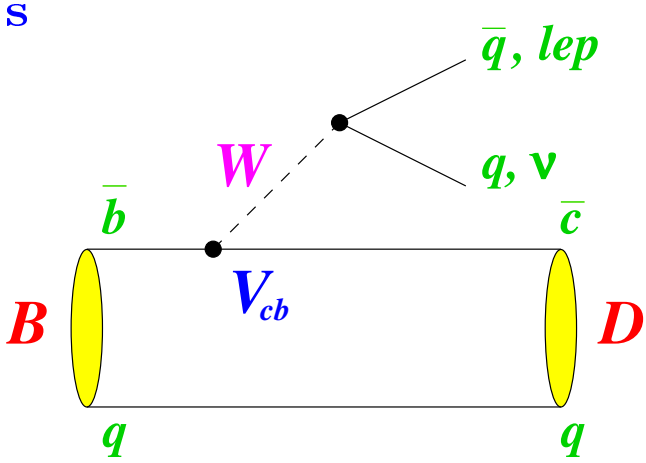
B Hadron Lifetimes

⋆ Why are we interested in B lifetimes?

- Fundamental particle properties
- Needed to determine SM parameter V_{cb}
  - In principal, τ_B related to V_{cb}
  - $B^0 \to D^{*-}\ell^+\nu$, need $\tau(B^0)$ to extract V_{cb}
- Important test of our understanding of the interactions involved in B meson decays

$\Longrightarrow$ Non-spectator effects

⋆ Spectator model of B hadron decay:



- b quark decays like free particle

$$\frac{1}{\tau_B} = \Gamma_B \propto \frac{G_F^2\, m_b^5}{192\,\pi^3} \cdot |V_{cb}|^2 \cdot \mathcal{F}$$

$\Longrightarrow$ $$\tau(B^+) = \tau(B^0) = \tau(B_S^0) = \tau(\Lambda_b)$$

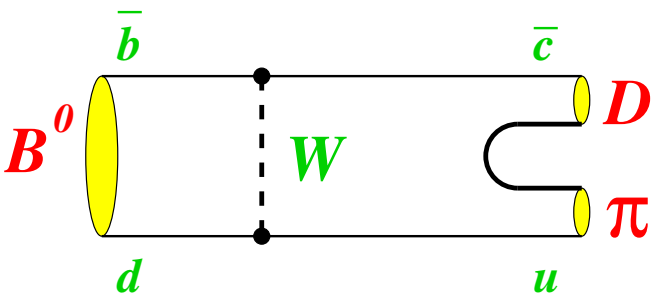
- This did not work for charm system:

$$\tau(D^+) \sim 2.5\,\tau(D^0) \sim 2.5\,\tau(D_S^-) \sim 5\,\tau(\Lambda_c)$$

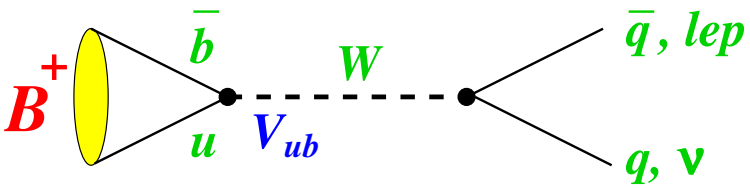
$\Longrightarrow$ Significant non-spectator contributions

B Hadron Lifetimes

Non-spectator effects:

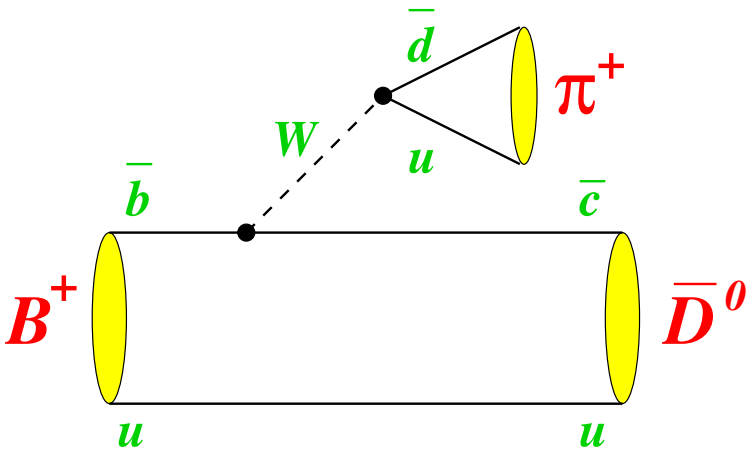


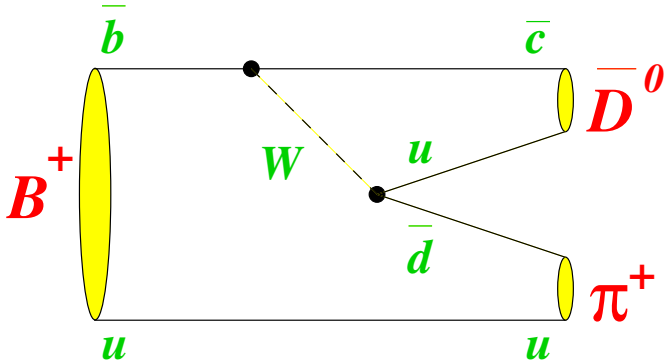
W exchange



Annihilation

Final state interference





destructive interference: not present in B^0

$\Longrightarrow$ $\tau(B^+) > \tau(B^0)$ (expect 5% difference)

B_S^0 Meson Lifetime

★ What is interesting about B_S^0 lifetime?

- B_S^0 system: 2 CP-conjugate states:

  $|B_S^0\rangle = |\bar{b}s\rangle$ and $|\bar{B}_S^0\rangle = |b\bar{s}\rangle$

- Mass eigenstates $\neq$ Flavour eigenstates

  $|B_S^H\rangle = p\,|B_S^0\rangle + q\,|\bar{B}_S^0\rangle$ H: heavy

  $|B_S^L\rangle = p\,|B_S^0\rangle - q\,|\bar{B}_S^0\rangle$ L: light $\quad (p^2+q^2=1)$

