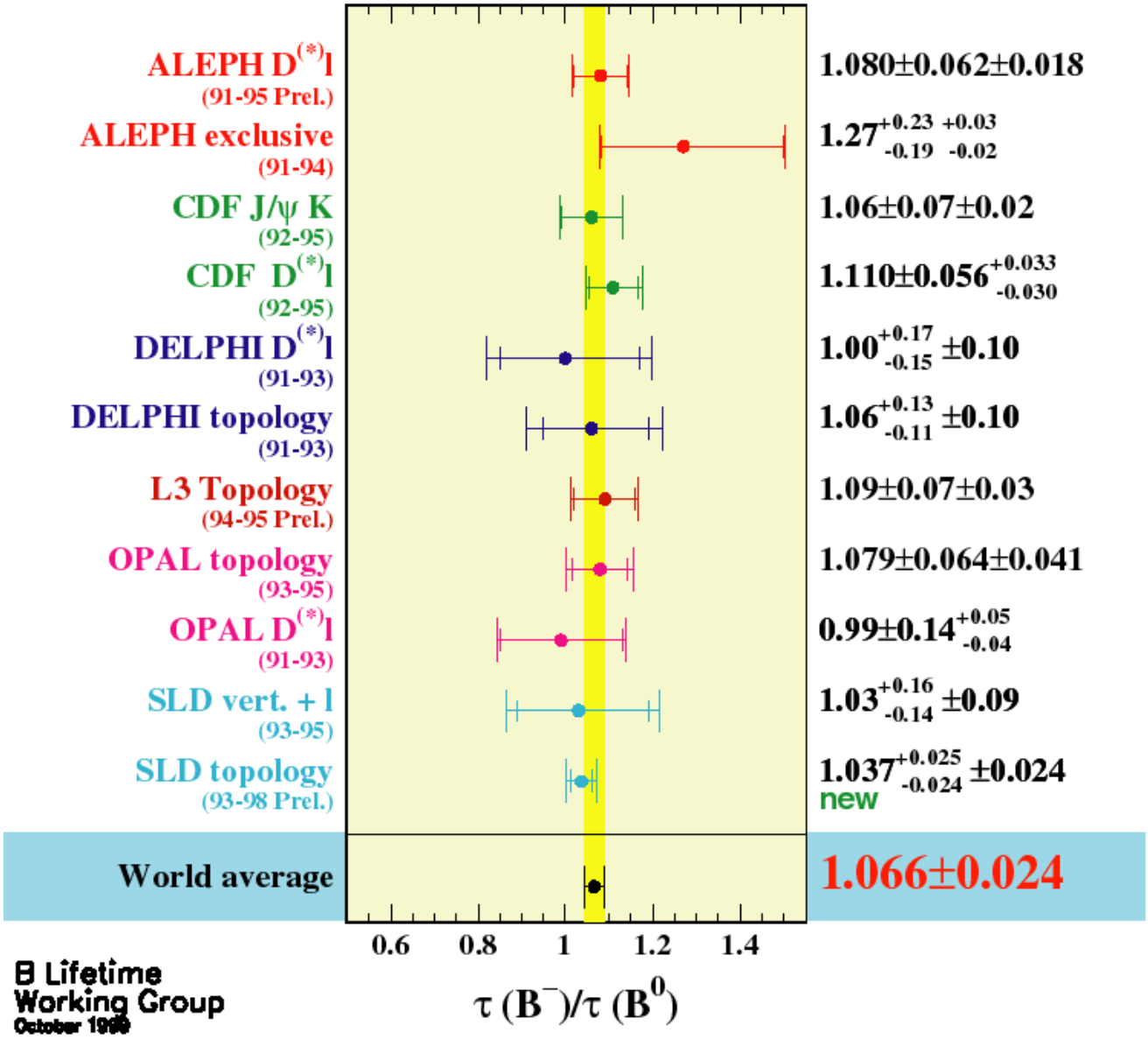



B Lifetime Working Group
October 1999

# $B^0, B^\pm$ Lifetimes

## Methods:

- $D^{(*)}\ell\nu$ with full reconstruction of $D^{(*)}$
- $B_d^0$, $B^\pm$ exclusive reconstruction
- $D^{(*)}\ell\nu$ with partial $D^*$ reconstruction
- Charge of inclusive secondary vertex

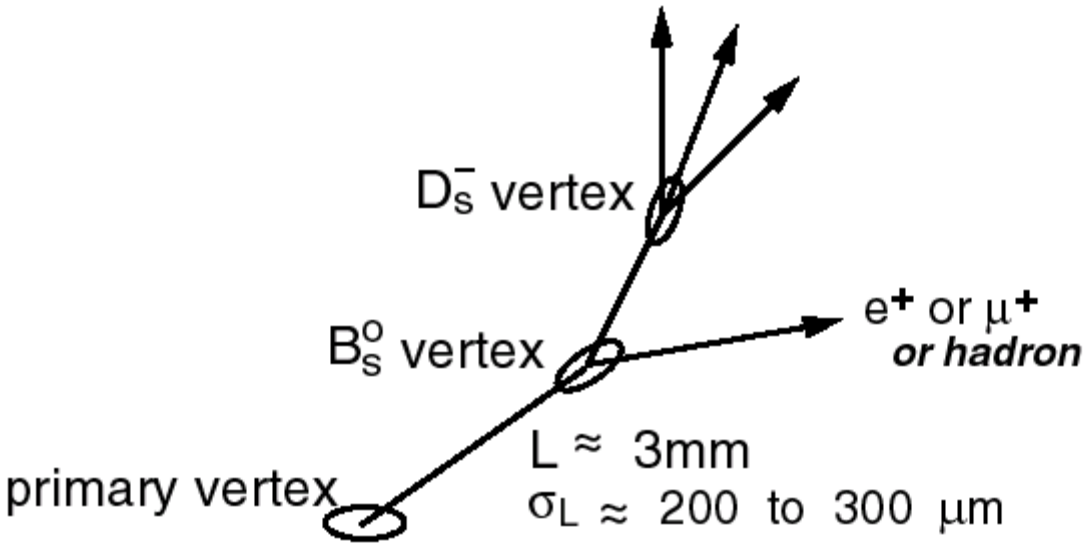


# $B_s^0$ LIFETIME

**Popular method(ALEPH, DELPHI, OPAL, CDF)**

$B_s^0 \longrightarrow D_s^- \ell^+ \nu_\ell X$ decays

$B_s^0 \longrightarrow D_s^- h^+ \nu X$ decays ($h^+$ = hadron)




$D_s^- \longrightarrow \phi \pi^-$

$D_s^- \longrightarrow K^{*0} K^-$

$D_s^- \longrightarrow \phi \mu^- \nu$

$D_s^- \longrightarrow \phi e^- \nu$

$D_s^- \longrightarrow \phi \pi^+ \pi^- \pi^-$

} have been reconstructed

$D_s^- \longrightarrow K^{*0} K^{*-}$

$D_s^- \longrightarrow \phi \pi^- \pi^0$

CDF Also uses $B_s^0 \longrightarrow J/\Psi\ \phi$

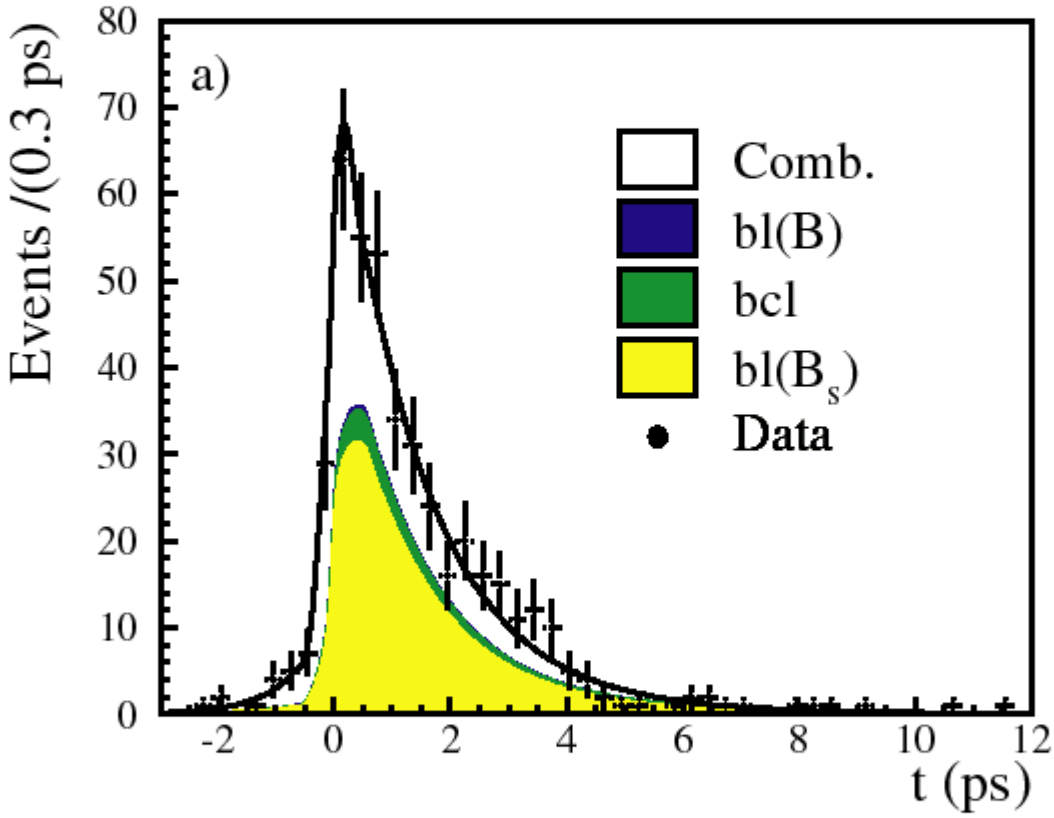
# $B_s^0$ Lifetime:

**DELPHI:** [ EPS-HEP'99 #4_520]

$B_s^0 \to D_s^- \ell^+ \nu_\ell X$ decays

$\phi\pi^-$, $K^{*0}K^-$, $K_S^0K^-$, $K^{*0}K^{*-}$, $\phi\pi^+\pi^-\pi^-$, $\phi\pi^-\pi^0$, $\phi e^-\nu$, $\phi\mu^-\nu$