- $\Delta m \equiv m_H - m_L \;\Rightarrow\; B\bar{B}$ mixing

- $\Delta\Gamma \equiv \Gamma_L - \Gamma_H \;\Rightarrow$ lifetime difference

- Theory: $\Delta\Gamma/\Gamma \sim$ 10-20% in B_S^0 system

  Note: heavy = long lived = CP odd

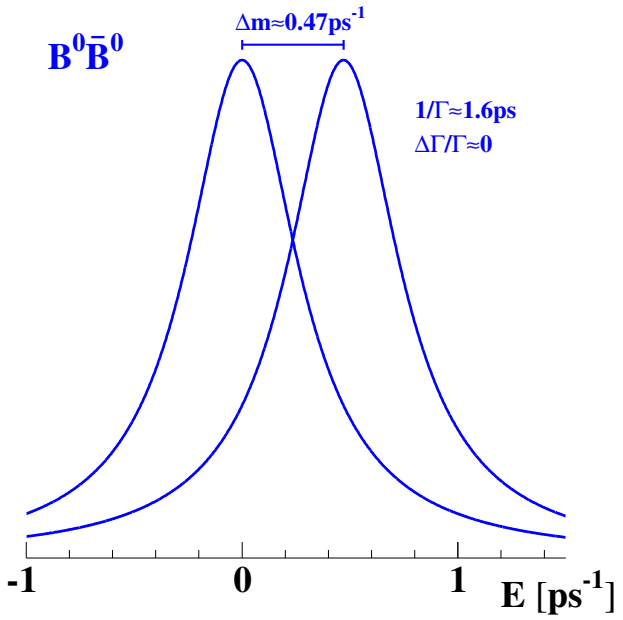
  light = short lived = CP even

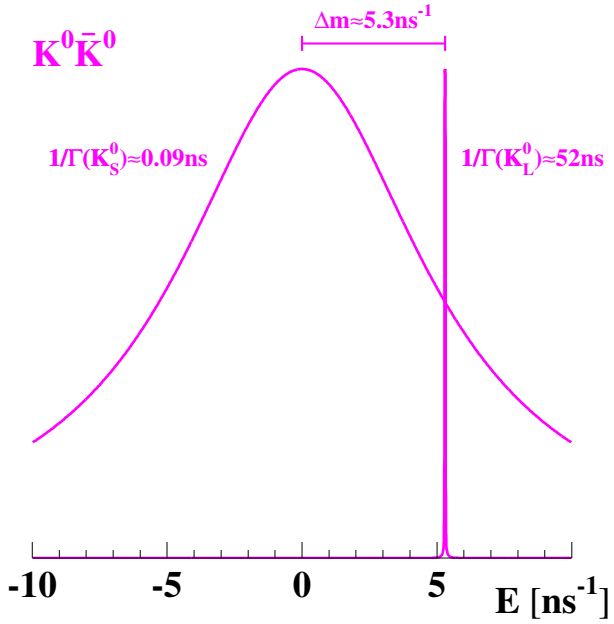
- $\Delta\Gamma/\Delta m$ = const. in SM
  (depends only on QCD corrections)

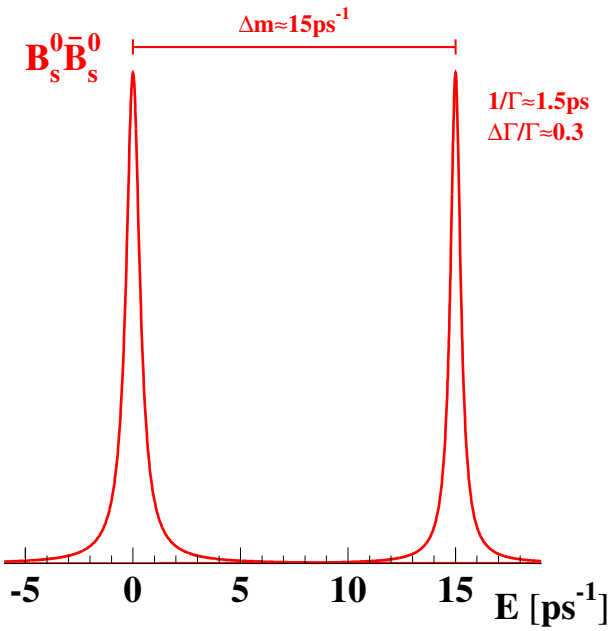
$\Longrightarrow$ Measurement of $\Delta\Gamma_S$ would allow determination of Δm_S ($B_S^0\bar{B}_S^0$ oscillations)

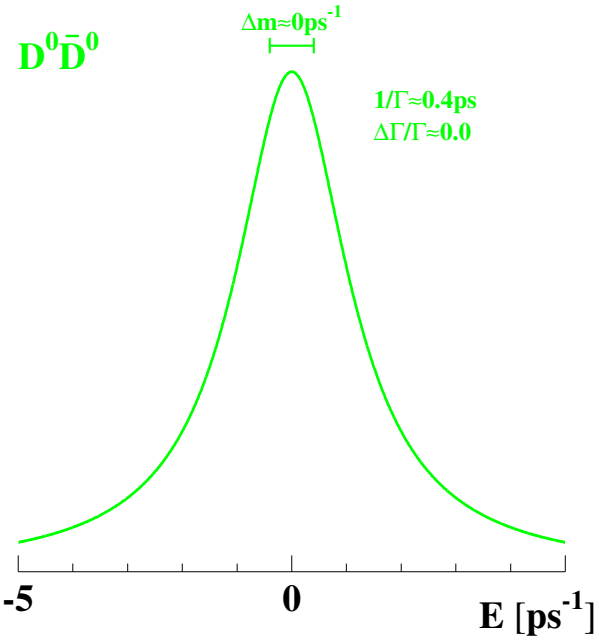
B_S^0 Meson Lifetime

$\Delta\Gamma$ and Δm in neutral meson systems:



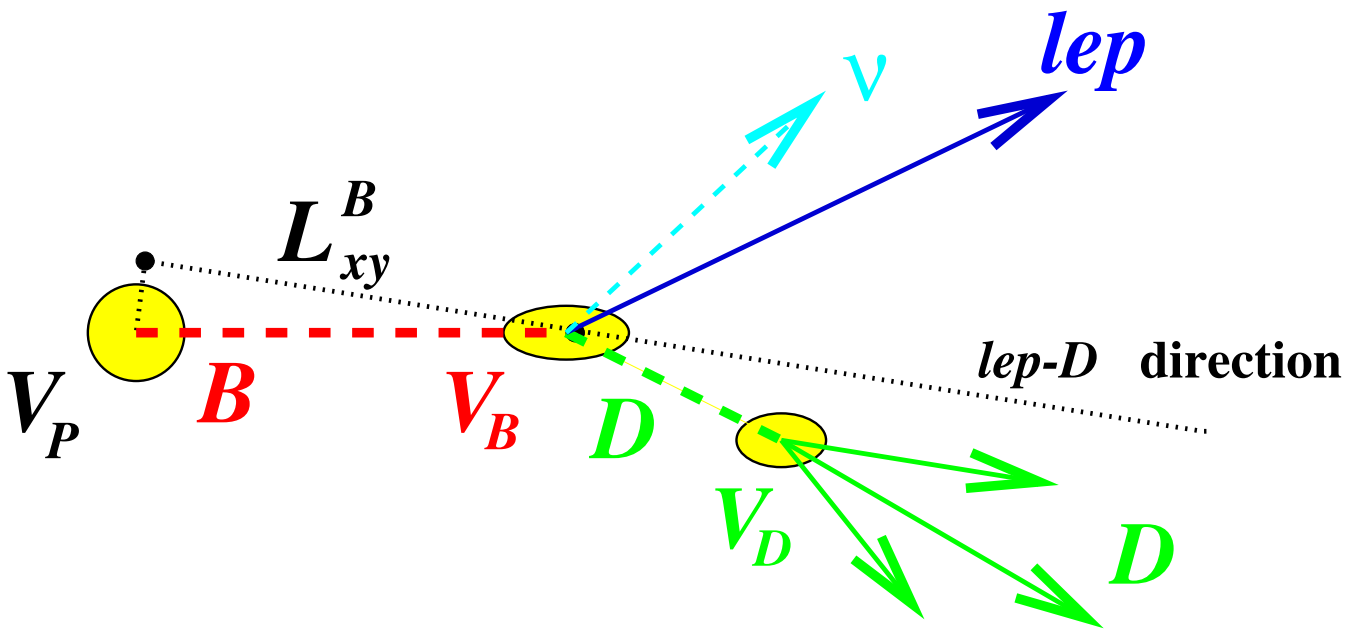






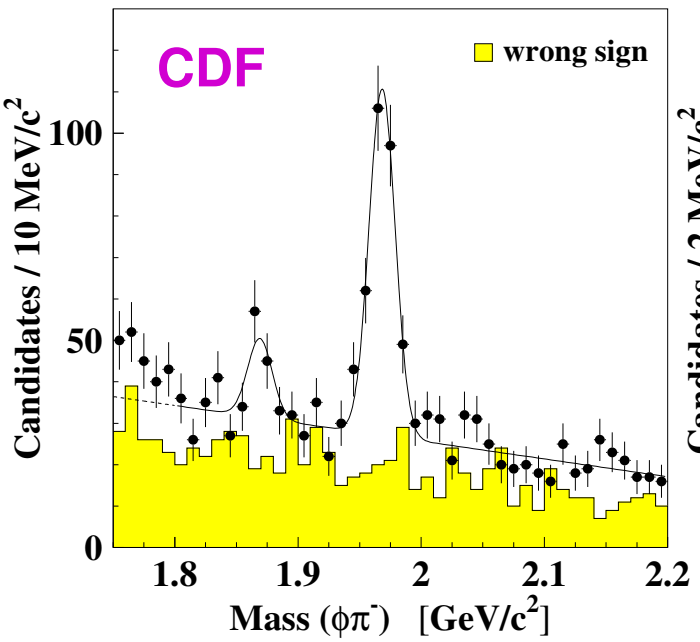
B_S^0 Meson Lifetime

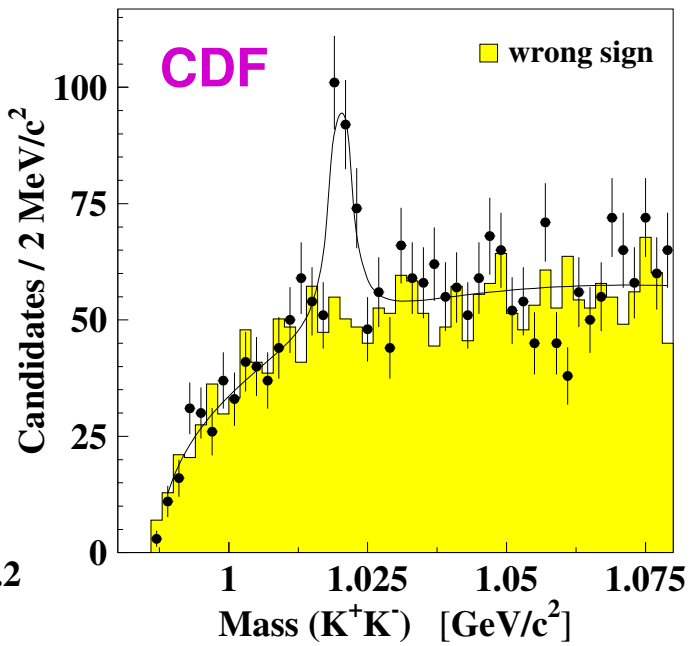
B_S^0 lifetime as example of B lifetime measurement



Reconstruct $B_S^0 \to D_S^- \ell^+ \nu X$ $(\ell = e, \mu)$ with

e.g. $D_S^- \to \phi\pi^-$, $D_S^- \to \phi\mu^-\nu$





B_S^0 Meson Lifetime

- Transverse decay length:

$$L_{\rm xy}^B = \frac{\vec{X} \cdot \vec{p_T^B}}{|\vec{p_T^B}|}$$

- Proper decay length:

$$c\tau(B_S^0) = L_{\rm xy}^B \cdot \frac{m(B_S^0)}{p_T(B_S^0)} = L_{\rm xy}^B \cdot \frac{1}{(\beta\gamma)^B}$$

- B_S^0 not fully reconstructed $\Longrightarrow$ use $p_T(D_S^- \ell^-)$ as estimate of $p_T(B_S^0)$
- Pseudo proper decay length:

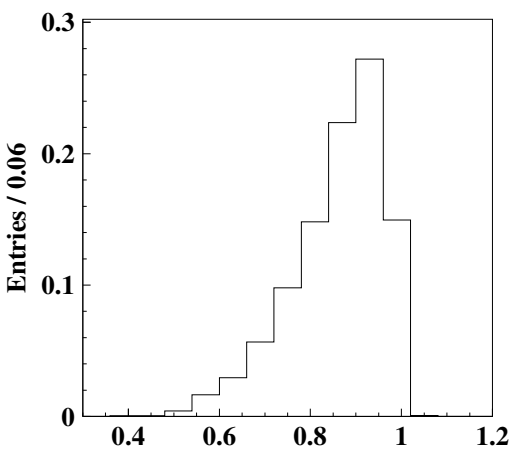
$$c\tau^*(B_S^0) = L_{\rm xy}^B \cdot \frac{m(B_S^0)}{p_T(D_S^- \ell^-)}$$

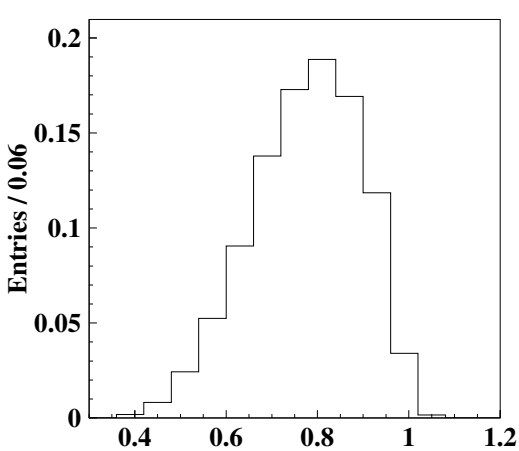
- Correction factor K determined from MC:

$$K \equiv \frac{p_T(D_S^- \ell^-)}{p_T(B_S^0)}$$

- Proper decay length:

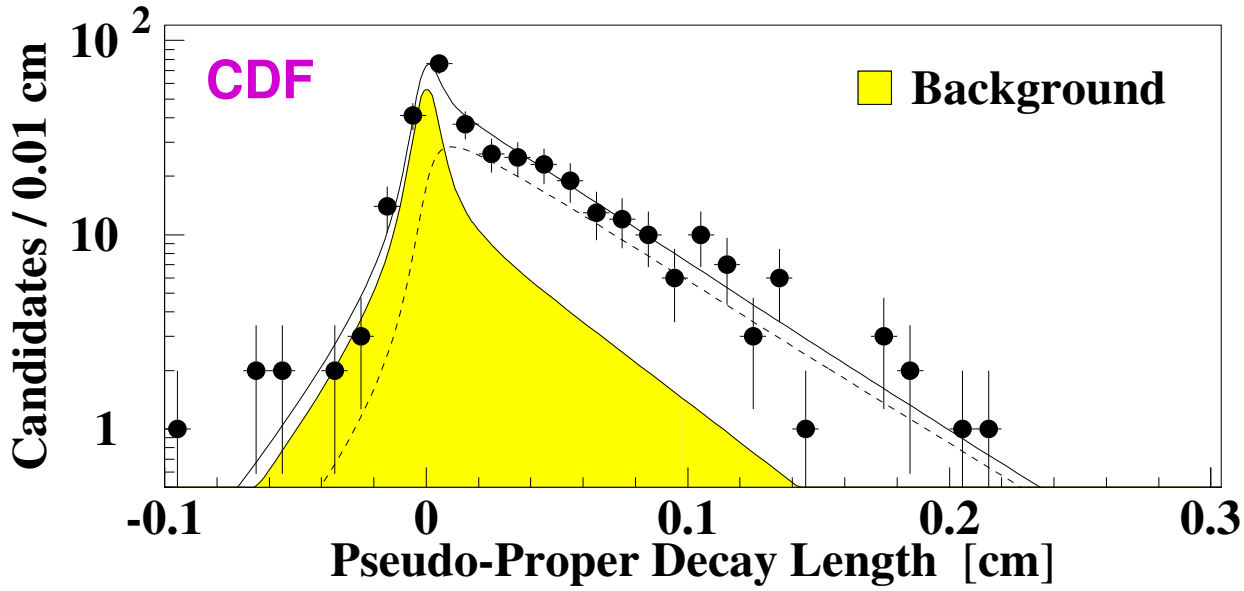
$$c\tau(B_S^0) = L_{\rm xy}^B \cdot \frac{m(B_S^0)}{p_T(D_S^- \ell^-)} \otimes K$$

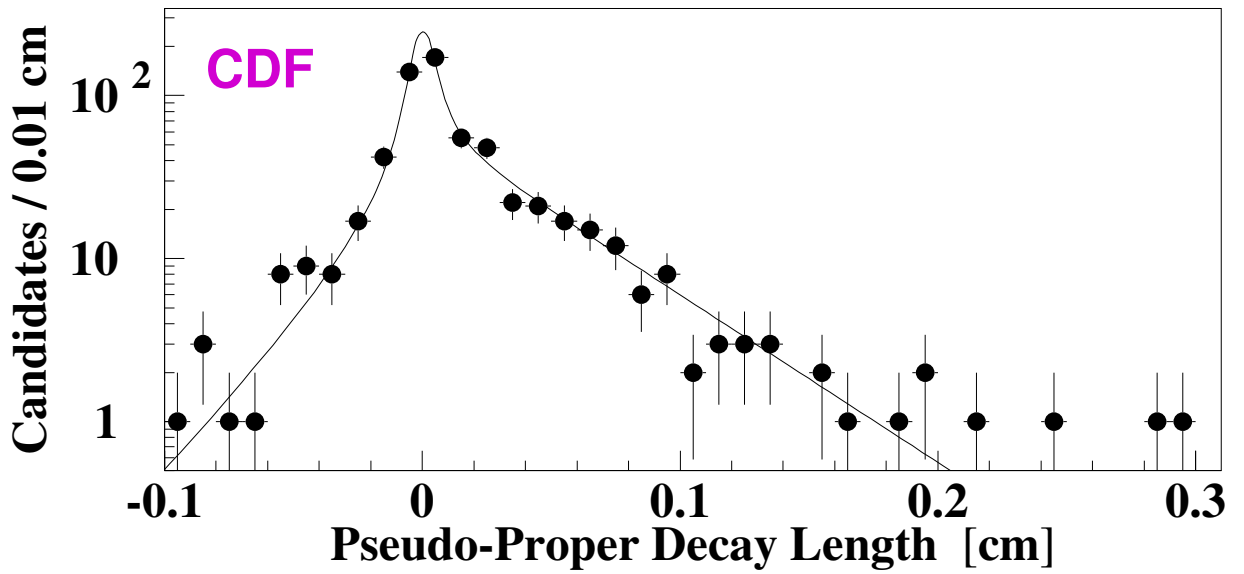




B_S^0 Meson Lifetime

- Simultaneous fit to signal and background
  - Signal described by exponential convoluted with Gaussian convoluted with correction factor
  - Background described by prompt Gaussian and pos. & neg. exponentials convoluted with Gaussians
- E.g. $D_S^- \to \phi\pi^-$: $c\tau(B_S^0) = (418\ ^{+43}_{-39})\ \mu$m