**Signal: 286±26 $D_s^-\ell^+$**



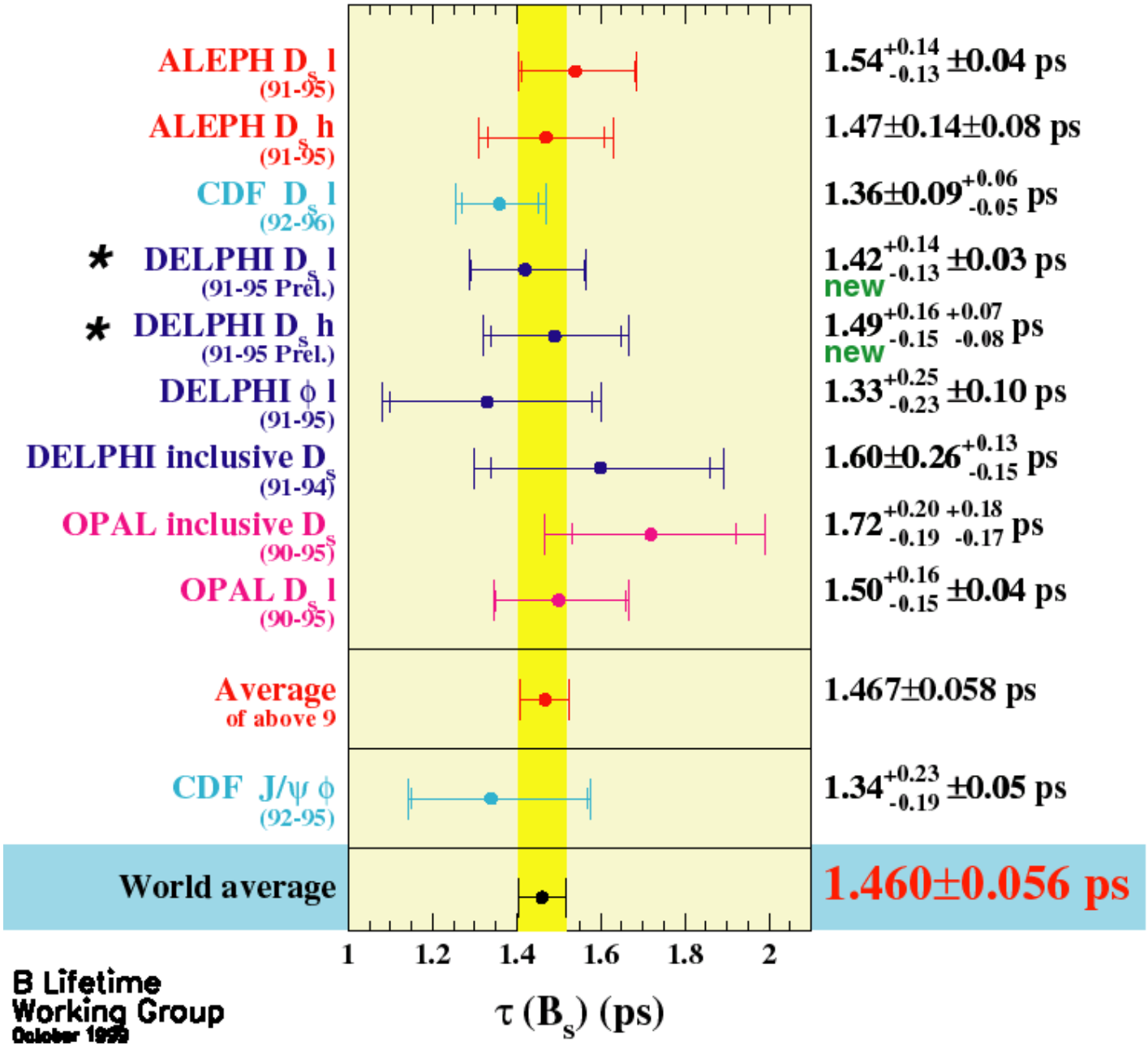

$$\tau(B_s^0) = (1.42^{+0.14}_{-0.13} \pm 0.03)\text{ps}$$

**Limit on difference between $\tau(B_s^0)_S$ and $\tau(B_s^0)_L$ :**

$\Delta\Gamma_s/\Gamma_s < 0.42$ @95% CL $(D_s^-\ell^+ + D_s^-h^+)$

*(also L3 and CDF)*

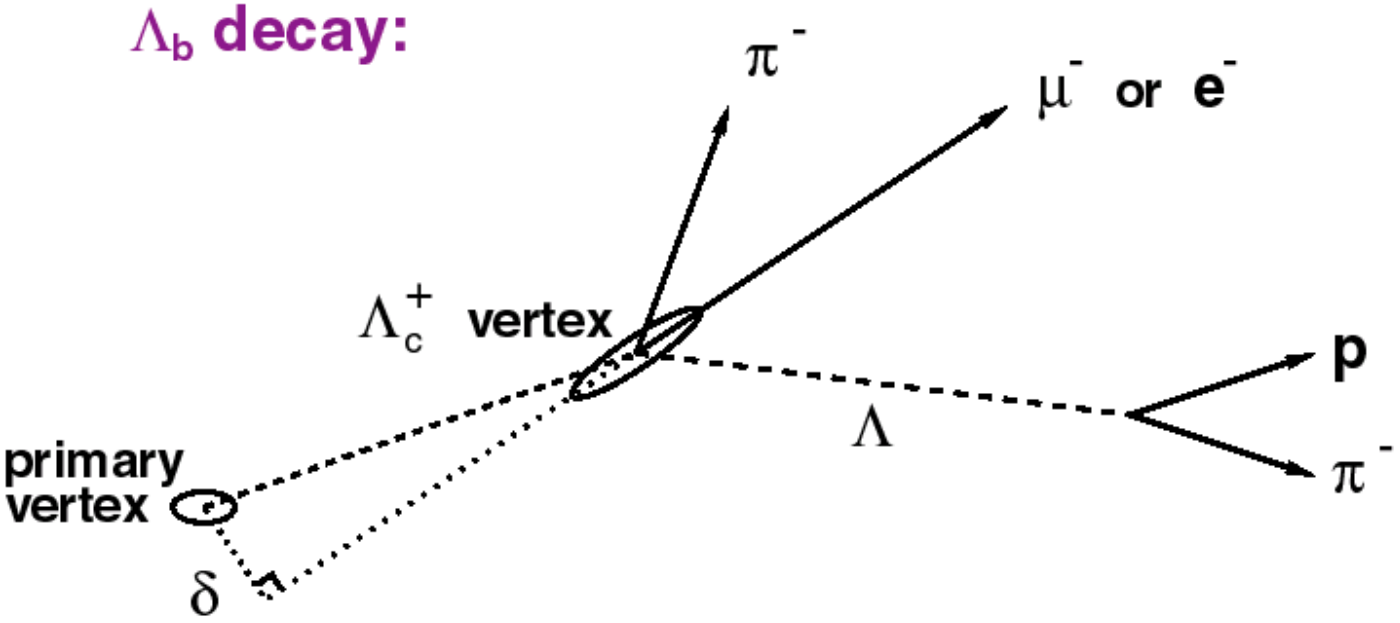
# World Average $B_s^0$ Lifetime




* *Preliminary*

# b Baryon Lifetime

$\Lambda_b$ decay:




**Two methods: (ALEPH, DELPHI, OPAL, CDF)**

1) $\Lambda_b \to \Lambda_c^+ \ell^- \nu_\ell X$

$\hookrightarrow$ $pK^-\pi^+$, $p\bar{K}^0$, $\Lambda\pi^+\pi^+\pi^-$, $\Lambda\pi^+$, $\Lambda\ell^+\nu_\ell$

*measure $\Lambda_c^+\ell^-$ vertex decay length*

$\Rightarrow$ *gives $\tau(\Lambda_b)$*

2) $\Lambda_b \to \Lambda_c^+ \ell^- \nu_\ell X$

$\hookrightarrow$ $\Lambda X$

$\hookrightarrow$ $p\pi^-$

*measure $\ell^-$ impact parameter, $\delta$*

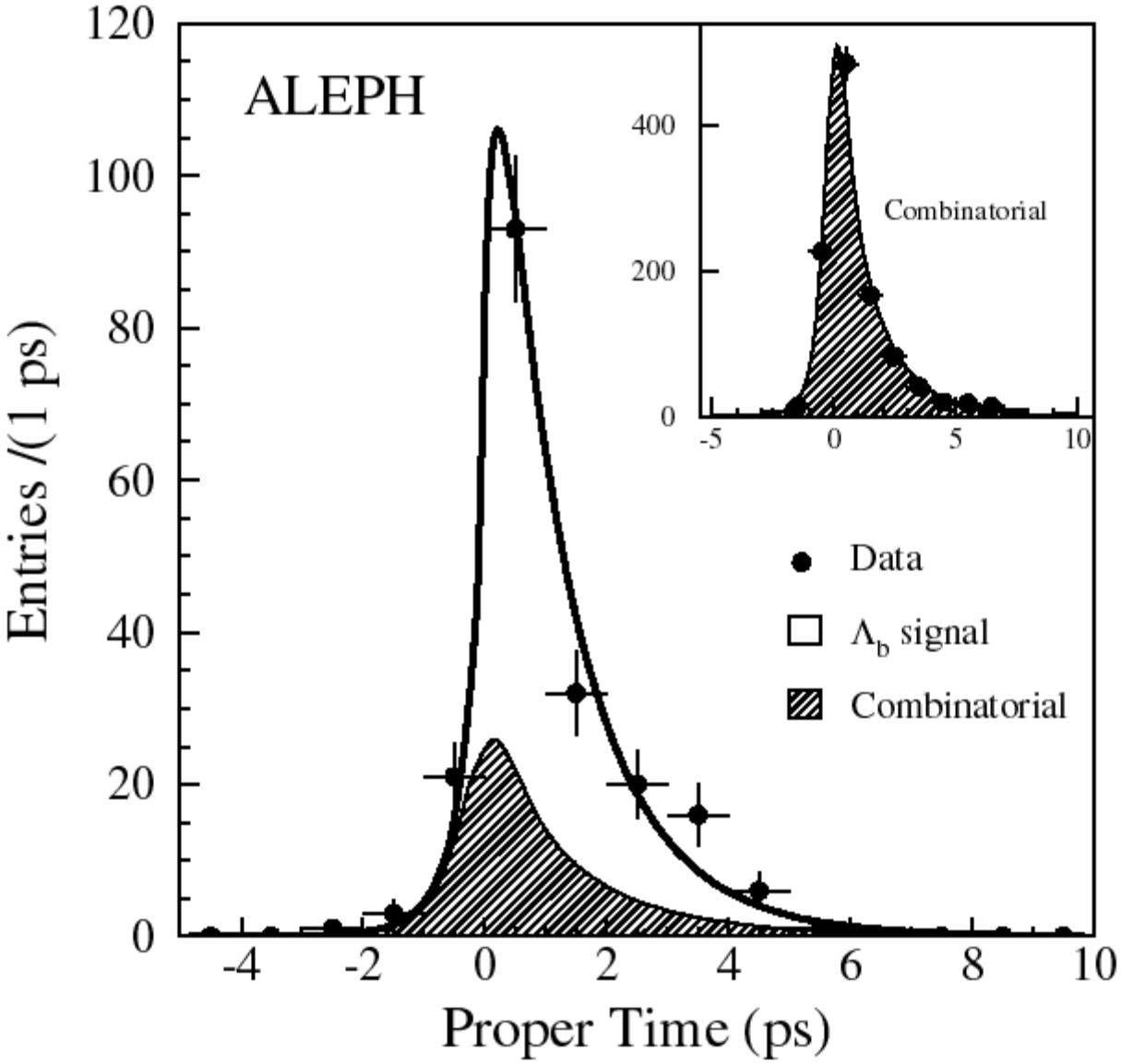
$\Rightarrow$ *gives average b baryon lifetime*

# $\Lambda_b$ Lifetime

*Decay length method:*

*ALEPH* [EPJ **C2** (1998) 197]