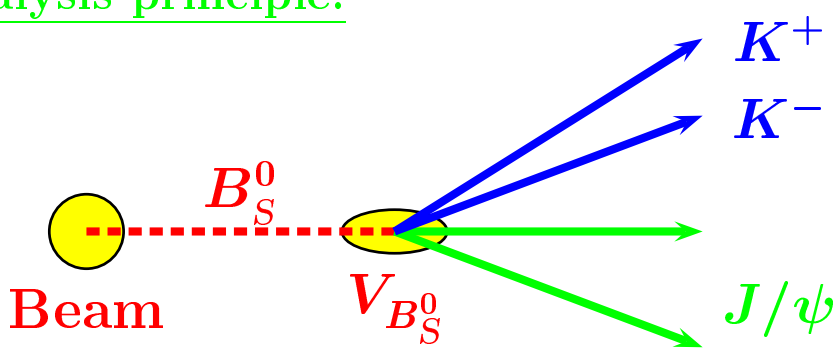




B_S^0 Meson Lifetime

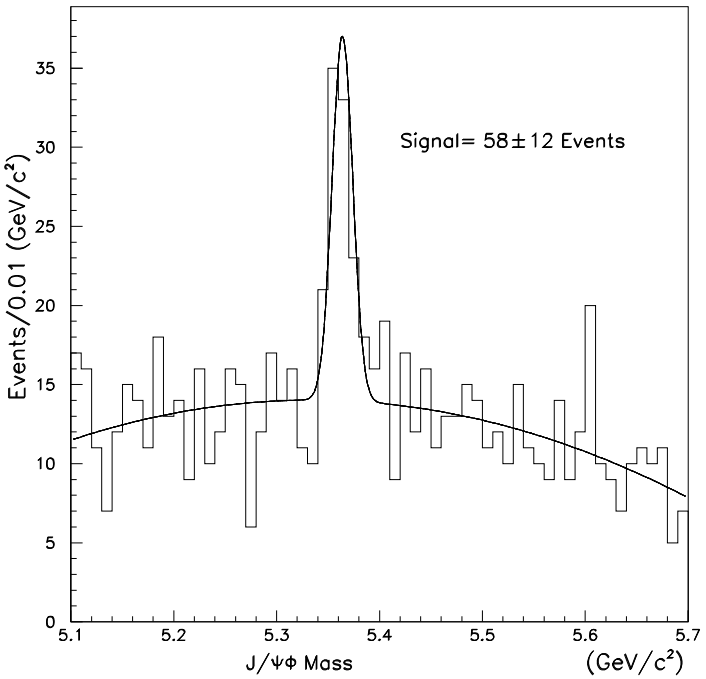
- $B_S^0 \to J/\psi\phi$:

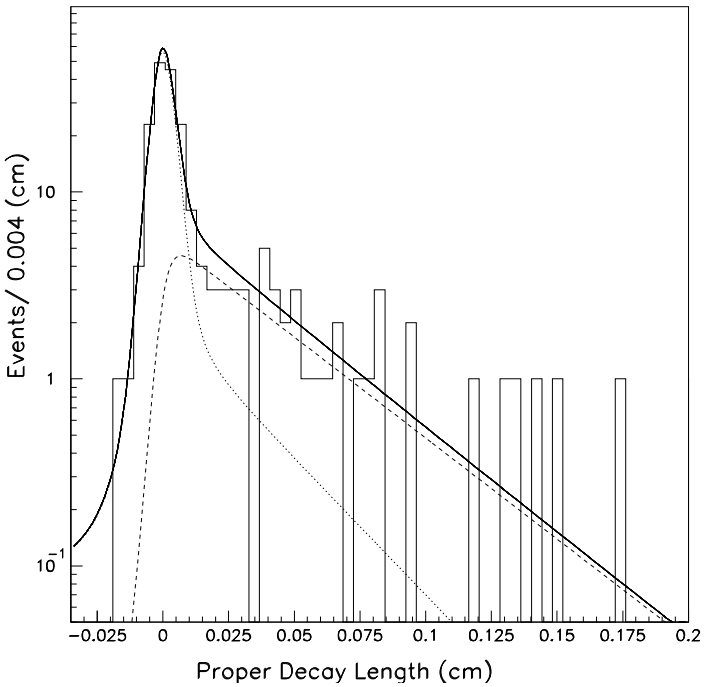
The analysis principle:



- Fully reconstruct $B_S^0 \to J/\psi\,\phi$, $\phi \to K^+K^-$
- B_S^0 momentum known, no $\beta\gamma$ correction
- Lower statistics, $N = 58 \pm 12$ events

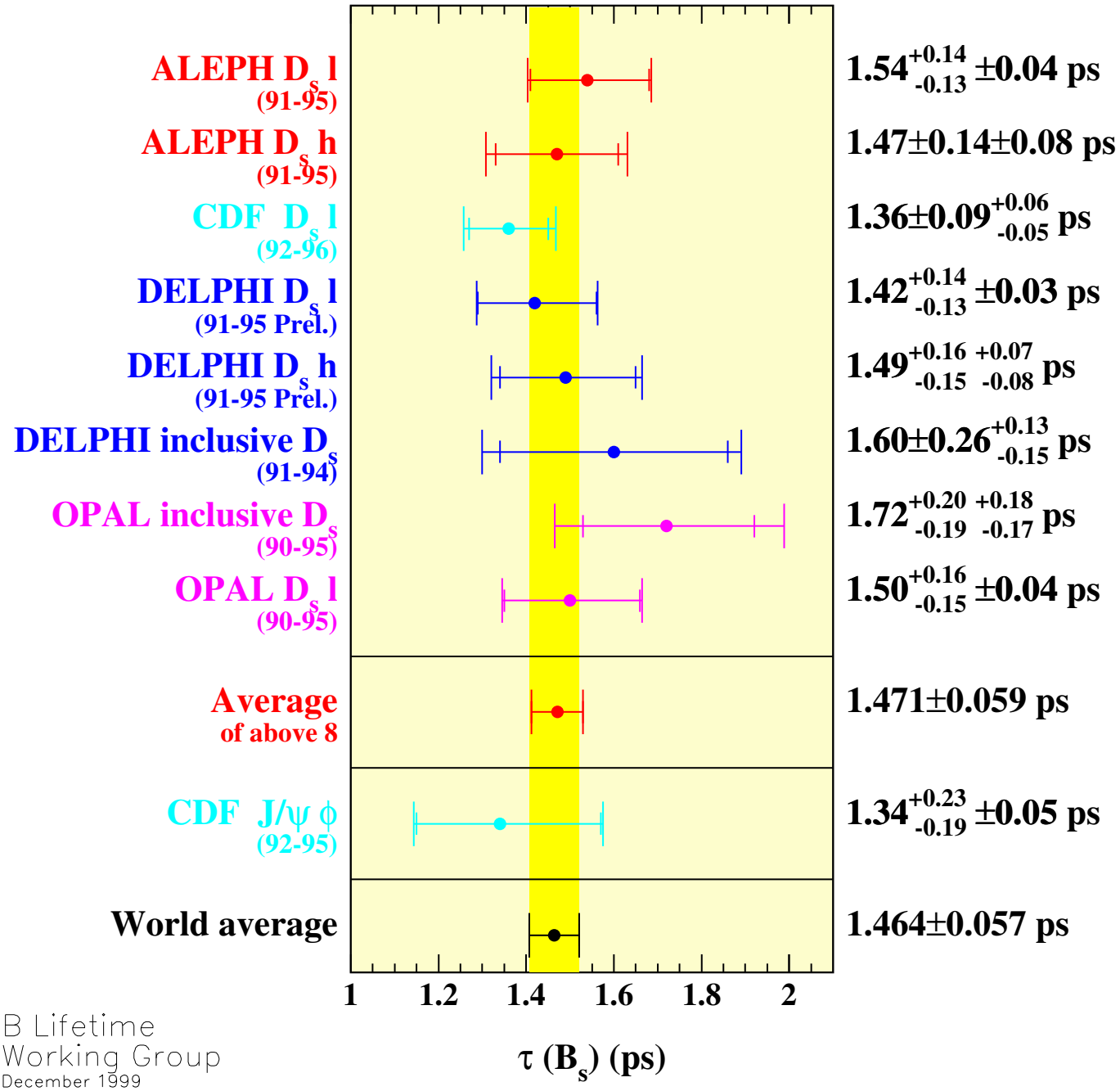
$$\tau(B_S^0) = (1.34\ ^{+0.23}_{-0.19} \pm 0.05)\ \text{ps}$$





B_S^0 Lifetime Comparision

LEP working group determines world averages:



B_S^0 Lifetime Difference

Ways to measure Lifetime Difference $\Delta\Gamma/\Gamma$

- B_S^0 mesons produced as equal mix of B_S^H- B_S^L
- Semileptonic decays $B_S^0 \to D_S^- \ell^+ \nu$:

  Fit B_S^0 proper decay length distribution with

  $$\Gamma_H \Gamma_L / \Gamma \cdot \left(e^{-\Gamma_H t} + e^{-\Gamma_L t} \right)$$

  instead of one exponential $\Gamma \cdot e^{-\Gamma t}$

- Hadronic modes: $B_S^0 \to J/\psi\phi$, $B_S^0 \to D_S^{(*)} D_S^{(*)}$

  In principle mixtures of CP even and CP odd that can be separated by a transversity analysis

$\Rightarrow$ Γ_L or Γ_H can be directly measured from the two CP modes

- If decay mode e.g. CP even dominated ($J/\psi\phi$?) $\Rightarrow$ Γ_L measured and $\Delta\Gamma$ obtained by comparing with lifetime from semilaptonic mode

- Current world average limit (LEP & CDF):

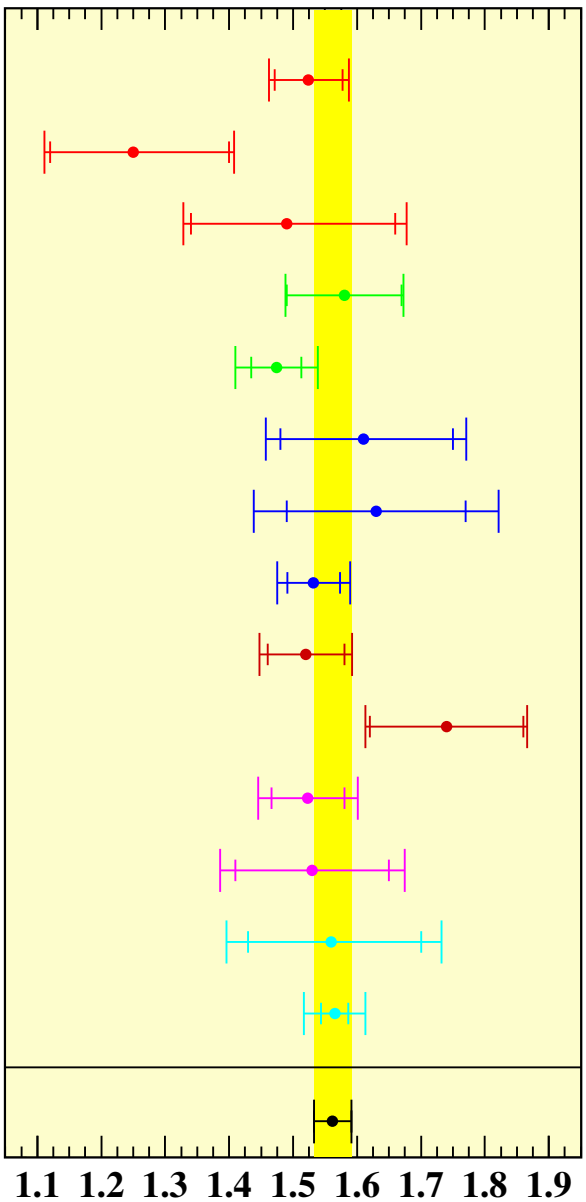
  $$\underline{\Delta\Gamma/\Gamma < 0.33} \quad (95\% \text{ C.L.}).$$

  Use $\Delta\Gamma/\Delta m = (5.6 \pm 2.6) \cdot 10^{-3}$ [PRD54, 4419 (1996)]

- Standard Model limit:

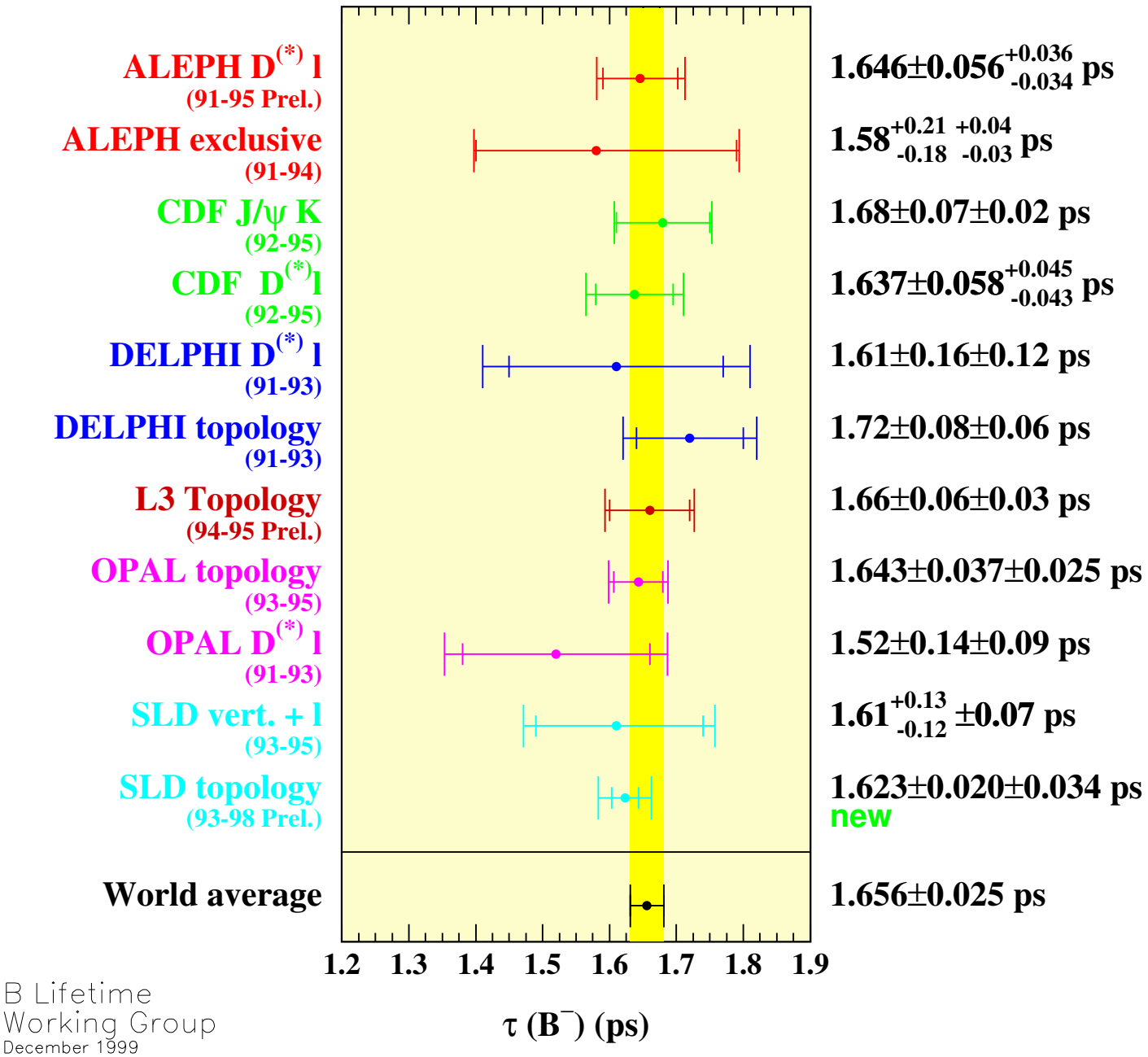
  $$\Delta m_S < 38 \text{ ps}^{-1} \times \left(\frac{5.6 \cdot 10^{-3}}{\Delta\Gamma/\Delta m} \right) \quad (95\% \text{ CL}).$$