Signal: 137±14 $\Lambda_c^+ \ell^-$



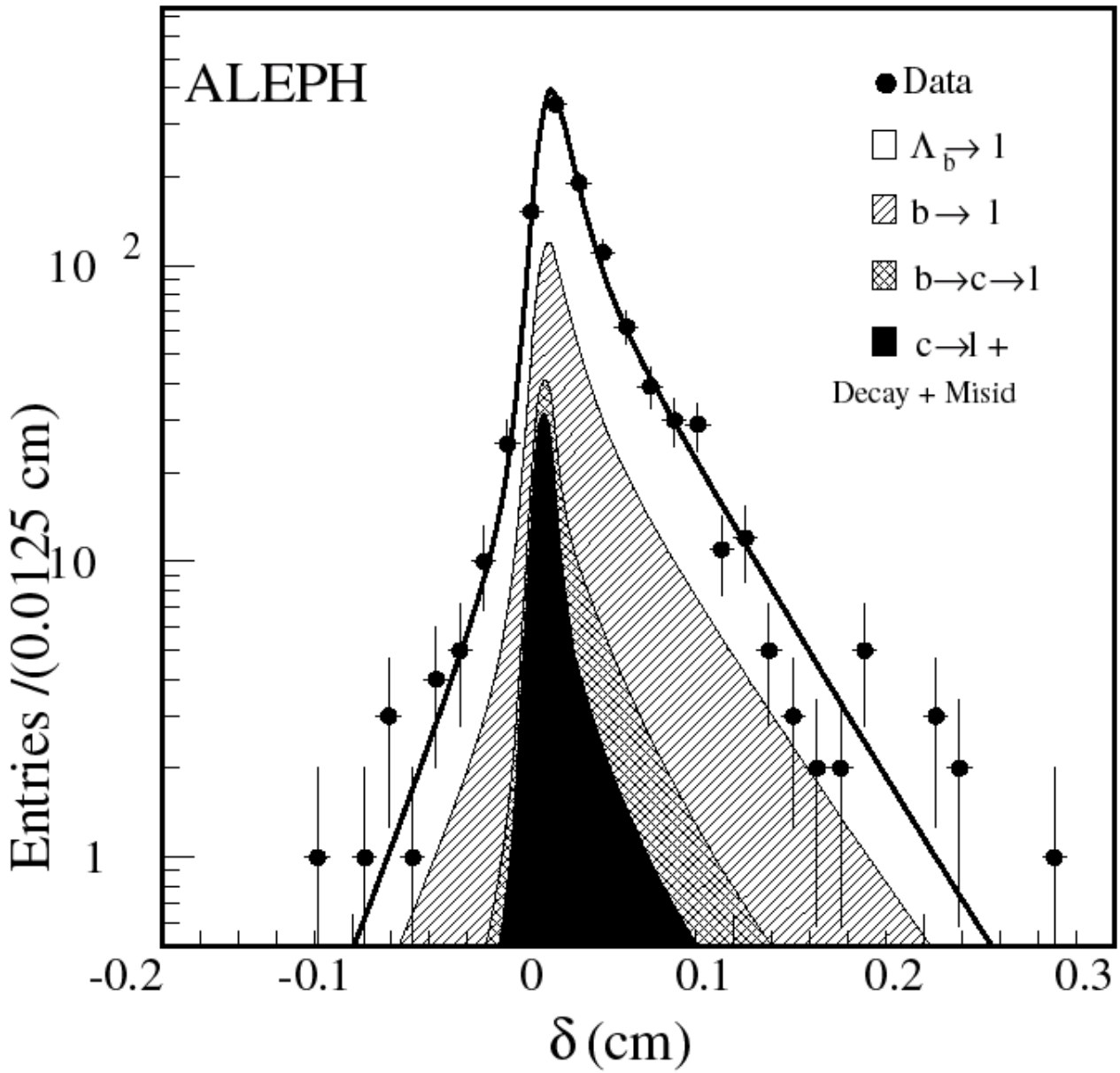

$$\tau(\Lambda_b) = (1.18^{+0.13}_{-0.12} \pm 0.03)\,ps$$

# b Baryon Lifetime

***Impact parameter method:***

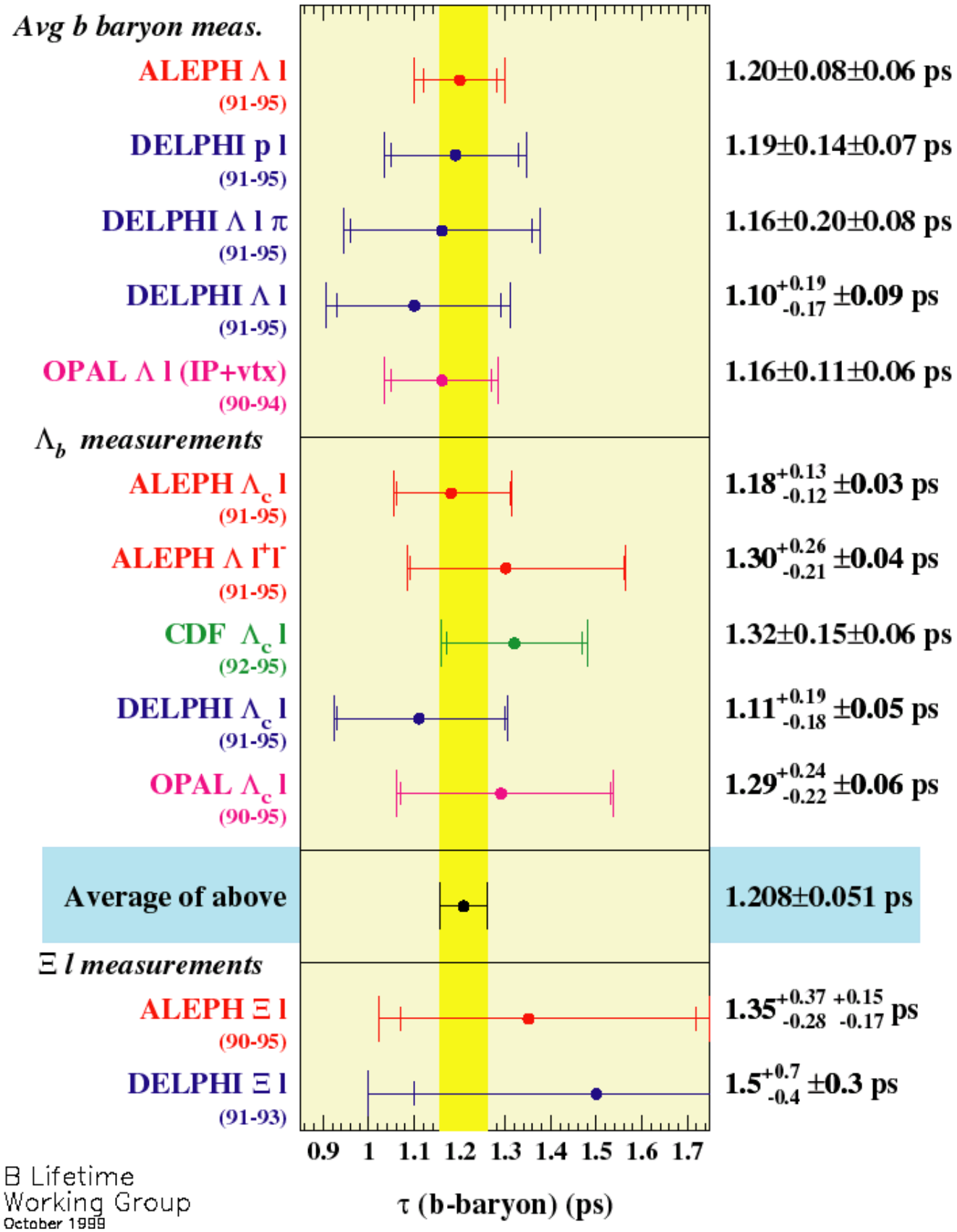
***1063 $\Lambda\ell^-$ combinations***

***$\Rightarrow$ 705 ± 69 due to $\Lambda_b$ signal***




***τ(b baryon) = (1.20±0.08±0.06)ps***

# World Average b Baryon Lifetime

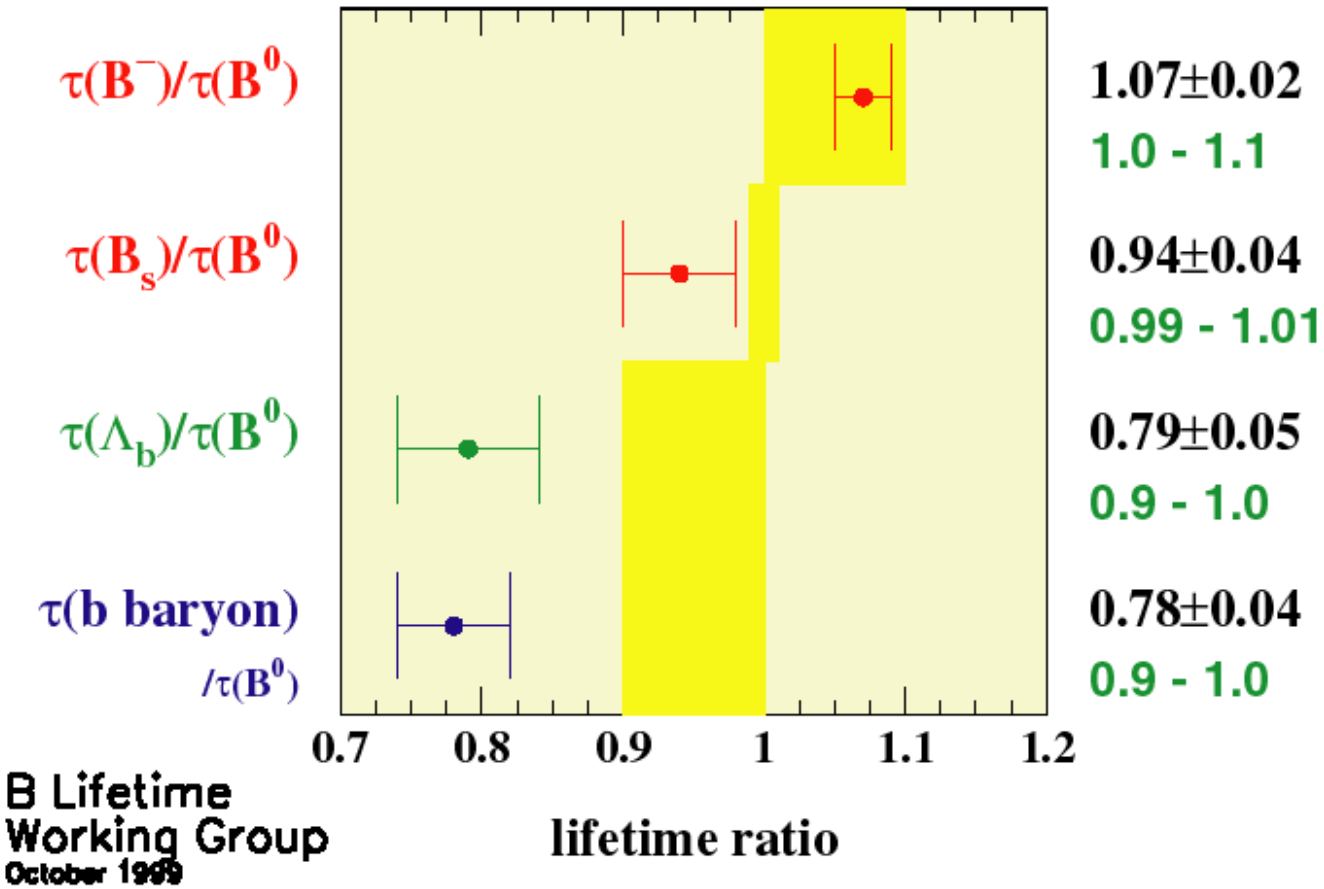



B Lifetime
Working Group
October 1999

# b Lifetime Summary

*Compare averages with theoretical predictions:*

[I. Bigi]




*$B^-$ has longer lifetime than $B^0$ ($3\sigma$)*

*$B_s^0$ lifetime compatible with $B^0$*

*$\Lambda_b$ lifetime shorter than expected: $3\sigma$*

*Unexplained by HQET and the OPE.*

*(Operator Product Expansion)*

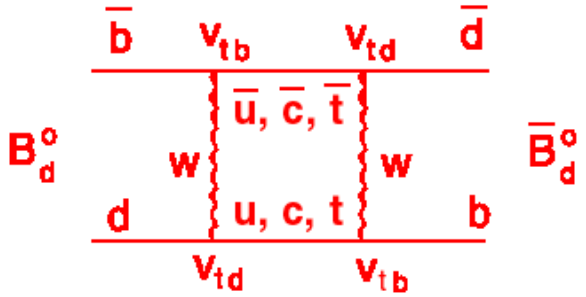
## Outline III

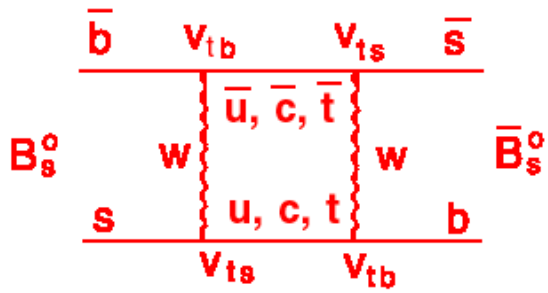
# Measurements Contributing to the CKM Matrix

- $B^0\ \overline{B}^0$ Oscillation ($B_d^0$, $B_s^0$)
- $|V_{cb}|$
- $|V_{ub}|$

# $B^0\ \bar{B}^0$ Oscillation

| | | | |
|---|---|---|---|
| **Flavor states** | $K^0\ \bar{K}^0$ | $B_d\ \bar{B}_d$ | $B_s\ \bar{B}_s$ |
| | $(\bar{s}d)\ (s\bar{d})$ | $(\bar{b}d)\ (b\bar{d})$ | $(\bar{b}s)\ (b\bar{s})$ |
| | ↓ | ↓ | ↓ |
| **Weak eigenstates** | $K_L,\ K_S$ | $(B_d)_L, (B_d)_S$ | $(B_s)_L, (B_s)_S$ |




The mass differences $\Delta m$ between the L (long) and S (short) states are due to higher-order weak interactions and therefore small. For example, for $K_L$, $K_S$

$$\Delta m_K = 3.5 \times 10^{-12}\ \text{MeV}$$

## *Mixing Probability*

At $t = 0$ pure $B^0$ state

$t > 0$ mixture of $B^0$ and $\bar{B}^0$

at decay

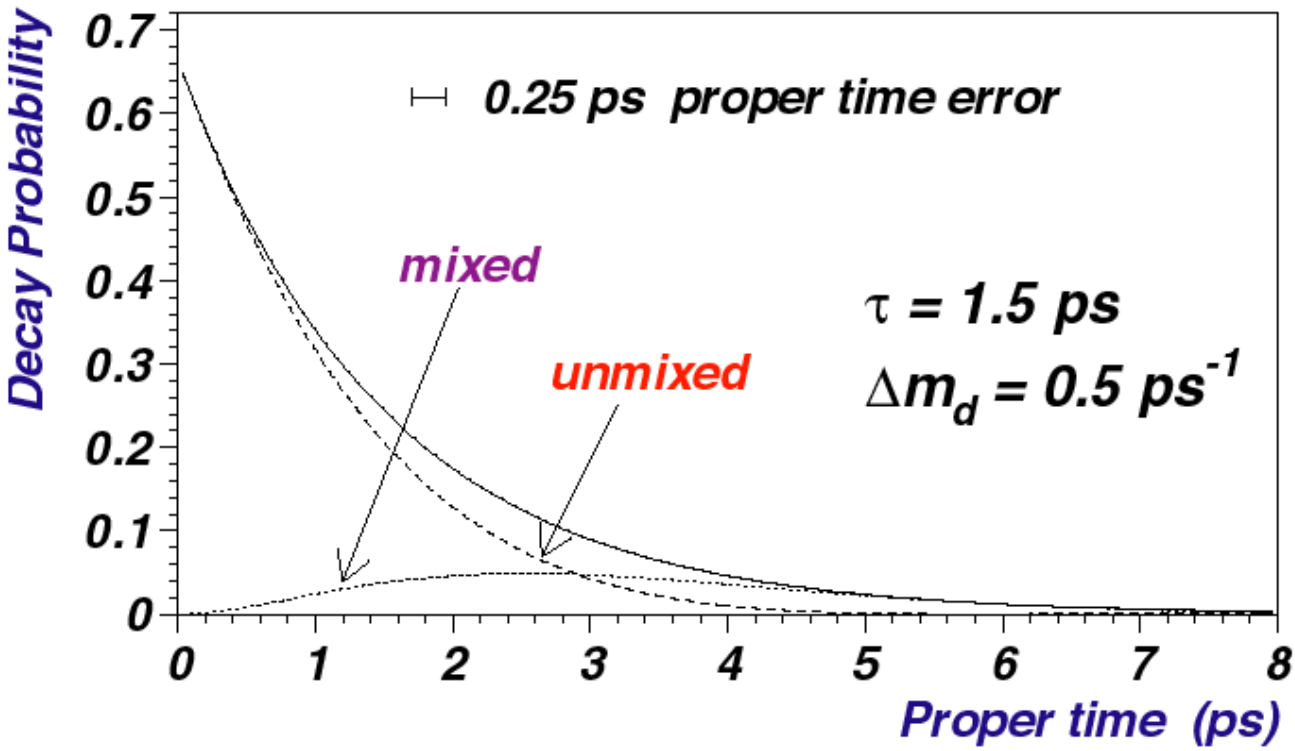
| | |
|---|---|
| $B^0$ (unmixed) | $P_u(t) = \frac{\Gamma}{2} e^{-\Gamma t} (1+\cos\Delta m t)$ |
| $\bar{B}^0$ (mixed) | $P_m(t) = \frac{\Gamma}{2} e^{-\Gamma t} (1-\cos\Delta m t)$ |