B^0 Lifetime Comparision



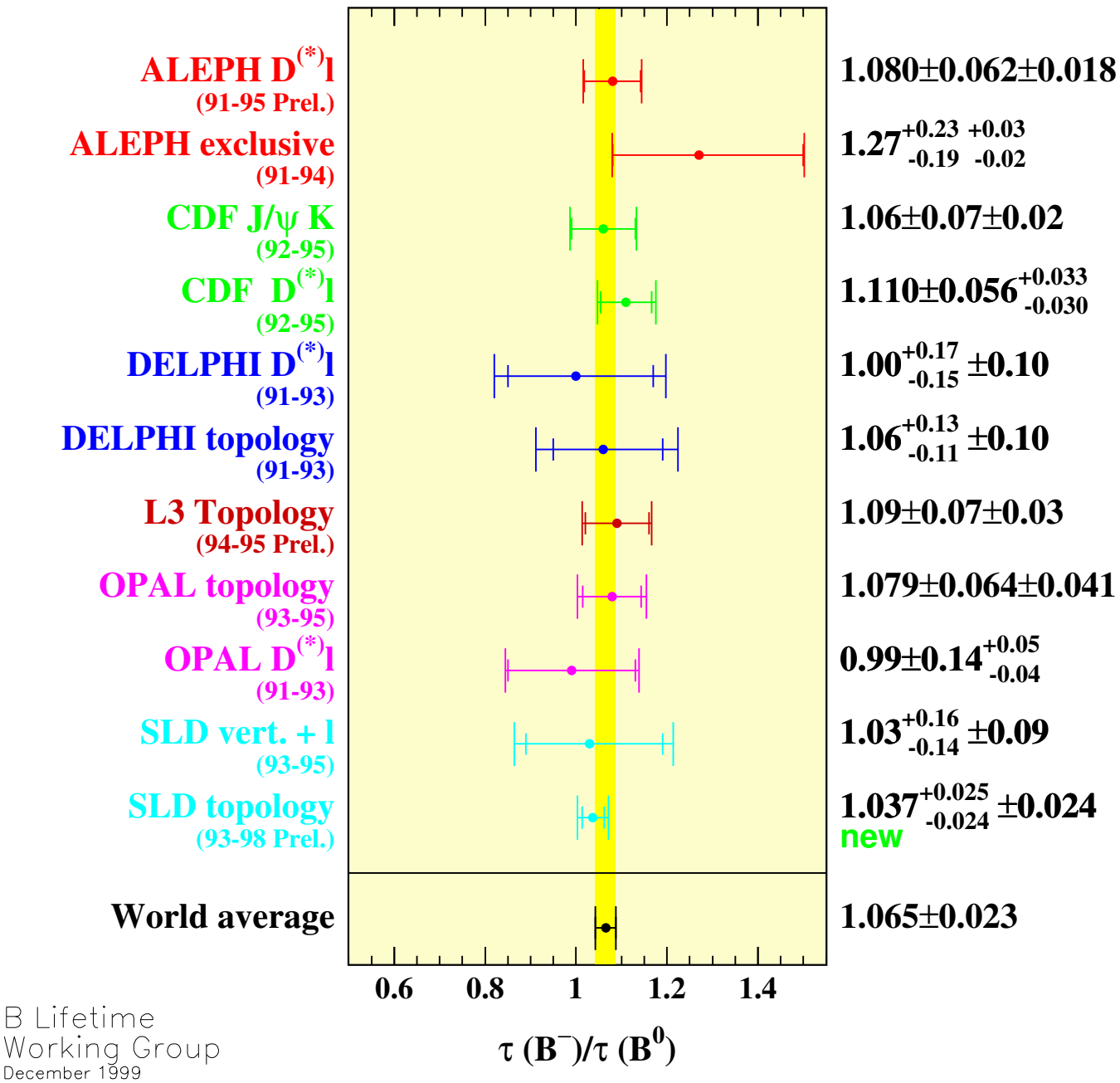
B Lifetime
Working Group
December 1999

B^+ Lifetime Comparision



B Lifetime
Working Group
December 1999

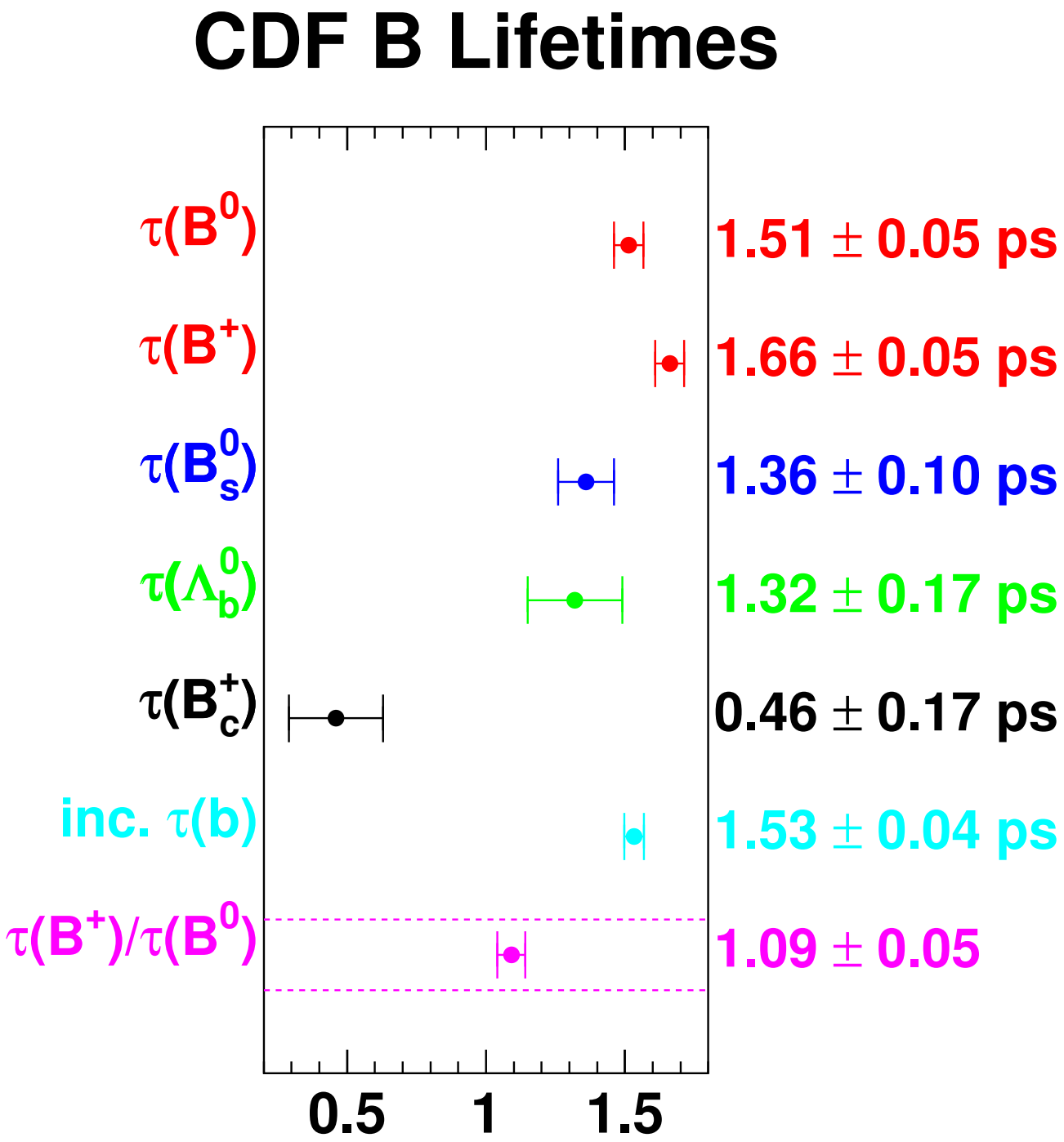
Lifetime Ratio Comparision