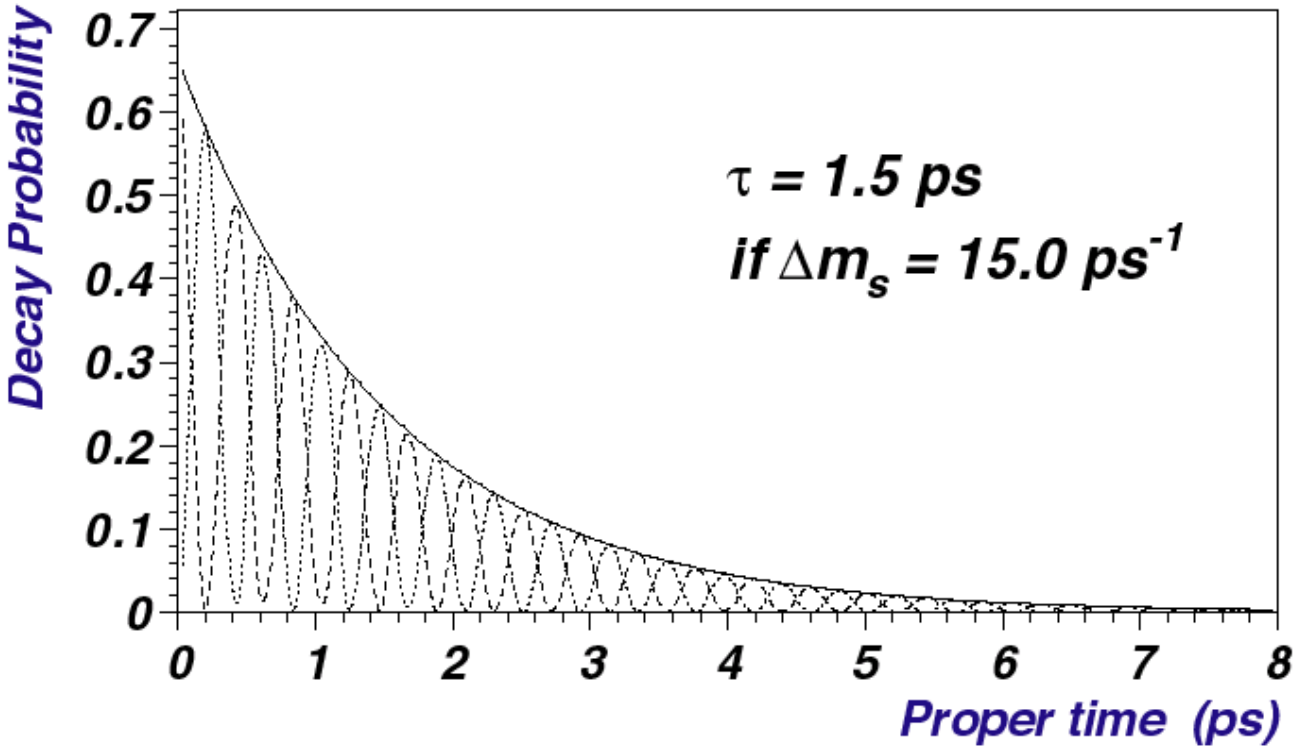
$$\Delta m = |m_L - m_S|, \quad \Gamma \approx \Gamma_L \approx \Gamma_S$$

$$\frac{\Delta m_s}{\Delta m_d} = \frac{M_{B_s}}{M_{B_d}} \xi^2 \left| \frac{V_{ts}}{V_{td}} \right|^2 \frac{\eta_{B_s}}{\eta_{B_d}}$$

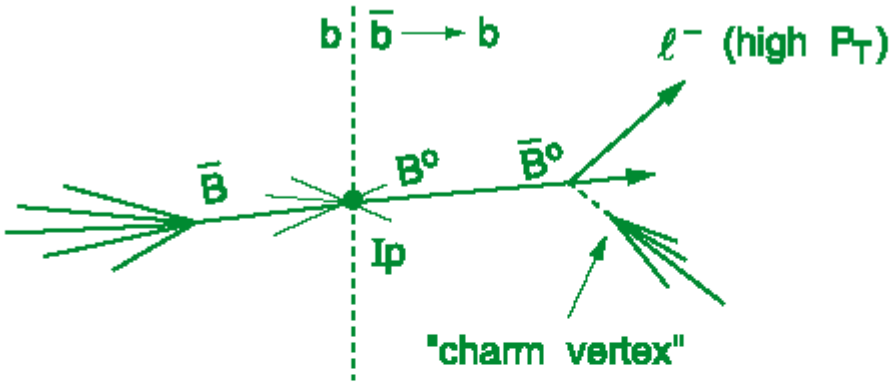
$\eta_{Bs}, \eta_{Bd}$: QCD correction factors

$\xi = 1.11 \pm 0.06$ (QCD)

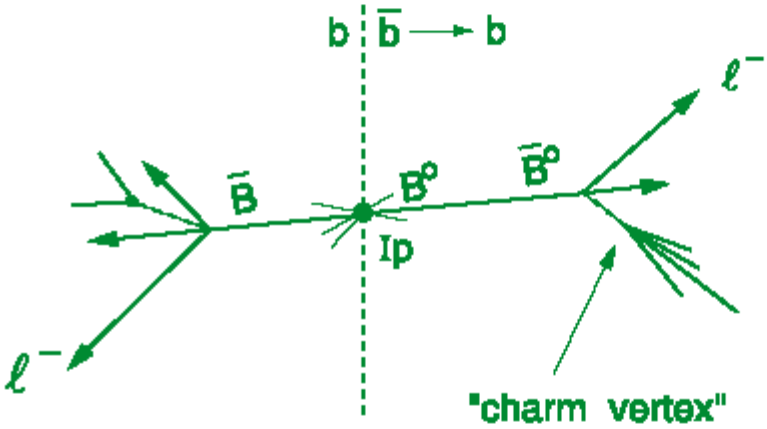

Decay Probability
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.25 ps proper time error
mixed
unmixed
τ = 1.5 ps
Δm_d = 0.5 ps^-1
0
1
2
3
4
5
6
7
8
Proper time (ps)


Decay Probability
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
τ = 1.5 ps
if Δm_s = 15.0 ps^-1
0
1
2
3
4
5
6
7
8
Proper time (ps)

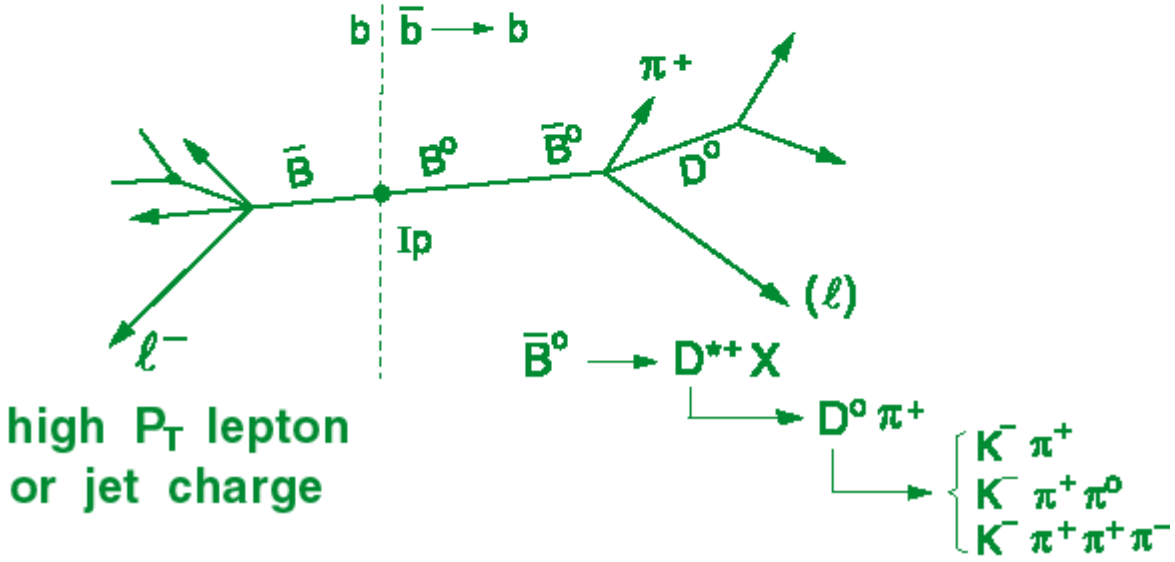
## *Lepton/Jet Charge*




## *Lepton / Lepton*

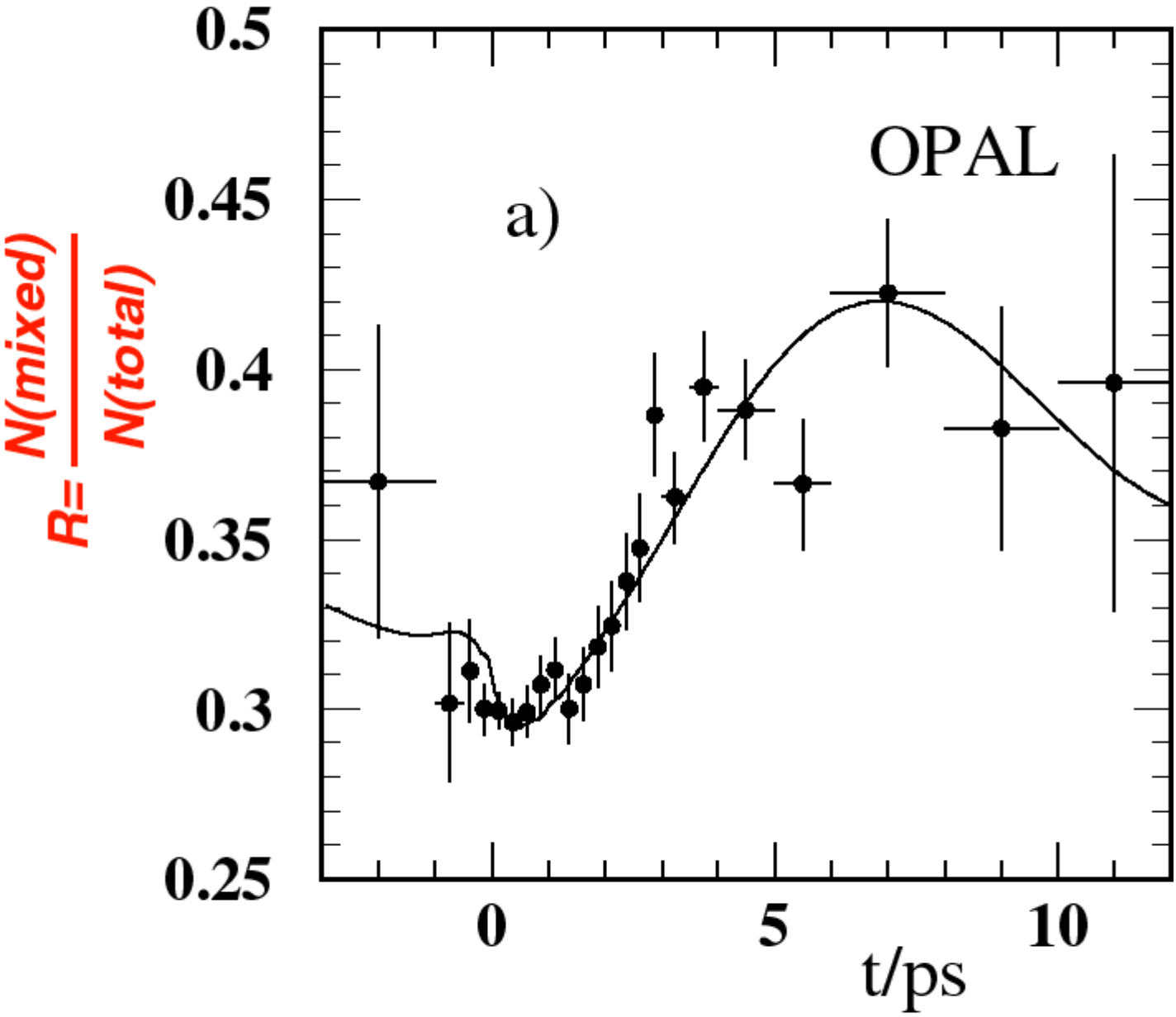



## *D* ($D_S$) / Lepton or Jet Charge*



# Example $\Delta m_d$ Measurement

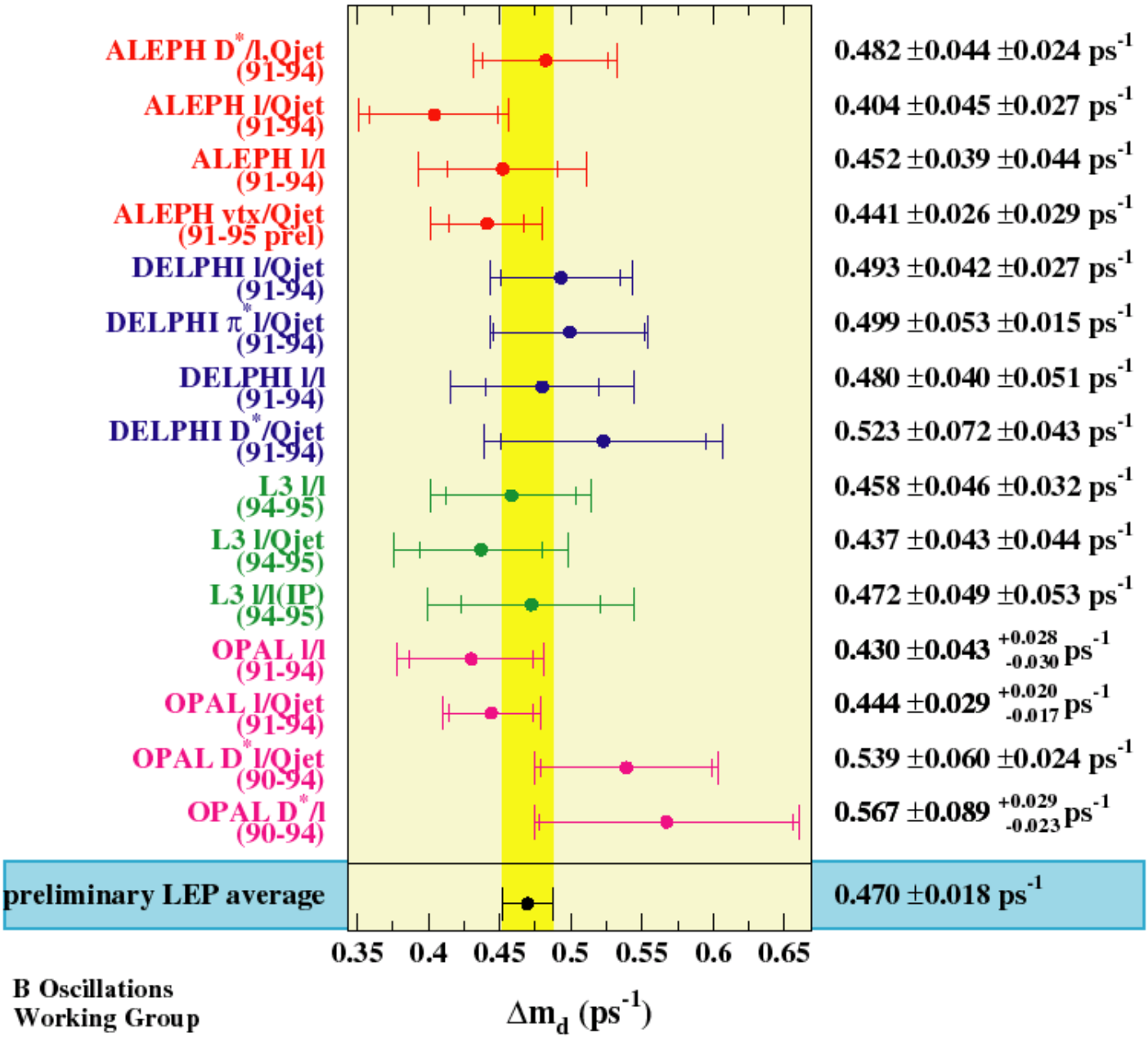
**OPAL use lepton & jet-charge**




$$\Delta m_d = (0.444 \pm 0.029^{+0.020}_{-0.017})\,ps^{-1}$$

[OPAL, ZP **C76**(1997)401.]

# $B_d^0$ Oscillation Frequency

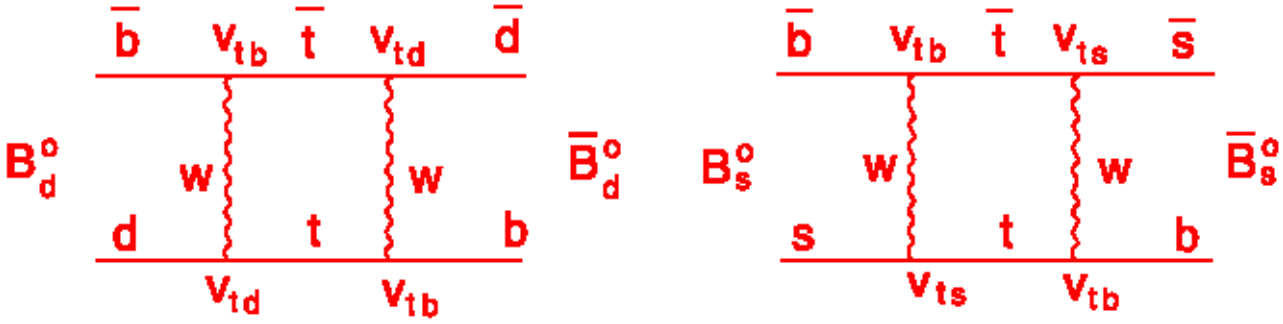



***Lep Average:*** $\Delta m_d = (0.470 \pm 0.018)\,ps^{-1}$

***World Average:*** $\Delta m_d = (0.482 \pm 0.016)\,ps^{-1}$

*(LEP+CDF+SLD)*

# $B_s^o$ $\bar{B}_s^o$ Oscillation




Ratio of oscillation frequencies: $\frac{\Delta m_s}{\Delta m_d} \propto \left| \frac{V_{ts}}{V_{td}} \right|^2$

ALEPH (1993)

$$\left.\begin{array}{l} \Delta m_s > 1.8\ ps^{-1} \\ X_s = \frac{\Delta m_s}{\Gamma} > 2.0 \end{array}\right\} \quad 95\ \%\ C.L.$$

[PL **B 322** (1994) 441]

ALEPH (1994)

$$\left.\begin{array}{l} \Delta m_s > 6.1\ ps^{-1} \\ X_s = \frac{\Delta m_s}{\Gamma} > 9.0 \end{array}\right\} \quad 95\ \%\ C.L.$$

*first reported in 1994 ICHEP Glasgow Conference*

**World Average (This Conference)**

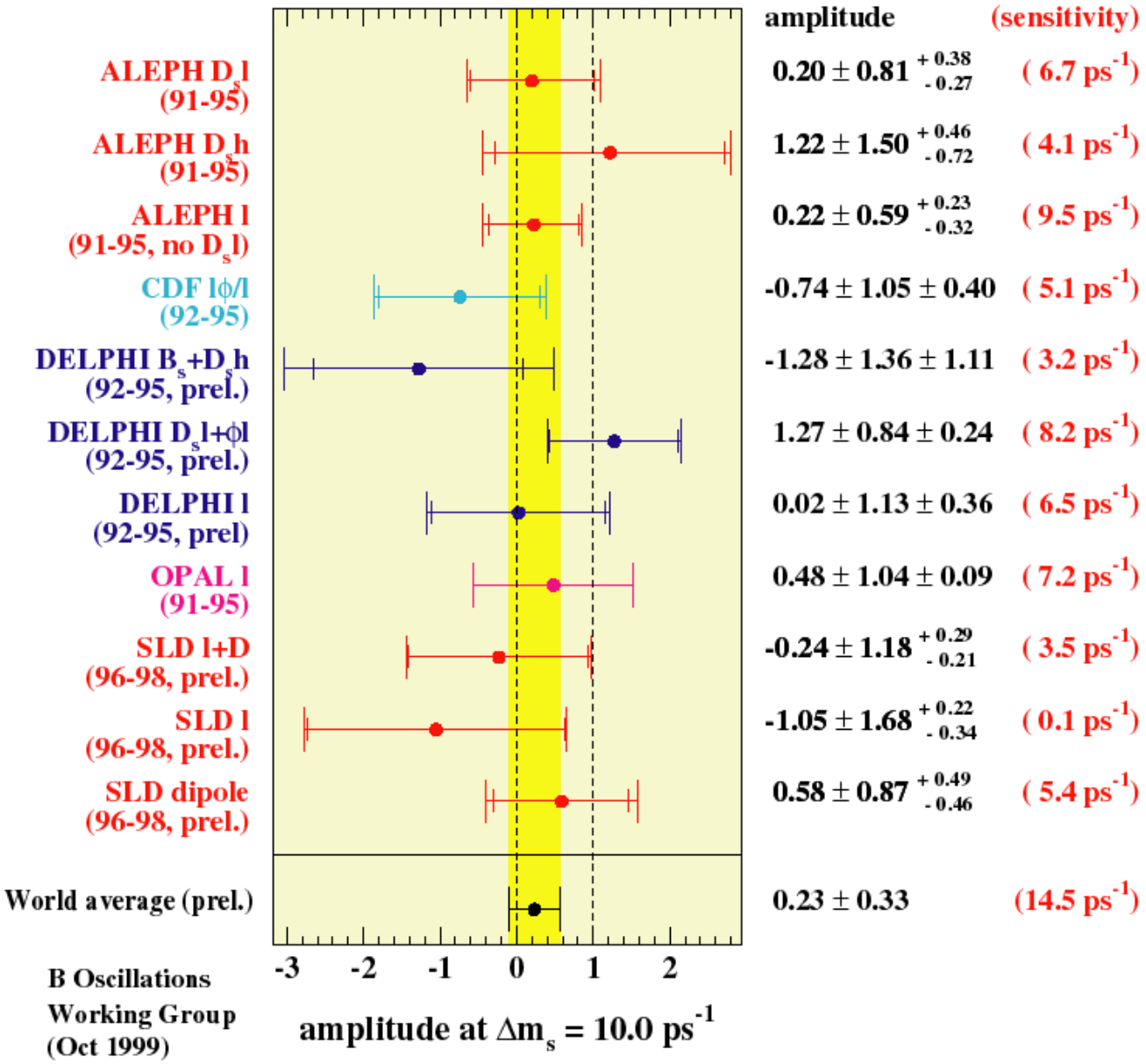
$$\left.\begin{array}{l} \Delta m_s > 14.3\ ps^{-1}\ (9.4 \times 10^{-3}\ eV) \\ X_s = \frac{\Delta m_s}{\Gamma} > 20.9 \end{array}\right\} \quad 95\ \%\ C.L.$$

*B Oscillation WG*
*(LEP + SLD+CDF)*

# $B_s^0$ Oscillation Amplitude Measurements

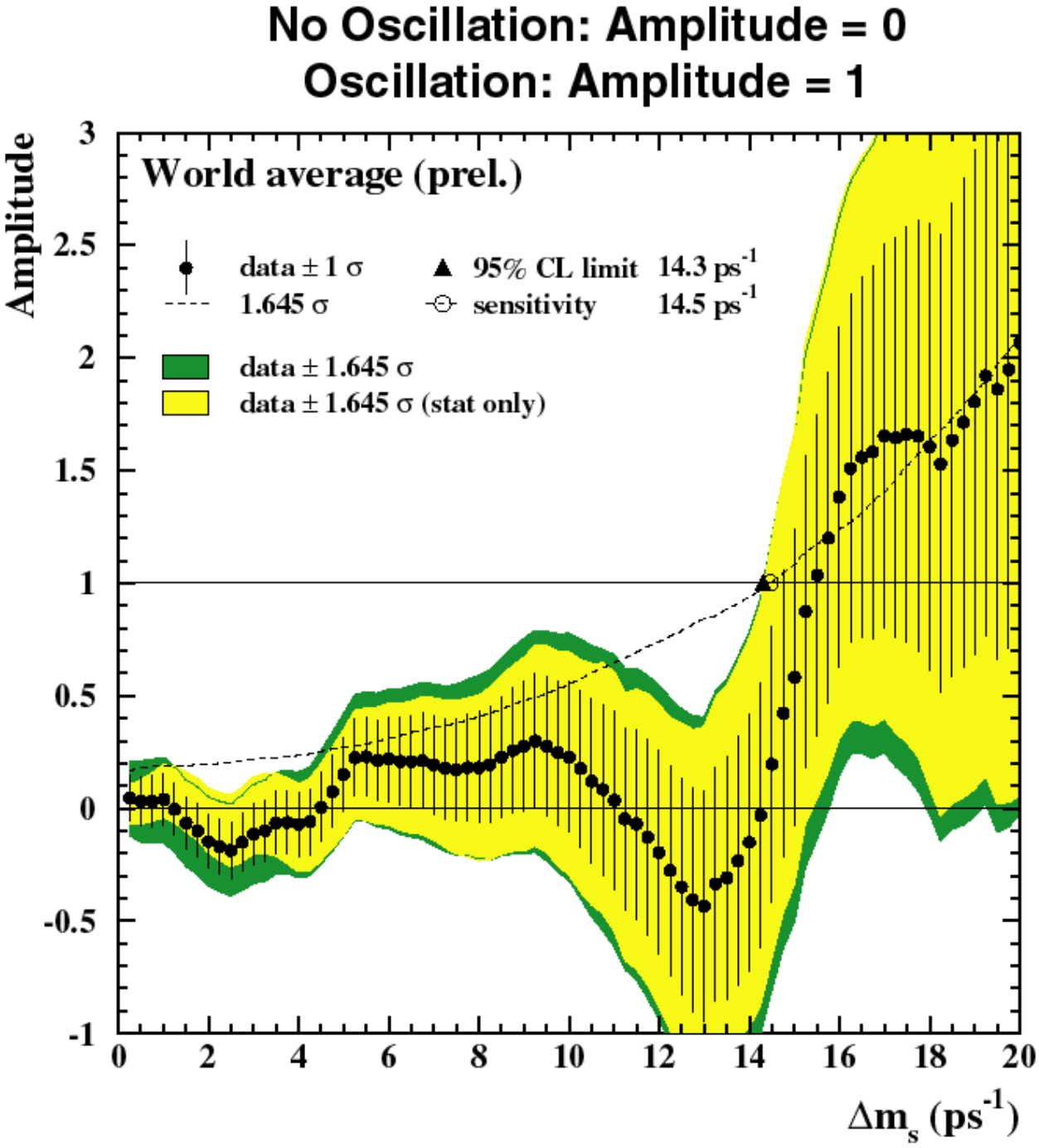
$$P(t) = \frac{\Gamma}{2} e^{-\Gamma t} (1 \pm A \cos \Delta m_s t)$$

Oscillations: $A=1$
No Oscillations: $A=0$




*Best single limit:* *ALEPH inclusive lepton*
$\Delta m_s > 9.5 ps^{-1}$ *at 95% CL*

# Combined $B_s$ Oscillation Amplitude in 1999




- The worldwide combination shows deviation near $\Delta m_s = 16.3\ ps^{-1}$ (2.0 standard deviations)
- This could suggest the presence of a signal, but it is beyond the sensitivity of 14.5 $ps^{-1}$

# Conclusion on $B^0$ Oscillation

*Results from ALEPH, DELPHI, L3, OPAL, SLD and CDF:*

- $B_d^0$ *oscillation frequency for time-dependent mixing has been measured accurately*
- *Bound on* $B_s^0$ *oscillation frequency for time-dependent mixing has been obtained*

| Mass differences for the long and short eigenstates | | |
|---|---|---|
| | $\Delta m$ ( $ps^{-1}$ ) | $\Delta m$ ( eV ) |
| $\Delta m_d$ | $0.482 \pm 0.016$ | $(3.17 \pm 0.11) \times 10^{-4}$ |
| $\Delta m_s$ (95%C.L) | $> 14.3$ ( $x_s > 20.9$ ) | $> 9.4 \times 10^{-3}$ |

$$\left| \frac{V_{ts}}{V_{td}} \right| > 4.5 \quad @95\% \text{ C.L.}$$

# $|V_{cb}|$

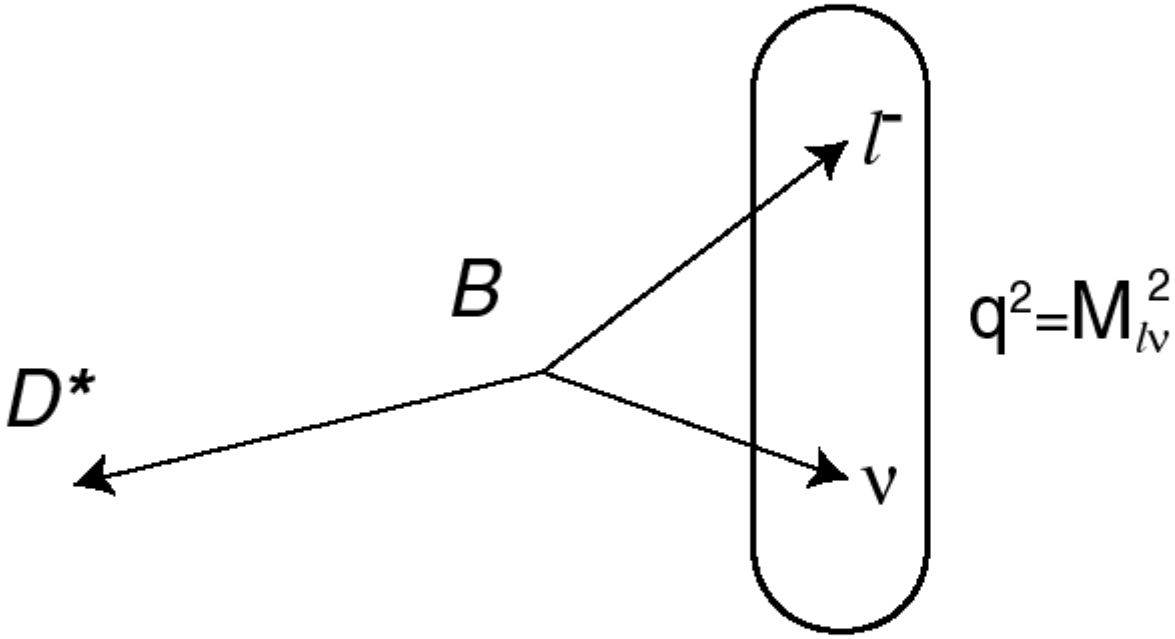
2 Methods:

Exclusive - using $\overline{B^0_d} \to D^{*+} \ell^- \overline{\nu}_\ell$

Inclusive - using $Br(b \to \ell^- \overline{\nu}_\ell X)$

Exclusive:

Study $\Gamma(\overline{B^0_d} \to D^{*+} \ell^- \overline{\nu}_\ell)$ as a function of $q^2$




$|V_{cb}|_{exclusive} = (38.4 \pm 1.1 stat \pm 2.2 syst \pm 2.2 theory) \times 10^{-3}$

*LEP Average*

Inclusive: $|V_{cb}|^2 \propto \Gamma(B \to \ell^- \overline{\nu}_\ell X_c)$

$Br(b \to \ell^- \overline{\nu}_\ell X)_{LEP} = (10.58 \pm 0.18)\%$

$Br(b \to \ell^- \overline{\nu}_\ell X_u)_{LEP} = (1.67 \pm 0.55) \times 10^{-3}$

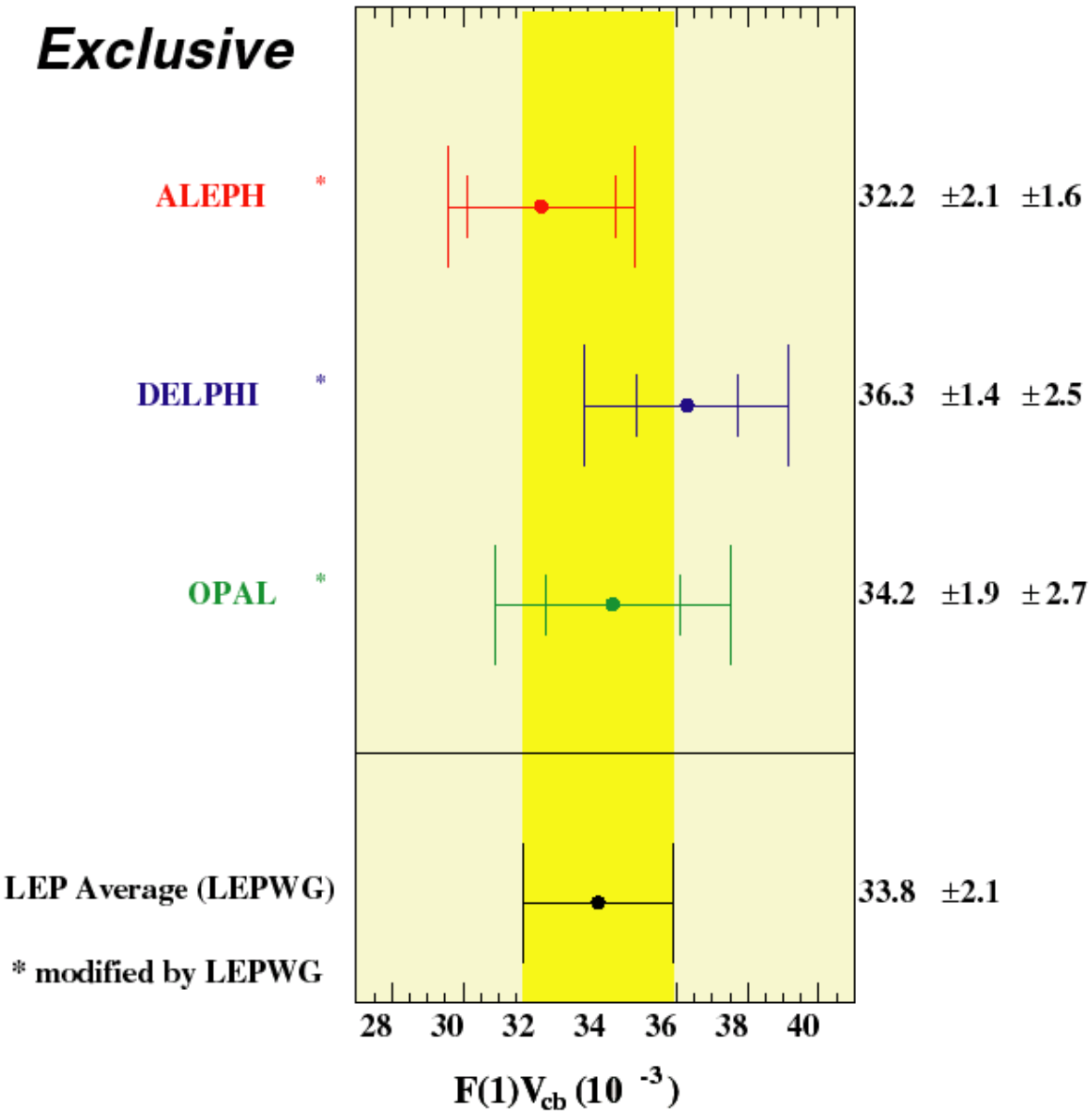
and $\langle \tau_b \rangle = (1.554 \pm 0.015)$ps

$|V_{cb}|_{inclusive} = (40.76 \pm 0.41 exp \pm 2.04 theory) \times 10^{-3}$

*LEP Average*

# $|V_{cb}|$ Results

## Exclusive




## Average of exclusive and inclusive:

$$|V_{cb}| = (40.2 \pm 1.9) \times 10^{-3}$$

LEP Average

(LEP $V_{cb}$ Working Group)

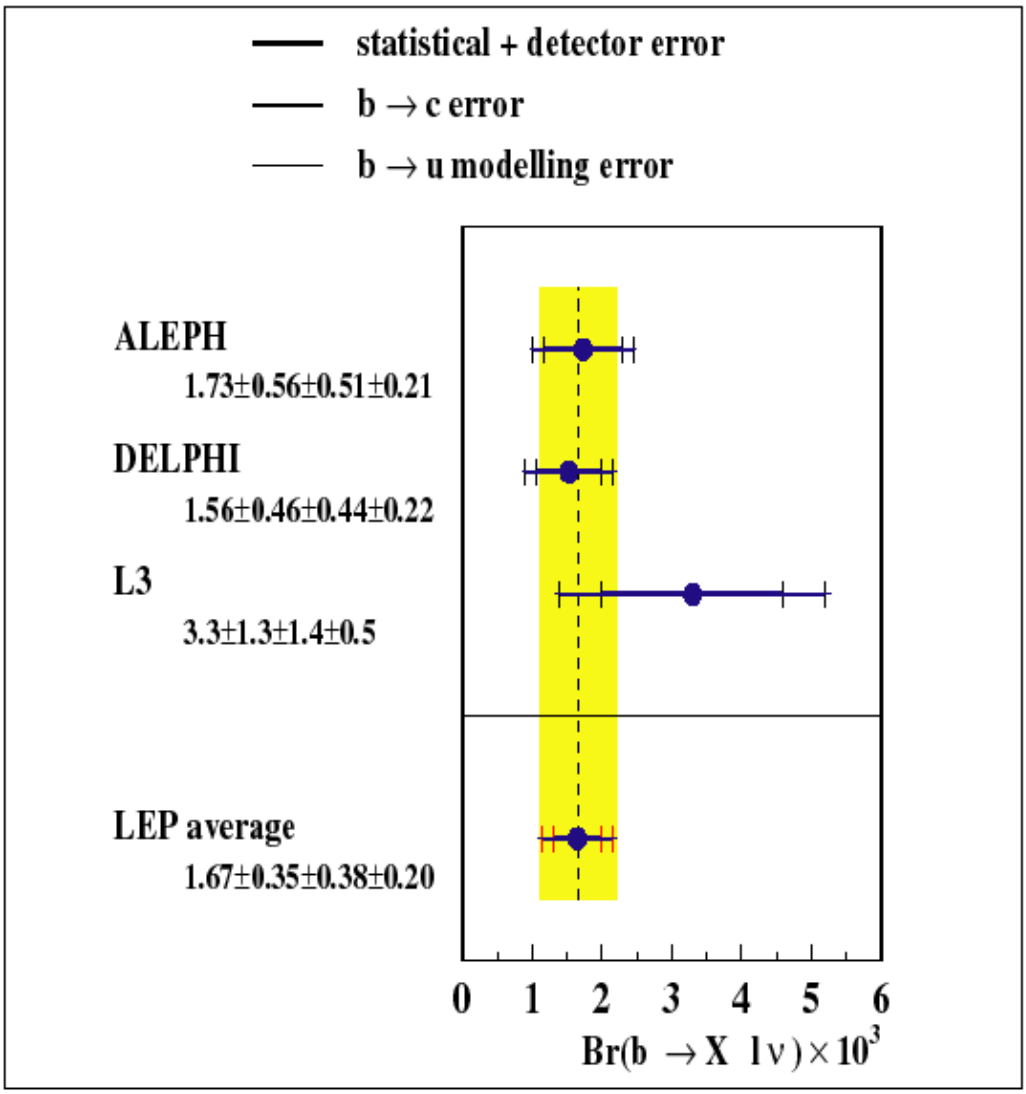
## CLEO measure (at $\Upsilon(4S)$):

$$|V_{cb}| = (39.9 \pm 3.7) \times 10^{-3} \quad \text{Exclusive}$$

$$|V_{cb}| = (40.4 \pm 2.5) \times 10^{-3} \quad \text{Inclusive}$$

# $|V_{ub}|$

*ALEPH, DELPHI, L3 measure the inclusive yield of $b \to u$ transitions in $b \to \ell^- \bar{\nu}_\ell X$ decays*




$$|V_{ub}|^2 \propto Br(b \to X_u \ell^- \bar{\nu}_\ell)$$

$$|V_{ub}| = (4.04^{+0.62}_{-0.73}) \times 10^{-3}$$

LEP $V_{ub}$ Working Group

**CLEO:** [Lepton-Photon '99]

$|V_{ub}| = (3.25^{+0.61}_{-0.64}) \times 10^{-3}$ from $B \to \rho \ell \nu$

$|V_{ub}| = (3.2 \pm 0.8) \times 10^{-3}$ Inclusive

# Outline IV

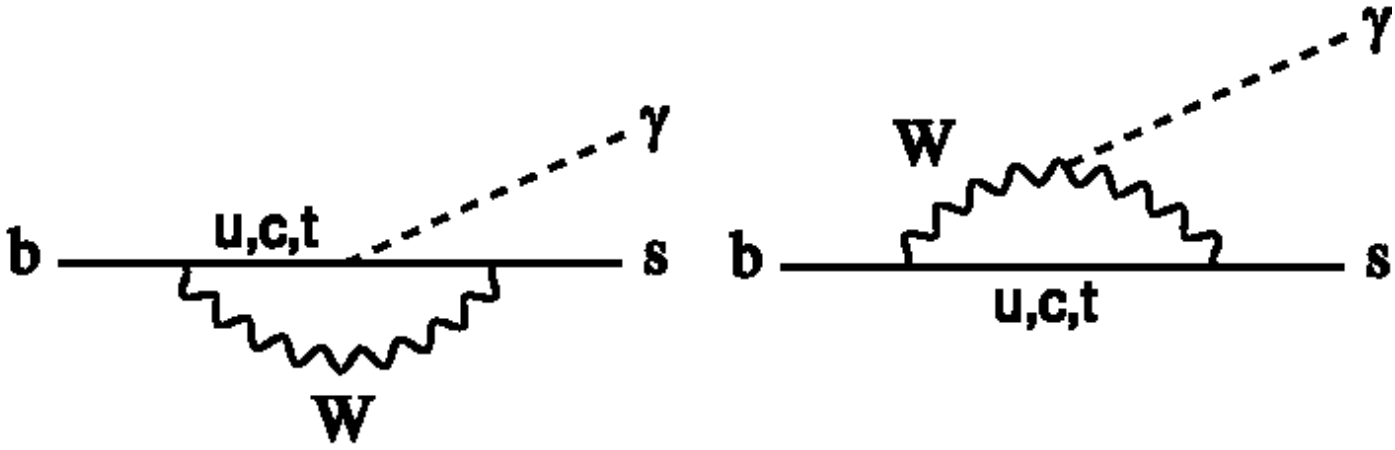
## Rare Decays and CP Violation

- $B \to s\gamma$
- CP Violation in B Decays

## $b \to s\gamma$

Flavor Changing Neutral Current Decay

via Electromagnetic Penguin:




**Sensitive to new physics -**

- **loop may contain $H^{\pm}$ or a SUSY particle**
- **new contributions could enhance or suppress the decay rate**

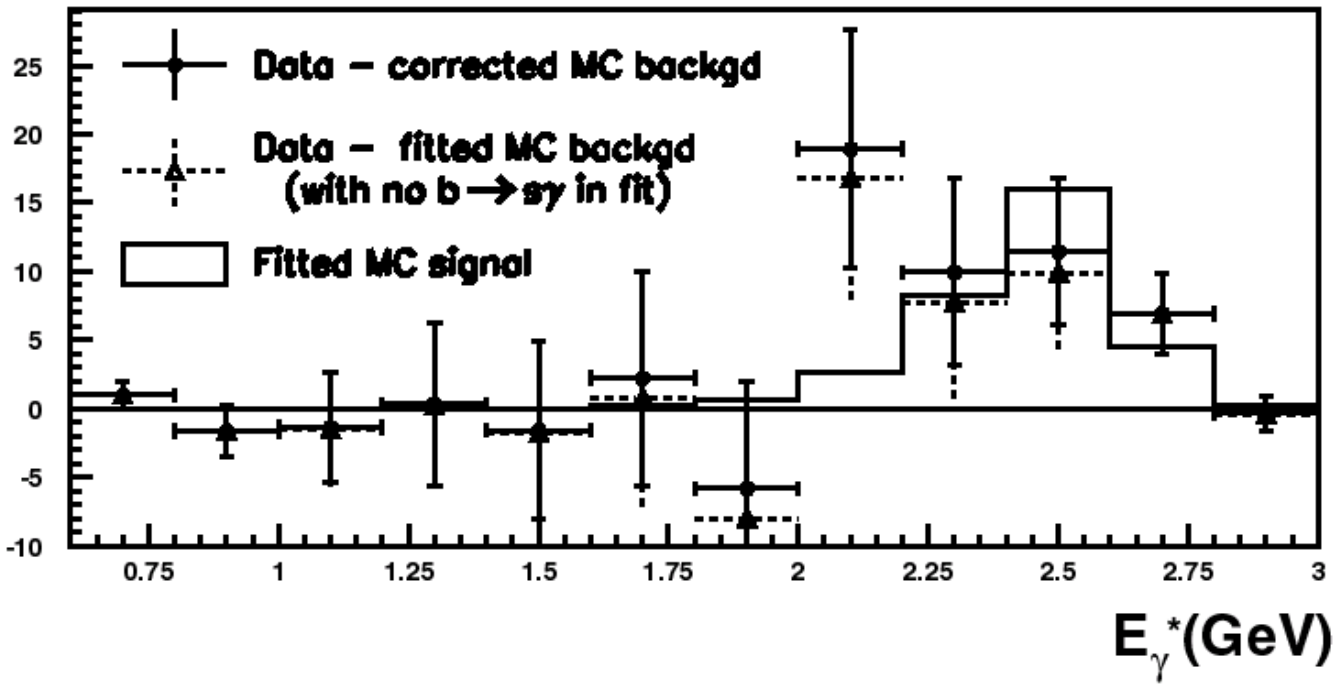
**First evidence of a penguin decay:**
**CLEO (1993)** [PRL **71** (1993)674]

**$B \to K^*(892)\,\gamma$**

$b \to s\gamma$

**ALEPH:** [PL **B 429** (1998) 169]

**Look for excess: 2.2GeV < $E_\gamma^*$ < 2.8 GeV**




**ALEPH** $Br\,(b \to s\gamma) = (3.11 \pm 0.80 \pm 0.72) \times 10^{-4}$

***Standard Model:*** $(3.28 \pm 0.33) \times 10^{-4}$

[Kagan & Neubert, EPJ **C7** (1999) 5]

***CLEO:*** $(3.15 \pm 0.35 \pm 0.32 \pm 0.26) \times 10^{-4}$

# CP Violation in $B^0$ Decay

***Golden channel:*** $\overline{B}^0, B^0 \to J/\psi\, K_s^0$ (CP eigenstate)

***CP violating asymmetry:***

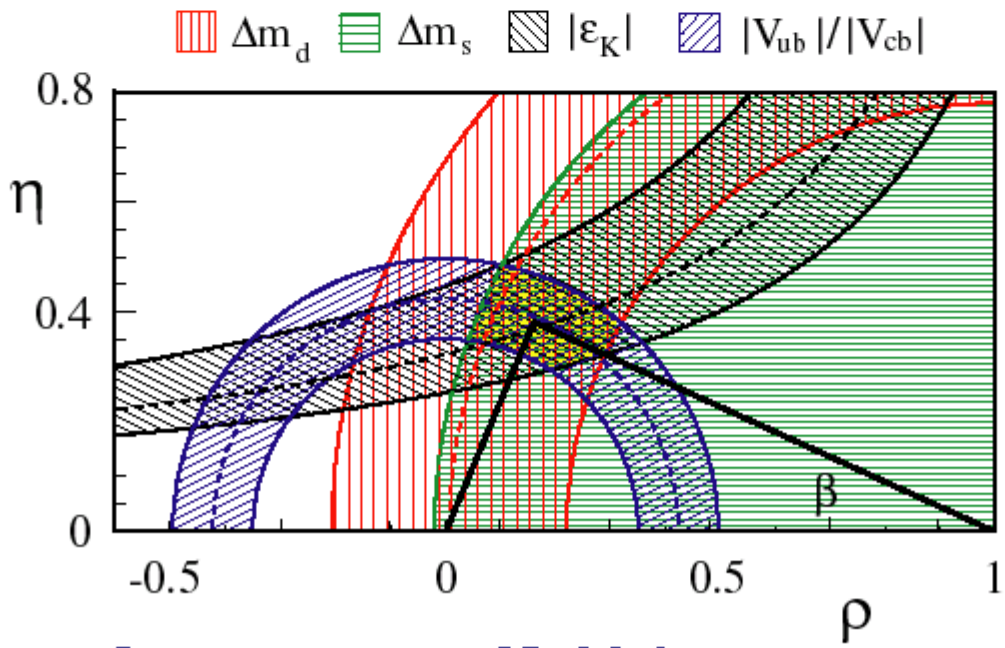
$$A(t) = \frac{\Gamma(B^0 \to J/\psi\, K_s^0) - \Gamma(\overline{B}^0 \to J/\psi\, K_s^0)}{\Gamma(B^0 \to J/\psi\, K_s^0) + \Gamma(\overline{B}^0 \to J/\psi\, K_s^0)}$$

$$= -\sin 2\beta \sin \Delta m_d t$$

***β is an angle of the "unitarity triangle":***

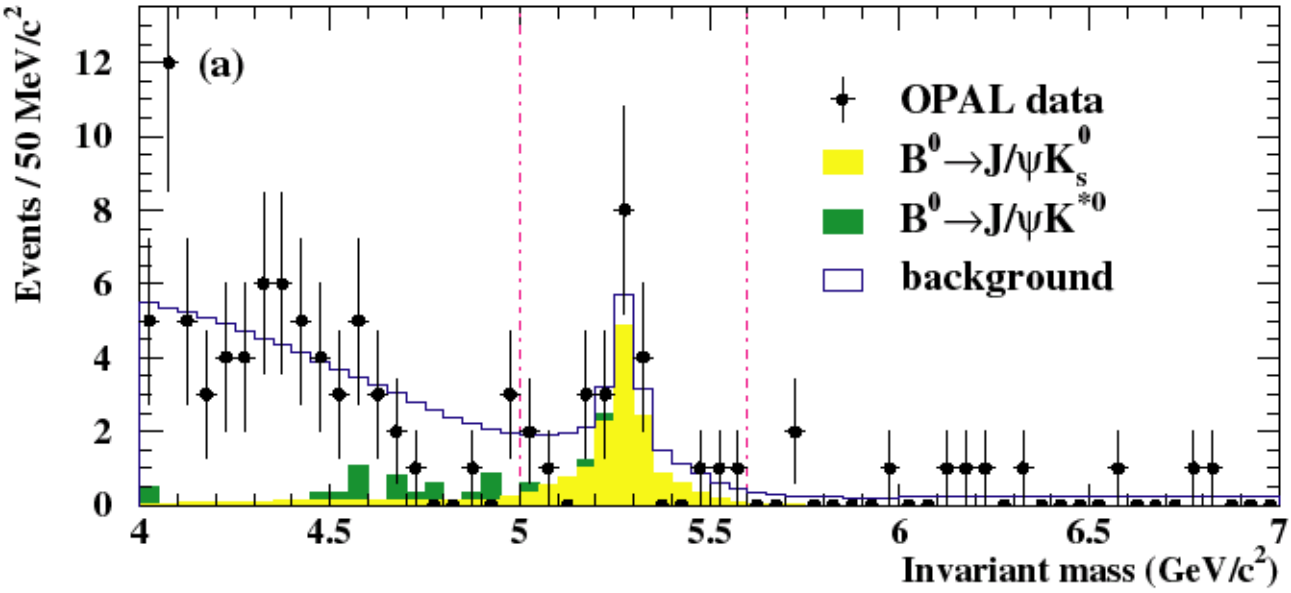
$$\beta = \arg\left(\frac{-V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

**Indirect determination from CKM constraints:**

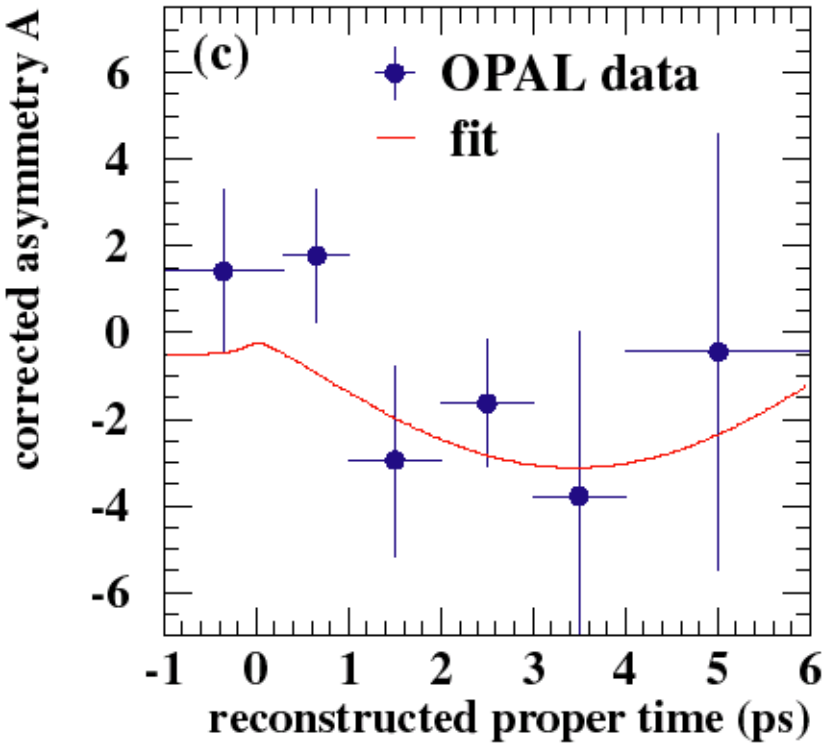



→ $\sin 2\beta = 0.75 \pm 0.09$ [S. Mele, PRD 59 (1999) 113011]

# CP Violation in $B^0$ Decay



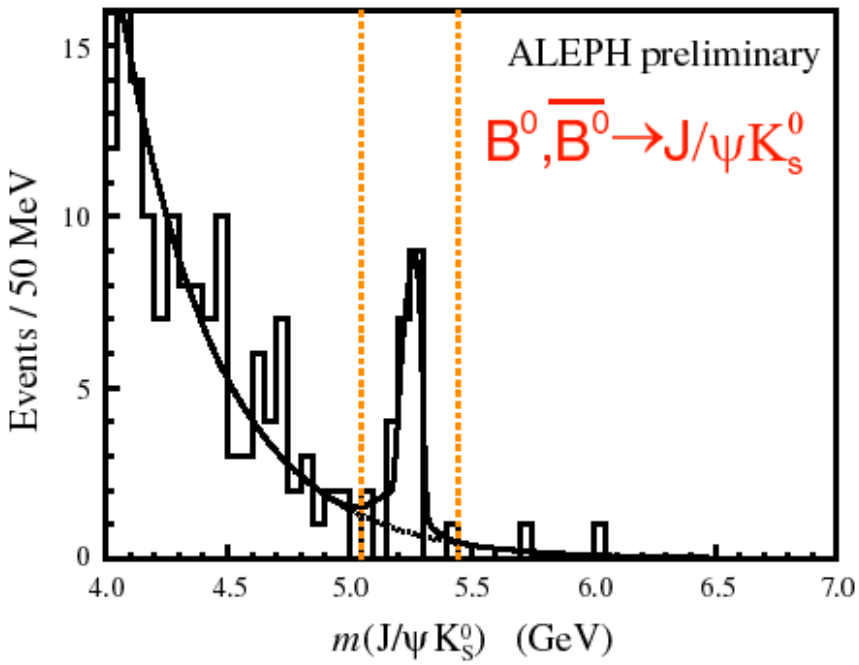

**24 events in signal region, purity=60±8%**




$$\sin 2\beta = 3.2\,^{+1.8}_{-2.0}\,(\text{stat}) \pm 0.5\,(\text{syst})$$

[OPAL, EPJ **C5** (1998) 379.]

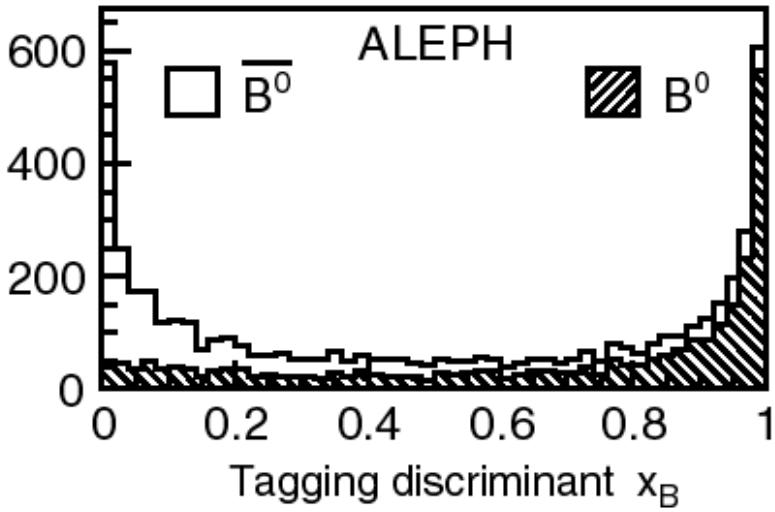
# CP Violation in $B^0$ Decay



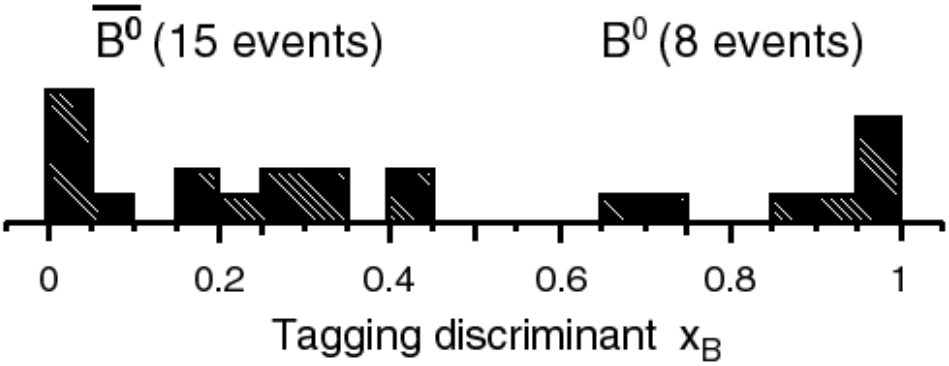

***23 events in signal region***

***purity=71±12%***

***six variable discriminant production - state tag: (jet charge, vertex charge, lepton $p_t$ x charge, etc.)***

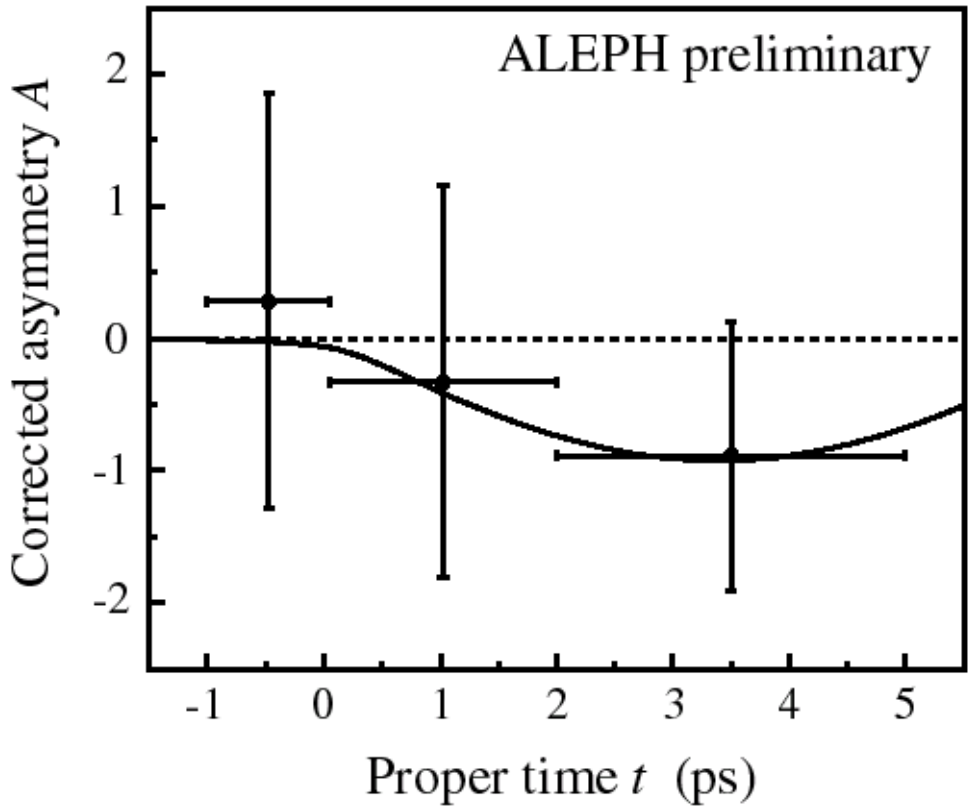



***(Monte Carlo)***




***(Data)***

# CP Violation in $B^0$ Decay




$$\sin 2\beta = 0.93\ ^{+0.64}_{-0.88}\ (\text{stat})\ ^{+0.36}_{-0.24}\ (\text{syst})$$

***Roger Forty, Contributed Evening Session I, "Study of CP Asymmetry of $B \to J/\psi\ K_S$ Decays in ALEPH"***

# CP Violation in $B^0$ Decay

First Results:

OPAL: $\sin 2\beta = 3.2\ ^{+1.8}_{-2.0}\,(stat) \pm 0.5(syst)$

[OPAL, EPJ C5 (1998) 379]

CDF: $\sin 2\beta = 0.79\ ^{+0.41}_{-0.44}$

[CDF, FERMILAB-PUB-99/225-E]

ALEPH: $\sin 2\beta = 0.93\ ^{+0.64}_{-0.88}\,(stat)\ ^{+0.36}_{-0.24}(syst)$

[Preliminary, this conference]

Combined result: $\boxed{\sin 2\beta = 0.91 \pm 0.35}$

Roger Forty

Prob ($\sin 2\beta < 0$) = 7 % (CDF alone)
1.5 % (all combined)

→ ***Confidence level that CP violation has been observed is almost 99%***

## Conclusion

*In the last 10 years, the four LEP experiments*

*ALEPH, DELPHI, L3, OPAL*

*have each collected ~0.9 million $b\bar{b}$ events.*

*With these data, they have produced an impressive array of results, advancing the field of B physics greatly.*

# Conclusion

***Among the highlights:***

- ***Discovery of b baryons and strange B mesons***
- ***Measurement of the mass and lifetimes of various b hadrons***
  ***low b baryon lifetime still a theoretical puzzle***
- ***First observation of $B_d^0$ oscillations and the precise determination of $\Delta m_d$***
  ***$\Delta m_d = (0.482 \pm 0.016) ps^{-1}$ (World Average)***
- ***First and best lower limit on the $B_s^0$ oscillation frequency, $\Delta m_s$***
  ***$\Delta m_s > 14.3 ps^{-1}$ (95% C.L.) World comb.***

- ***Contributions to the measurement of the CK M matrix elements $|V_{cb}|$, $|V_{ub}|$***
- ***Contributions to the measurement of $\sin 2\beta$***
  ***$\sin 2\beta = 0.91 \pm 0.35$ (CDF, OPAL, ALEPH)***