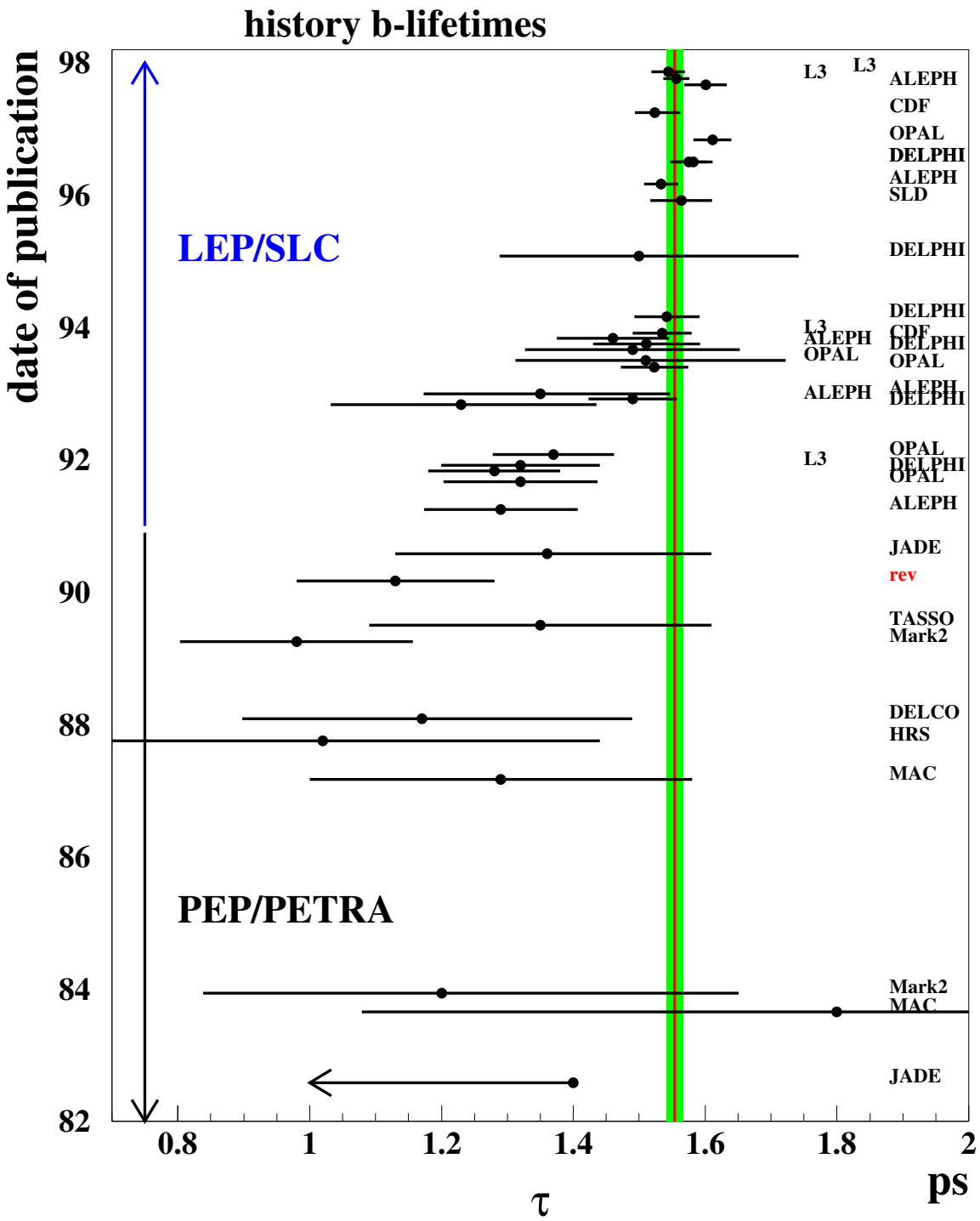


B Lifetime
Working Group
December 1999

Theoretically expected lifetime difference of 5% confirmed by measurement!

CDF Lifetime Comparision



B Lifetime Summary

History of B lifetimes: