The Ups and Downs of B Mixing and Lifetimes

- Measurements
  - Average B lifetime (1993-1995)
  - B^+ and B^0 lifetimes (1994-2000)
  - B^0 mixing (1995-…)
  - B_s mixing (1996-…)

People

- Direct contributors (1993-now)

Ken Baird
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Danning Dong
Mike Fero
Gary Gladding
Kazumi Hasuko (PhD)
Jenny Huber
Dave Jackson
John Jaros
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Inga Karliner
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Steve Manly
Tom Markiewicz
Thomas Moore (PhD)
Homer Neal
Bob Panvini
Greg Punkar
Sumit Sen (PhD)
Nick Sinev
Julia Thom (PhD soon)
Tracy Usher
Stéphane Willocq
Jodi Wittlin (PhD)
Geordie Zapalac

(apologies to those who have been left off this list)

Average B Lifetime (I)

- Back in 1993:
  - Surprisingly large lifetime $\Rightarrow$ $|V_{cb}|$ is small
  - LEP exploits silicon vertex detectors
    $\Rightarrow$ Measured average B lifetime moves a lot
  - At SLD: 2 "traditional" analyses
    Impact parameter of all tracks opposite b-tagged jets
    Summed impact parameter
    $\Rightarrow$ Exploit SLD 3-D CCD vertex detector
    to develop inclusive topological vertexing

Average B Lifetime (II)

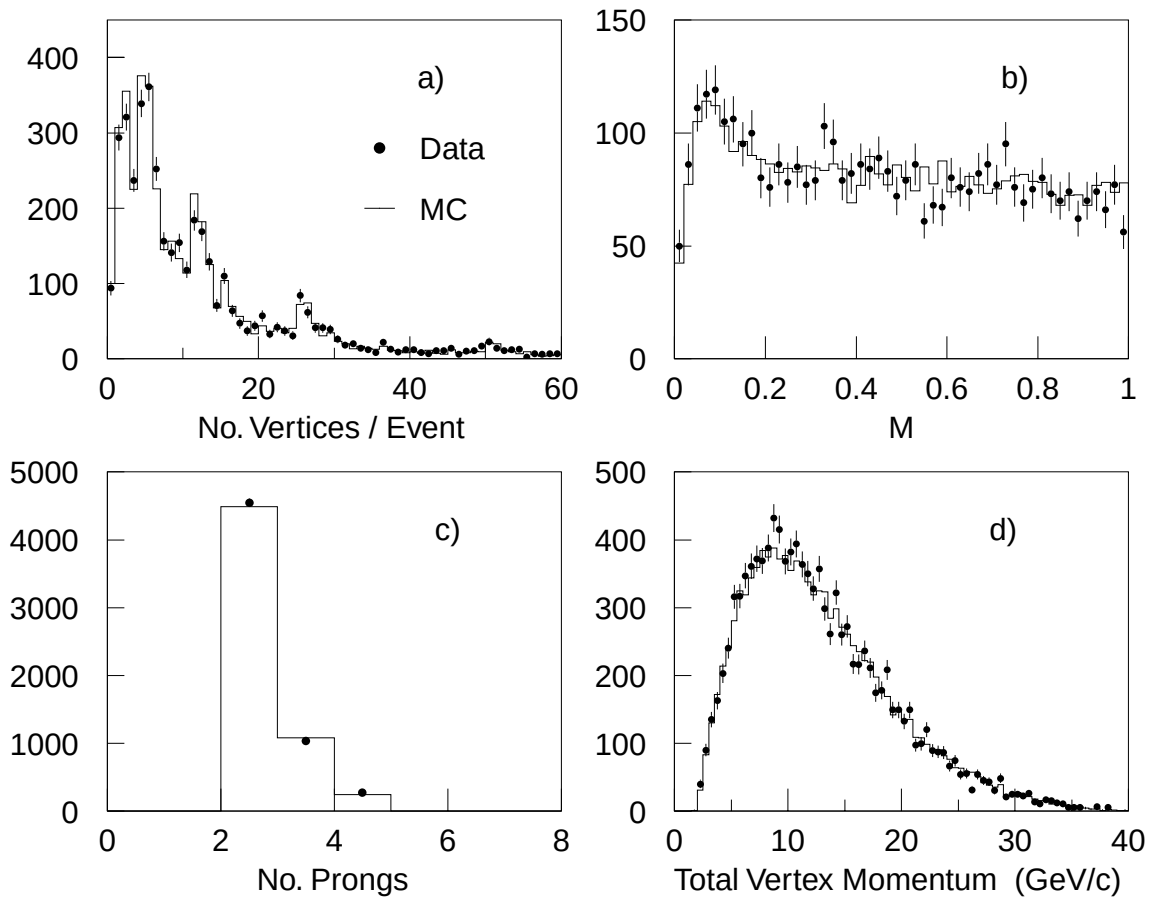
- Desire to exploit *3-D* CCD vertex detector led to the *first application of topological vertexing* by S.Manly (1994)

2D impact param tag
ε_b = 60% Π_b = 90%

Select partition with largest Π prob(χ^2,dof)

1993 data: 50K evts

Select ~2500 decay candidates



Average B Lifetime (III)

- First results: summer 1994 (S.Manly, S.Sen, S.Willocq)

  Published: PRL 75, 3624 (1995)

  1993 data sample: 50K evts

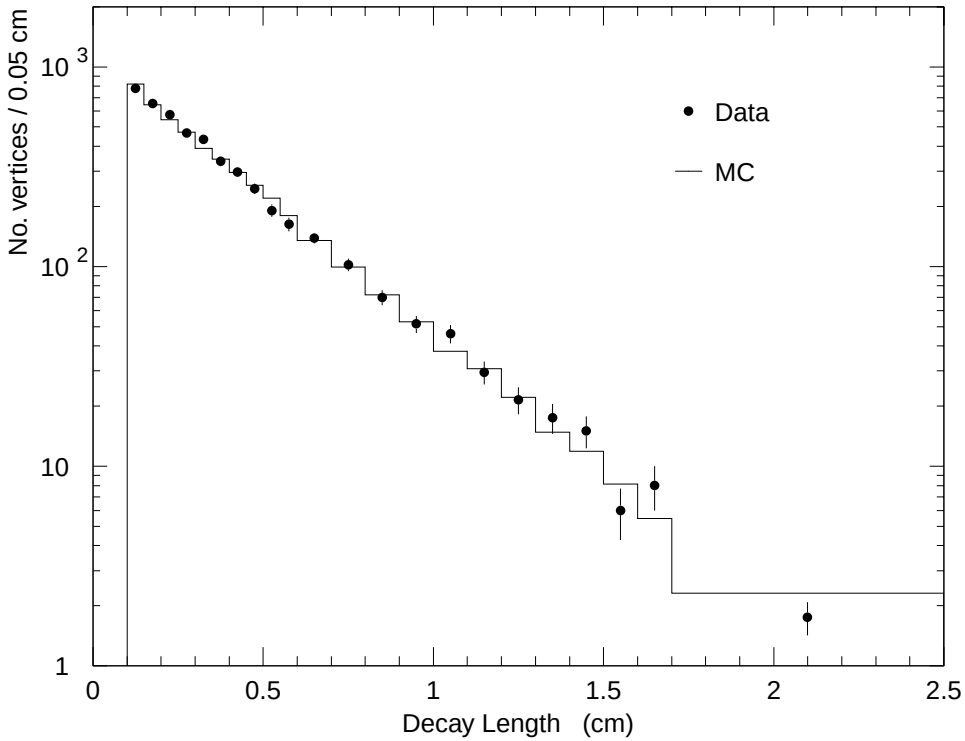
Fit to inclusive vertex decay length distribution

$\tau_B = 1.564 \pm 0.030 \pm 0.037$ ps

More powerful than Impact-parameter methods:

(δ) 1.617 ± 0.048 ± 0.086 ps

($\Sigma\delta$) 1.627 ± 0.054 ± 0.132 ps



Average B Lifetime (IV)

- Latest world average

$\tau_B = 1.564 \pm 0.014$ ps

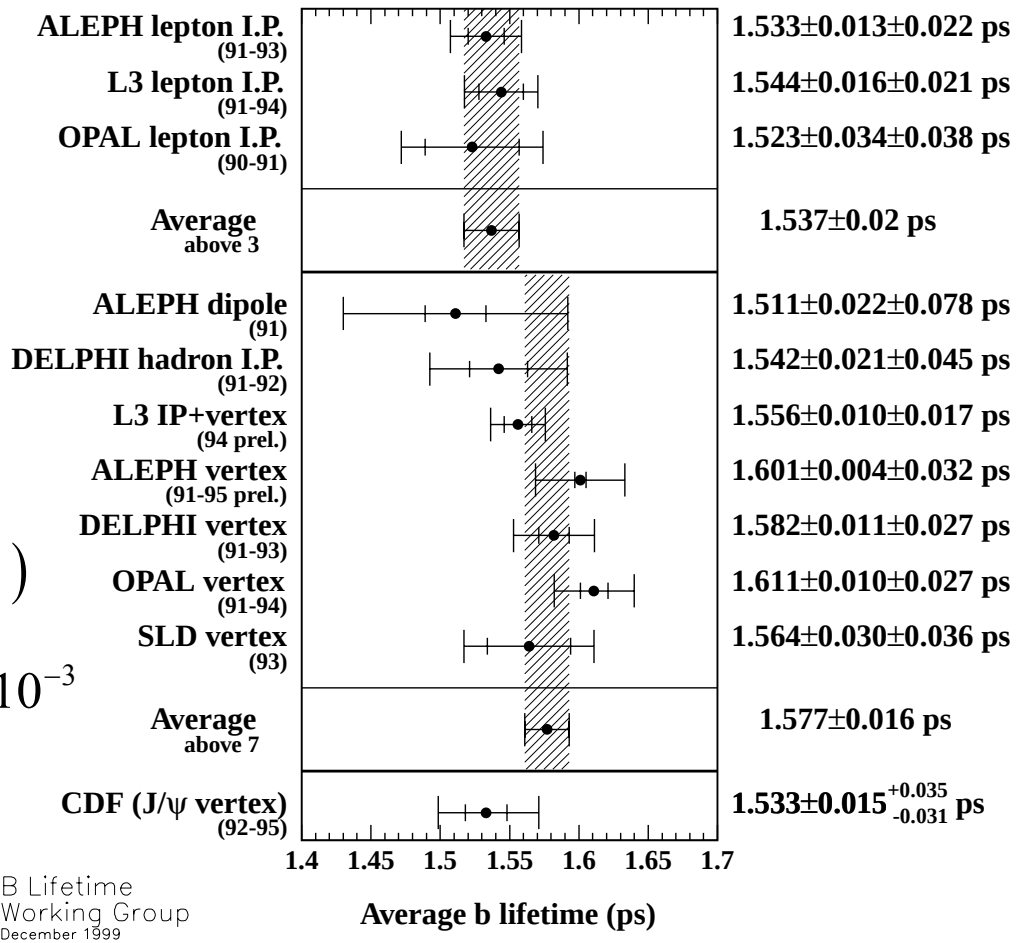
- Determination of V_{cb}

From τ_B and semileptonic branching fraction (Bigi, Shifman, Uraltsev)

$$|V_{cb}| = 0.0411 \sqrt{\frac{1.55}{0.105}\,\Gamma(b \to l\nu X)} \cdot (1+\delta)$$

$$= \left[40.76 \pm 0.41(\text{exp}) \pm 2.04(\text{theo})\right] \times 10^{-3}$$

δ is few percent correction



B^+ and B^0 Lifetimes (I)

- Test b-decay transitions and dynamics (strong interaction)

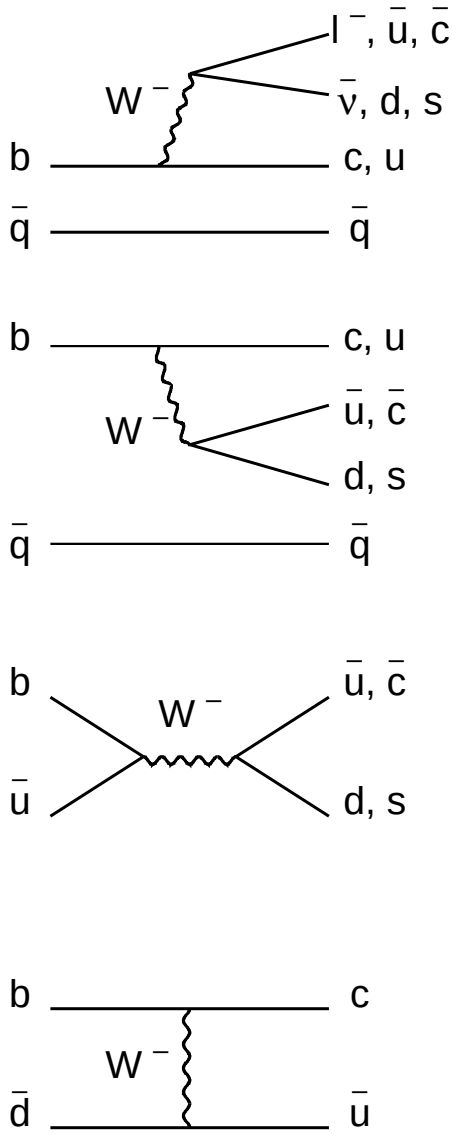
- Heavy Quark Expansion predicts small differences between b-hadron types

$$\tau(B^+) / \tau(B^0) = 1 + O(5\%)$$

$$0.9 < \tau(\Lambda_b) / \tau(B^0) < 1.0$$

Bigi et al.

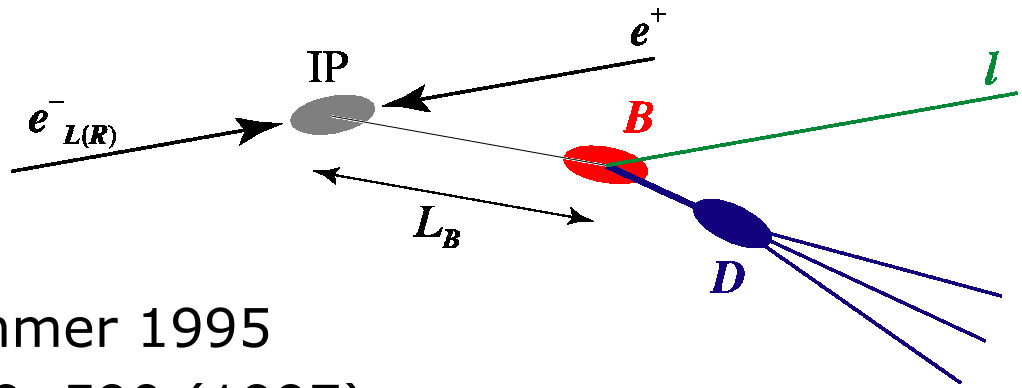
(somewhat contested by Neubert)



B^+ and B^0 Lifetimes (II)

- Refined *methods all based on vertexing* (1994):

  1. Lepton+D (G.Gladding, I.Karliner, T.Usher)



First results: summer 1995

Published: PRL 79, 590 (1997)

1993-95 data sample: 150K evts

$\tau(B^+) = 1.61 \pm 0.13 \pm 0.07$ ps

$\tau(B^0) = 1.56 \pm 0.14 \pm 0.10$ ps

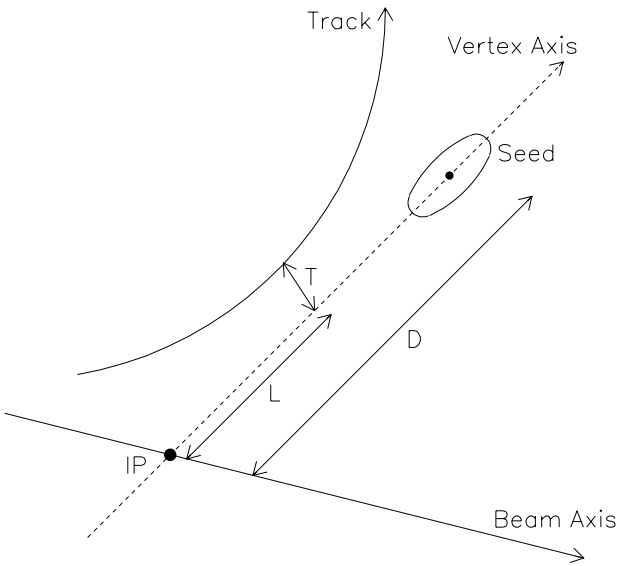
$\tau(B^+) / \tau(B^0) = 1.03 \pm 0.15 \pm 0.09$

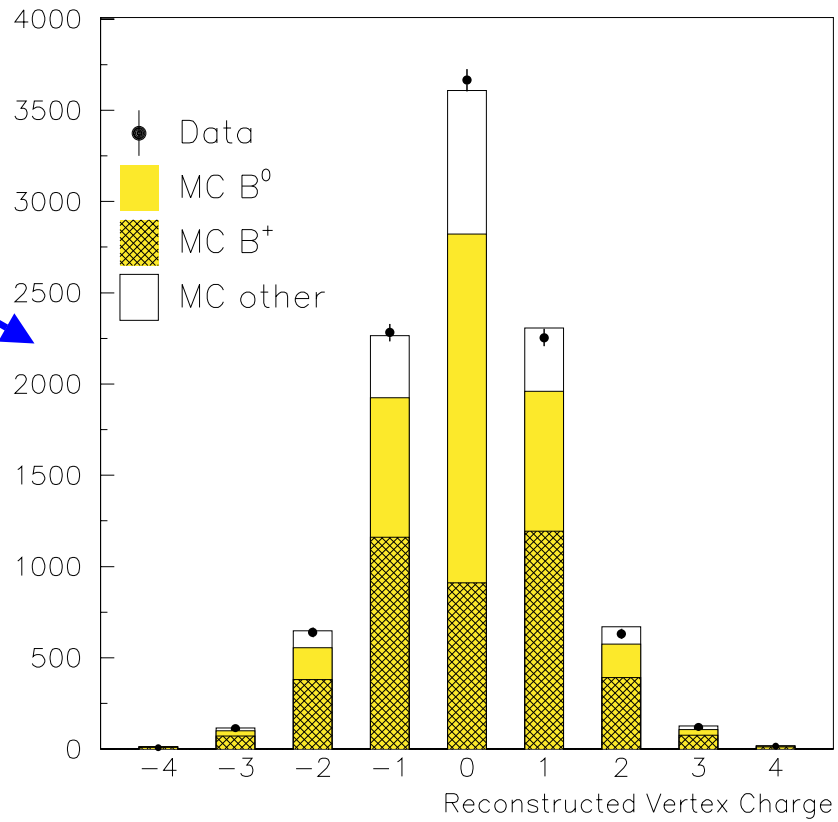
B^+ and B^0 Lifetimes (III)

2. Inclusive topological vertexing (D.Jackson)

first development and implementation of ZVTOP

- Select *seed* vtx with high track overlap density
- Attach tracks with L/D > 0.3 and T < 0.1 cm
- Lower quality tracks also attached to improve vtx charge





B^+ and B^0 Lifetimes (IV)

First results: summer 1995

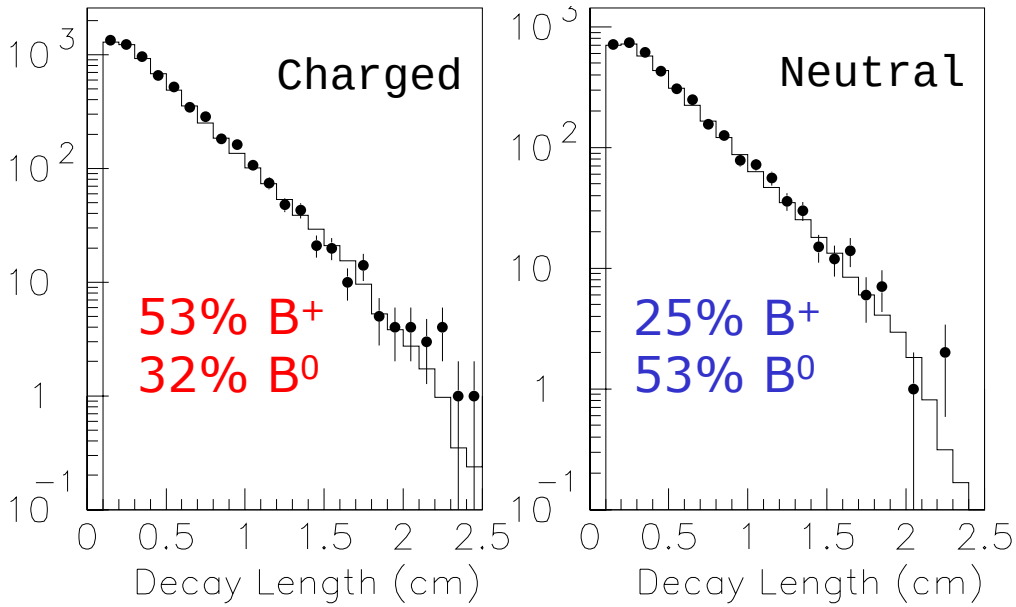
Published: PRL 79, 590 (1997)

1993-95 data sample: 150K evts

Topological analysis

9719 candidate B decays

B purity = 98%



$\tau(B^+) = 1.67 \pm 0.07 \pm 0.06$ ps

$\tau(B^0) = 1.66 \pm 0.08 \pm 0.08$ ps

$\tau(B^+) / \tau(B^0) = 1.01 \pm 0.09 \pm 0.05$

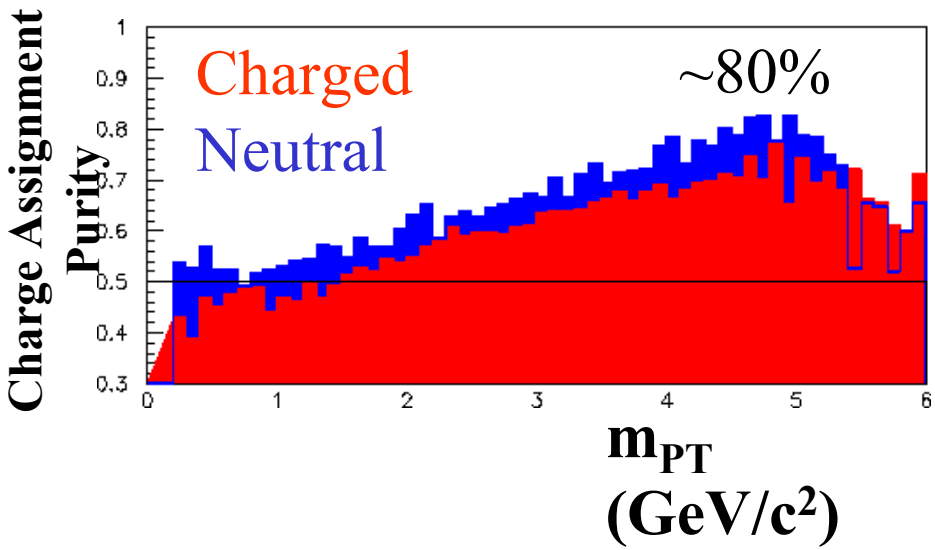
B^+ and B^0 Lifetimes (V)

Latest prelim results: summer 1999 (K.Baird, D.Jackson)

[SLAC-PUB-8206]

1997-98 data sample: 350K evts

→ Use additional information to determine probability that the charge assignment is correct: vertex mass, P_e-, Q_{jet}



$\tau(B^+) = 1.613 \pm 0.023$ ps

$\tau(B^0) = 1.565 \pm 0.024$ ps

$\tau(B^+) / \tau(B^0) = 1.030 \pm 0.028$

B^+ and B^0 Lifetimes (VI)

- For 1993 – 1998 Data:

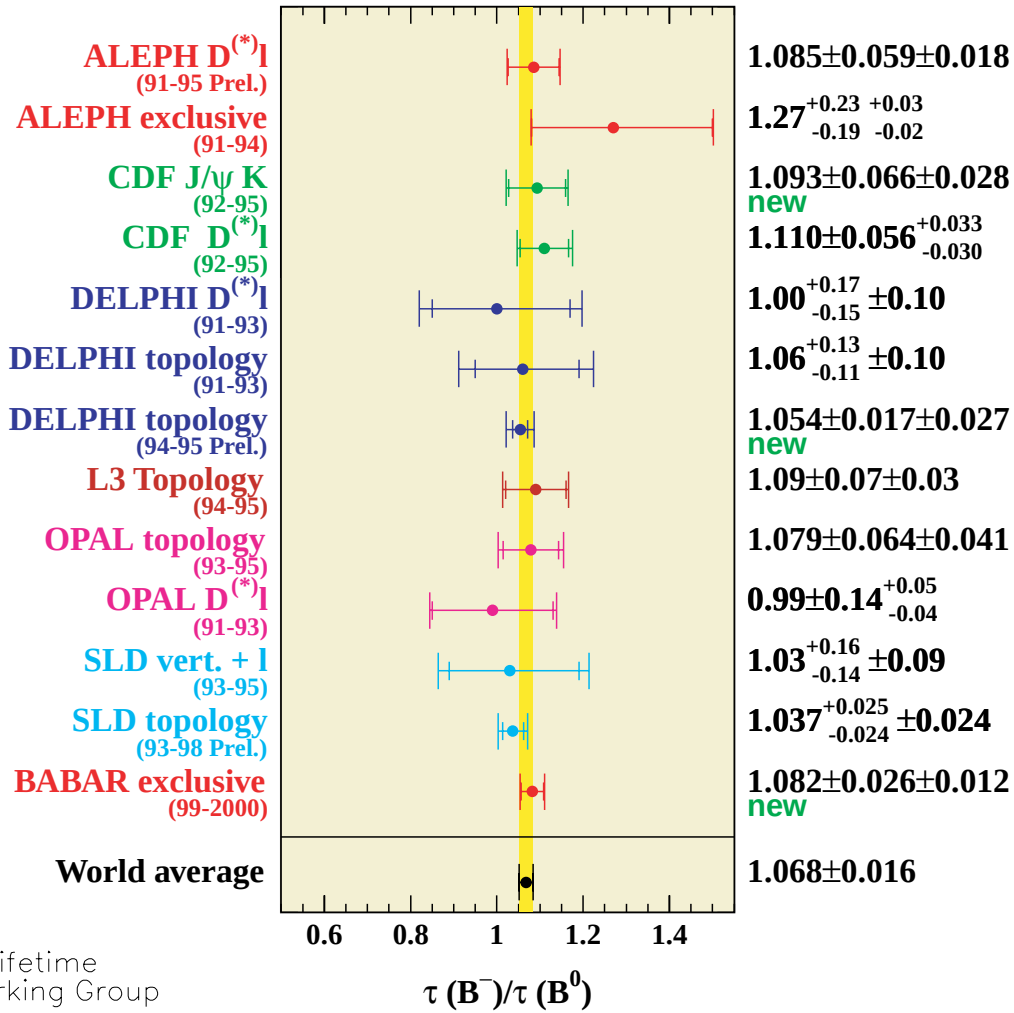
(Preliminary)

$$\tau_{B^+} = 1.623 \pm 0.020 \pm 0.034 \text{ ps}$$

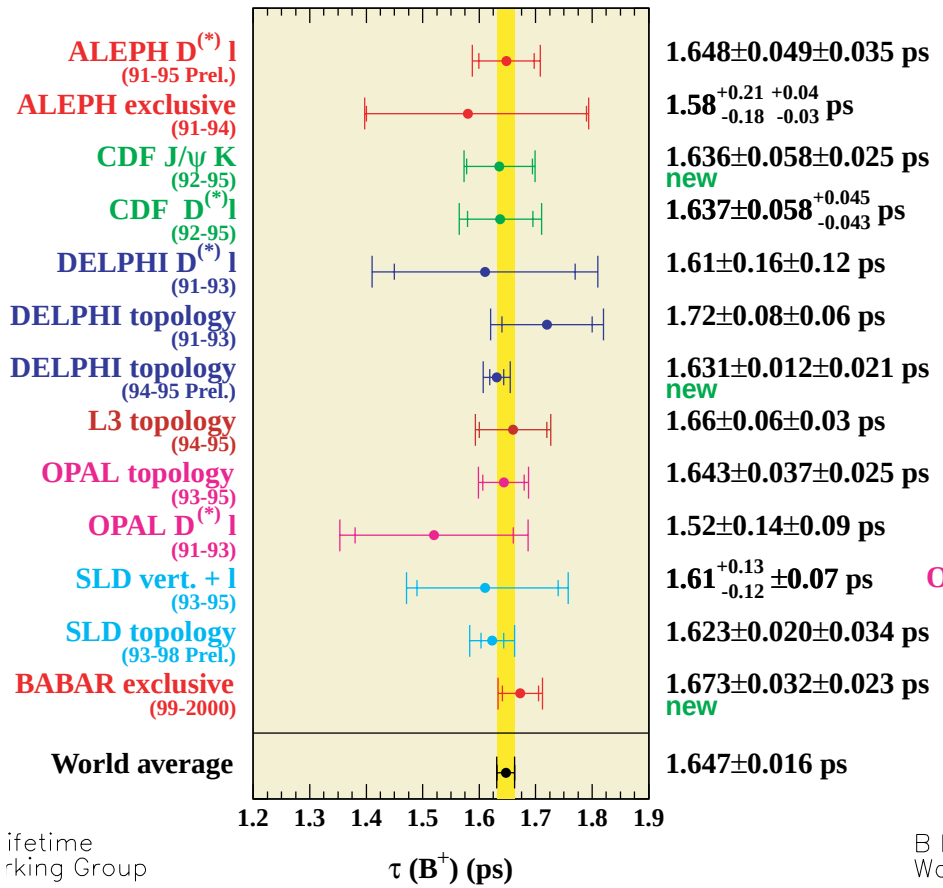
$$\tau_{B^0} = 1.565 \pm 0.021 \pm 0.043 \text{ ps}$$

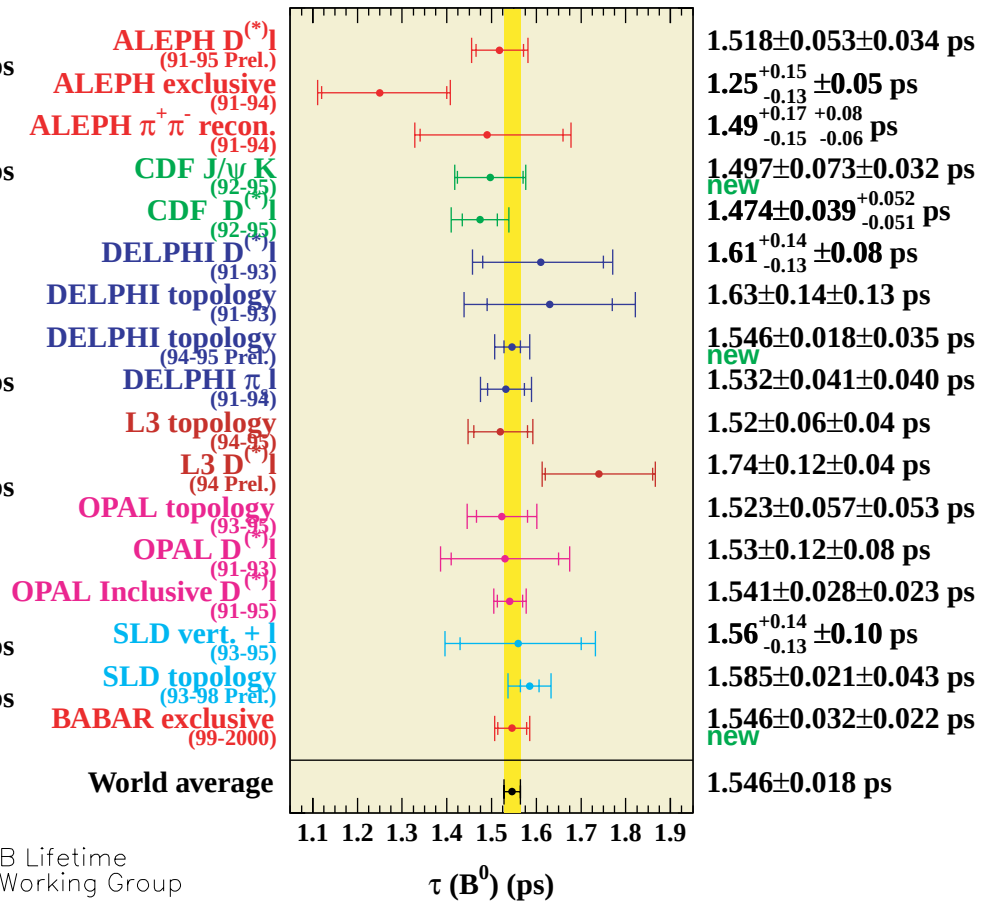
$$\tau_{B^+}/\tau_{B^0} = 1.037 \; {}^{+0.025}_{-0.024} \pm 0.024$$

Latest world average shows clear evidence for difference between B^+ and B^0 lifetimes



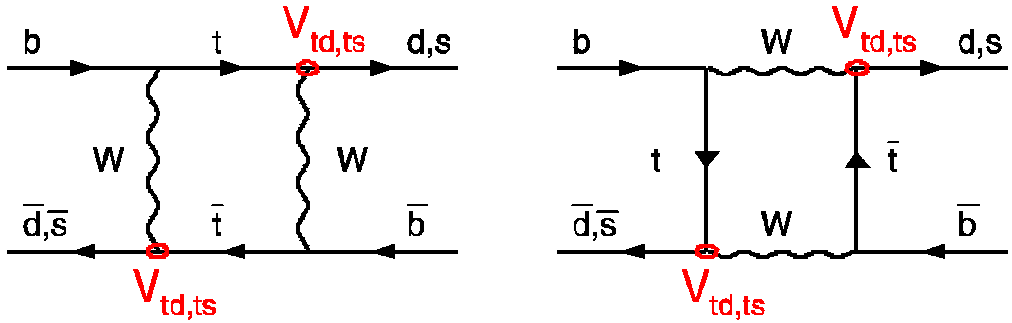
B^+ and B^0 Lifetimes (VII)





B^0 Mixing (I)

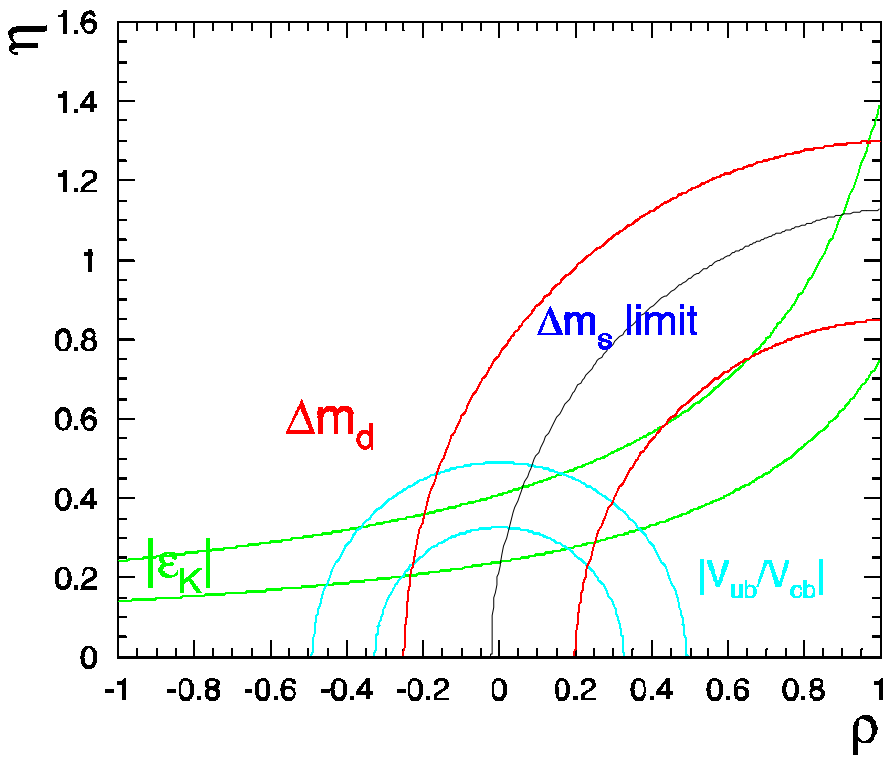
- $B^0 \leftrightarrow \bar{B}^0$ transitions occur via second order weak interactions



- Time-dependent oscillations with frequency $\Delta m_d \propto |V_{td}|^2$

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_{B_d} m_t^2 \, F\left(\frac{m_t^2}{m_W^2}\right) \times B_{B_d} f_{B_d}^2 \eta_{QCD} \left| V_{tb}^* V_{td} \right|^2$$

$\Rightarrow$ Measure $|V_{td}|$ and constrain CP violation in SM



B^0 Mixing (II)

- First results: summer 1996 (M.Fero, D.Jackson, M.Liu, S.Manly, T.Moore, SW)
  SLAC-PUBS: 7228, 7229, 7230
  1993-95 data sample

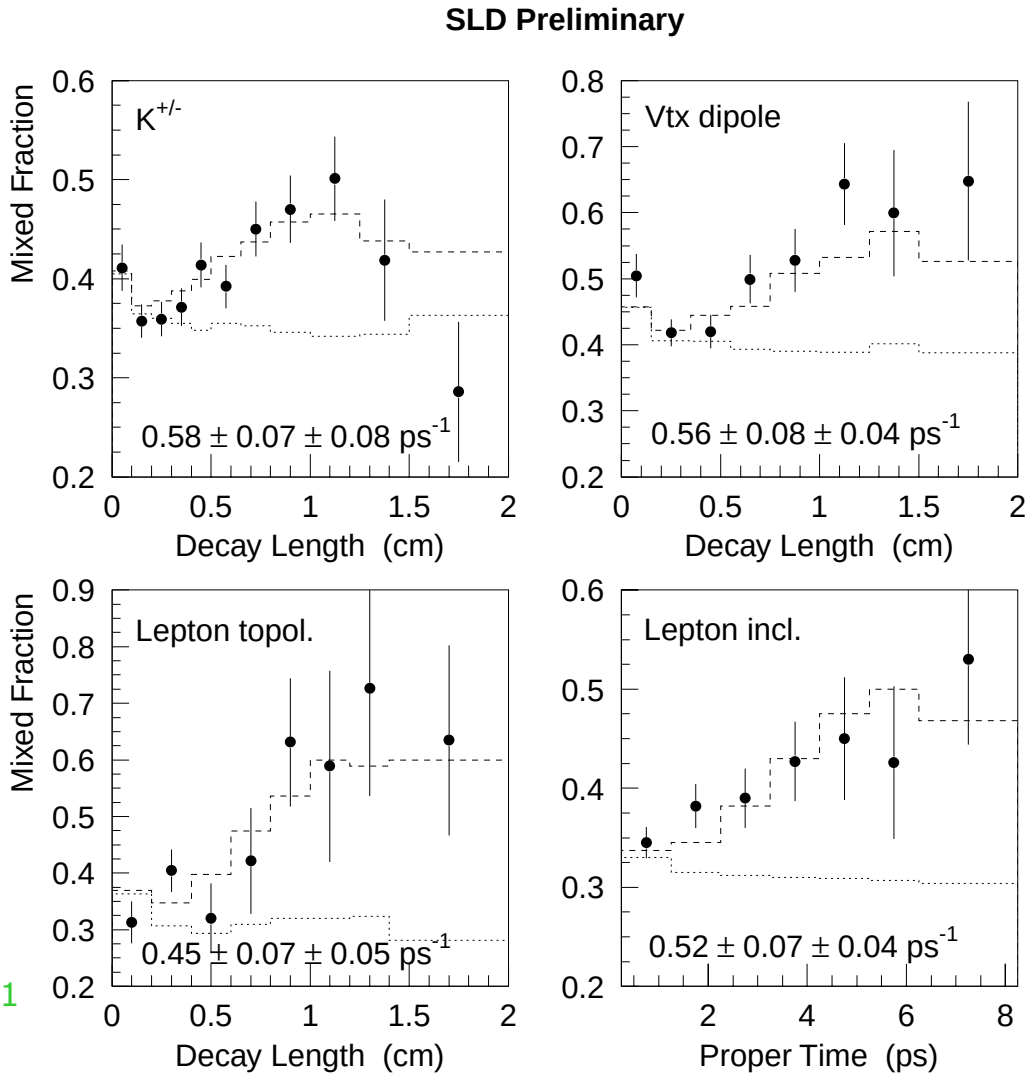
→ Adapt lepton+D and topological lifetime analyses

→ Tag initial and final B^0 / $\overline{B}^0$ flavor

NEW: lepton+tracks analysis
initial state tag (Pol+Qjet)
kaon tag
charge dipole tag

SLD avg:

$\Delta m_d = 0.531 \pm 0.043 \pm 0.034\ ps^{-1}$



B^0 Mixing (III)

- Latest results: summer 2001
  1996-98 data sample

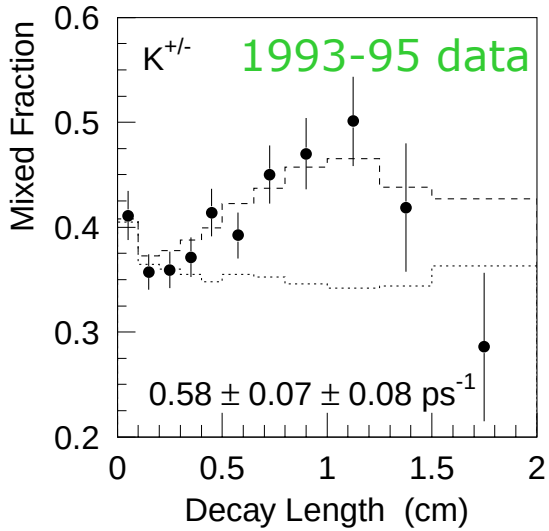
→ Revamped kaon tag analysis (J.Wittlin)
  unbinned likelihood
  multi-var initial state tag
  VXD-only tracks for b tag
  and neutral b-hadron selection

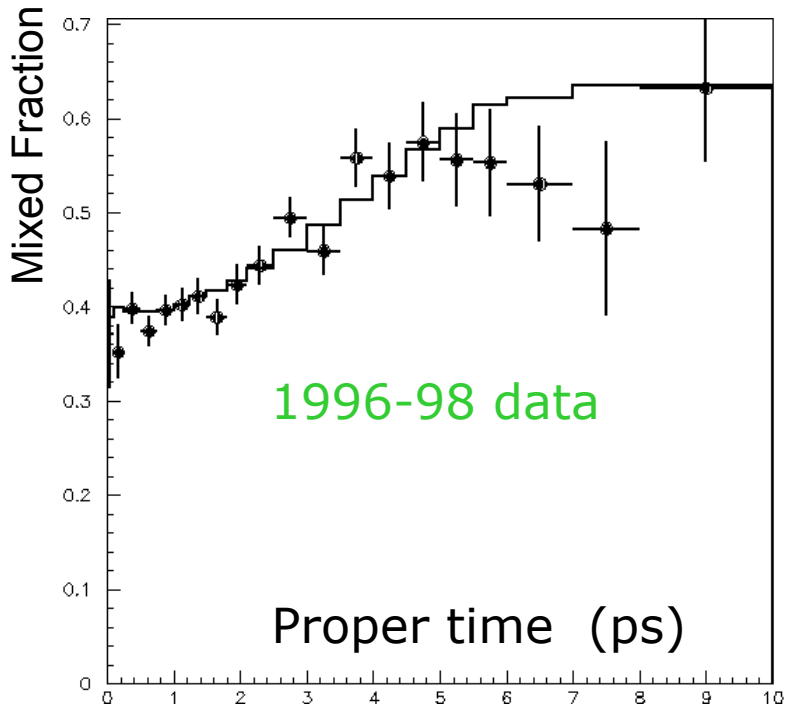
K tag:

$$\Delta m_d = 0.503 \pm 0.028 \pm 0.020 \text{ ps}^{-1}$$

B^0 K tag RSF = 0.797 ± 0.022

⇒ Much reduced K tag systematics





B^0 Mixing (IV)

- Summer 2001 world avg:

$$\Delta m_d = 0.489 \pm 0.008 \text{ ps}^{-1}$$

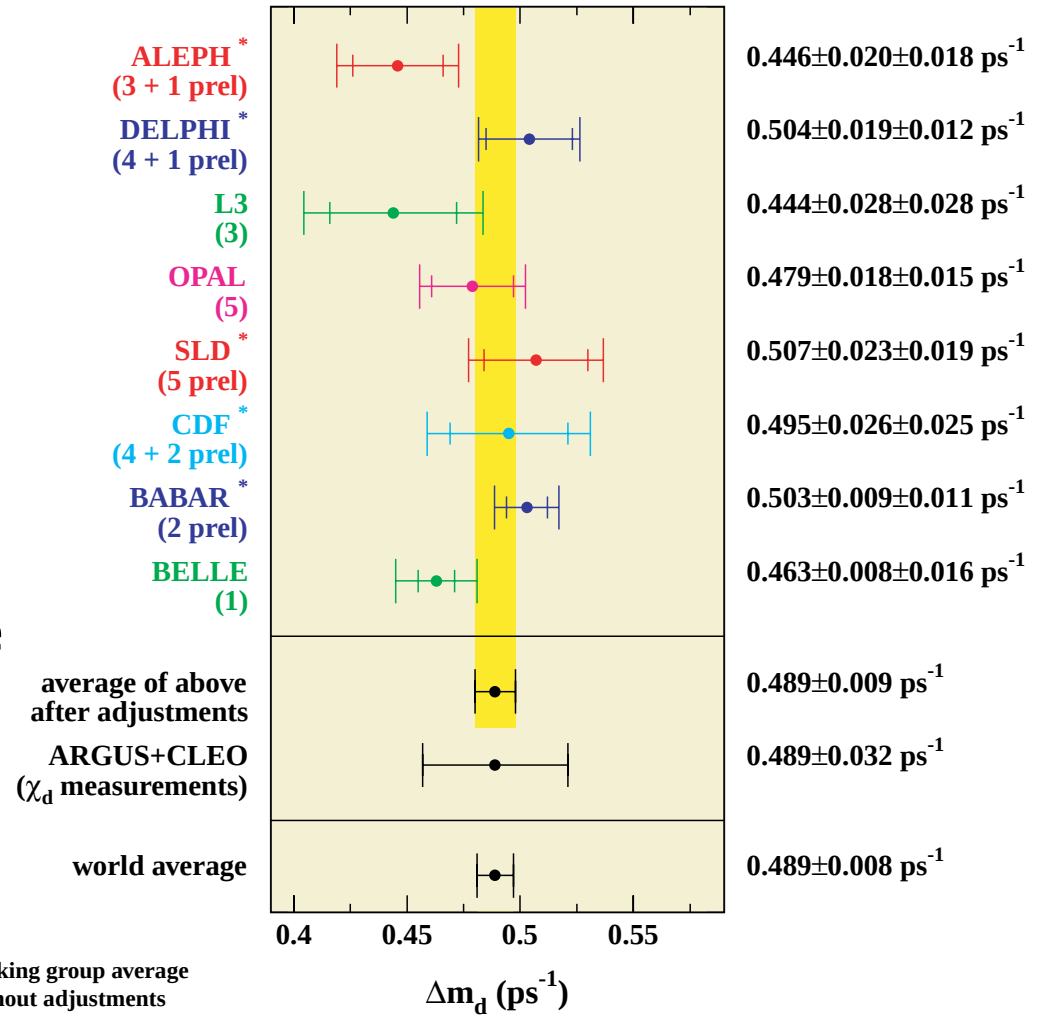
Precise measurement but…

Extraction of $|V_{td}|$ from Δm_d is affected by a ~20% uncertainty in $\sqrt{B_{B_d}} f_{B_d}$

⇒ Study B_s mixing to measure

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s} f_{B_s}^2 B_{B_s}}{m_{B_d} f_{B_d}^2 B_{B_d}} \cdot \left|\frac{V_{ts}}{V_{td}}\right|^2$$

$$= \frac{m_{B_s}}{m_{B_d}} \cdot (1.16 \pm 0.05)^2 \cdot \left|\frac{V_{ts}}{V_{td}}\right|^2$$



* working group average without adjustments

B_s Mixing (I)

Significance for B_s mixing signal:

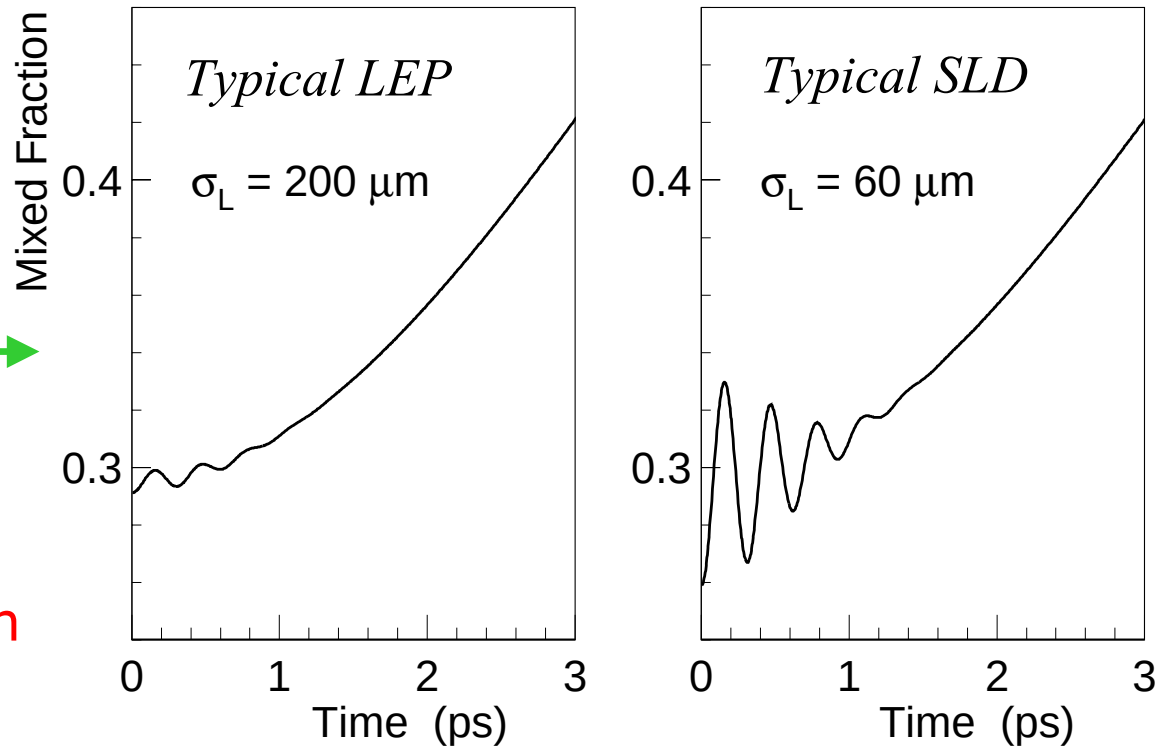
$$S = \sqrt{\frac{N}{2}}\, f_{B_s}\, (1-2w)\, e^{-\frac{1}{2}(\Delta m_s \sigma_t)^2}$$

statistics — B_s purity — mistag — resolution

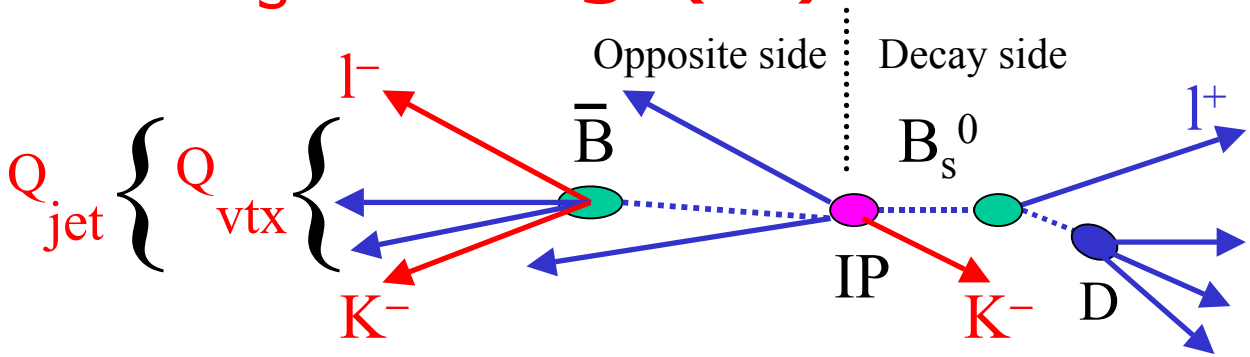
Small IP + CCD VXD
+ Polarization + PID
ALL IMPORTANT

$\Delta m_s = 20\ ps^{-1}$
$f(B_s) = 0.18$
$w = 0.25$
$\sigma_p / p = 0.10$

Decay length resolution is critical



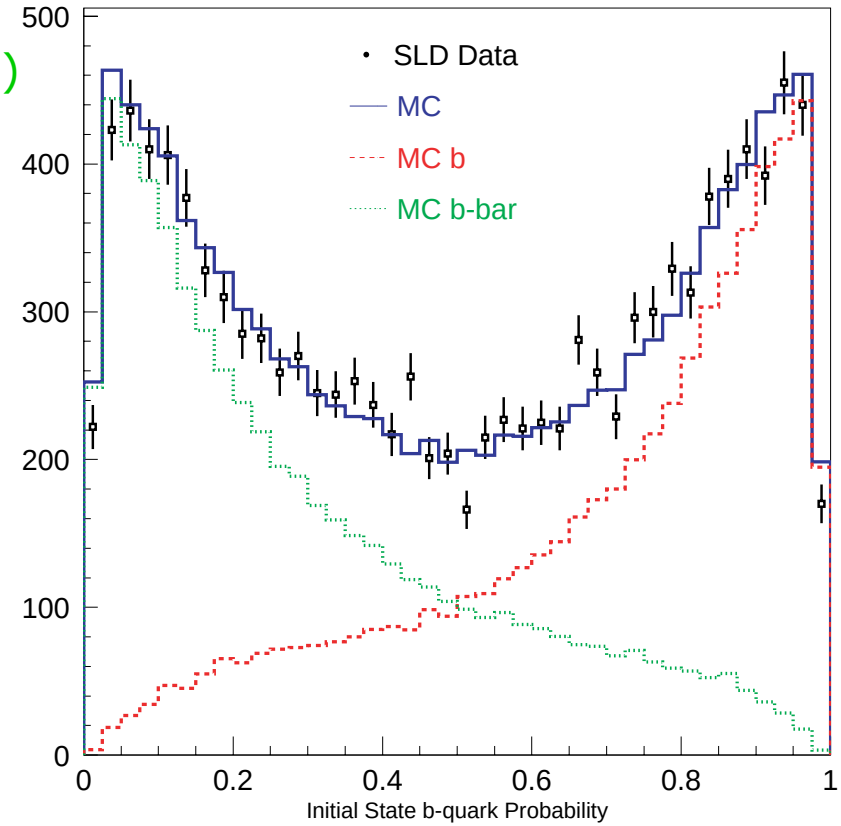
B_s Mixing (II): Initial State Tag



- Polarized F-B Asymmetry (w = 0.28)
- Opposite Side Tags
  - Lepton charge $b \rightarrow l^-$
  - Jet Charge $\Sigma_{tracks} Q_i |p_i . T|^\kappa$
  - Secondary vtx charge Q_{vtx}
  - Kaon charge $b \rightarrow c \rightarrow s$ (i.e. K^-)
  - Dipole charge

→ Combined with NN (T.Moore)

Overall mistag rate w ≈ 0.22-0.25



B_s Mixing (III)

→ Total of *3 different analyses* at SLD
using 400K hadronic Z decays (1996-98 data)
Differing in proper time recon and $B^0 / \overline{B}^0$ decay flavor tag

Efficiency

Purity

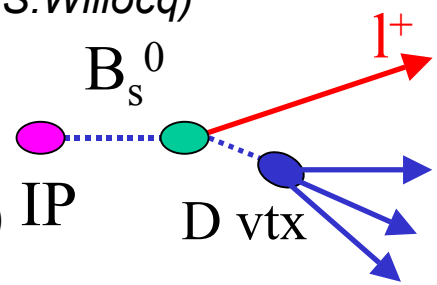
1) Inclusive

Fully inclusive: secondary & tertiary topological vtx

Charge Dipole: 11462 decays *(D.Jackson, J.Thom, S.Willocq)*

Semileptonic decays: lepton + topological D vtx

Lepton+D: 2087 decays *(H.Neal, T.Usher, K.Hasuko)*



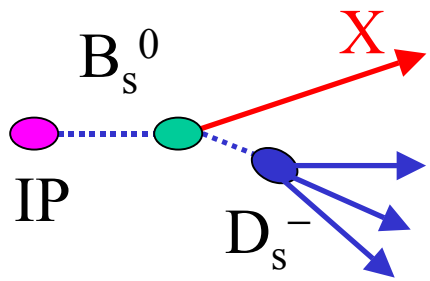
2) Semi-exclusive

Partial reconstruction: $B_s \rightarrow D_s^- X$

with full reconstruction of D_s decay

$D_s^- \rightarrow \phi\pi^-$, $K^{*0}K^-$

D_s+tracks: 361 decays *(C.Lin)*



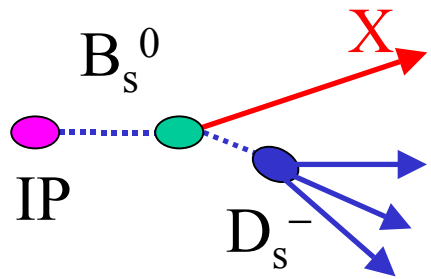
B_s Mixing with D_s + tracks

Partial reconstruction of $B_s \rightarrow D_s^- X$

full reconstruction of D_s decay

$D_s^- \rightarrow \phi\pi^-$, $K^{*0}K^-$

particle ID with Cherenkov Ring Imaging Detector (CRID)

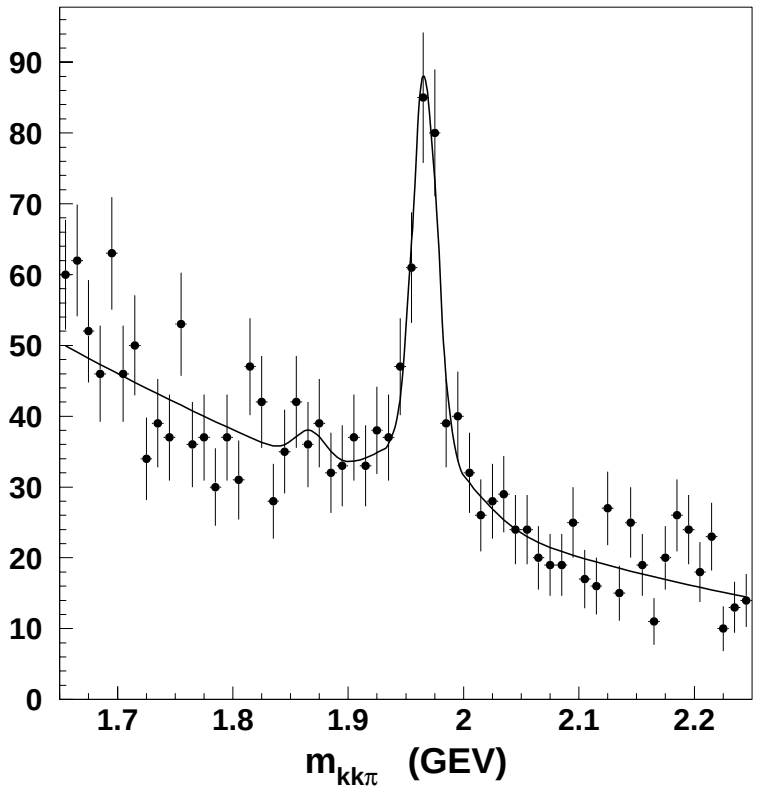


Neural Network D_s selection yields

280 $D_s^- \rightarrow \phi\pi^-$ candidates

81 $D_s^- \rightarrow K^{*0}K^-$ candidates

Both $B_s \rightarrow D_s^- l^+ X$ (39 events) and $B_s \rightarrow D_s^-$ hadrons are included in the analysis



D_s + tracks analysis (II)

Performance of the analysis:

superb decay length resolution

σ_L = 50 μm (60%) & 151 μm

σ_p / p = 0.08 (60%) & 0.19

high B_s purity

f(B_s) = 38% overall

for D_s signal:

f(B_s) = 65% neutral sample (D_s + hadrons)

90% neutral sample (D_s + lepton)

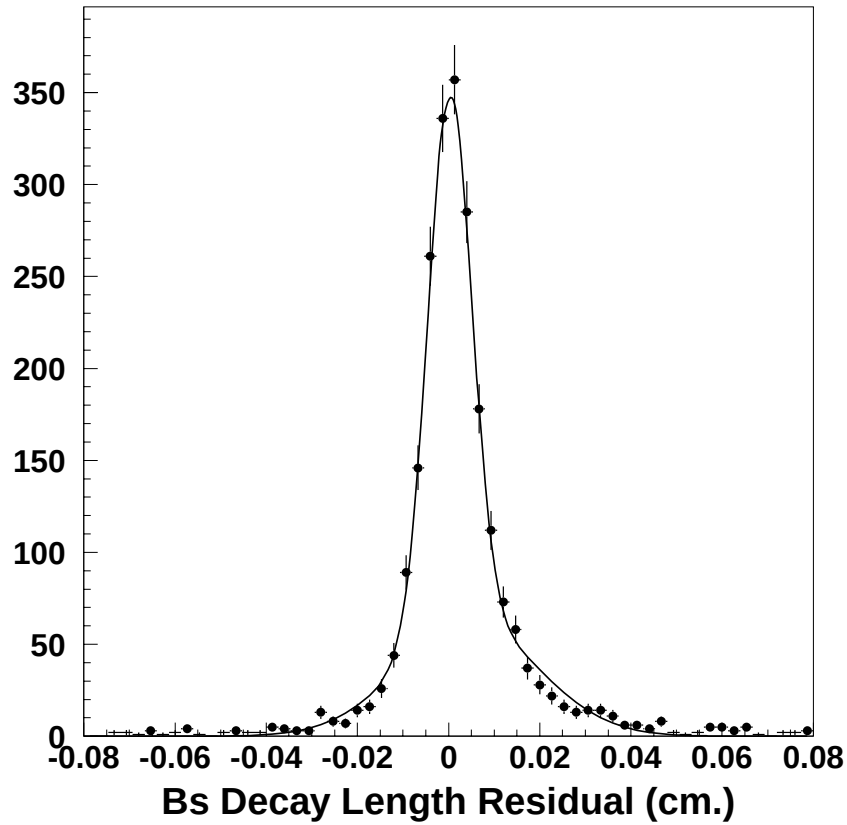
good tagging

initial state mistag = 22%

for D_s signal:

final state mistag = 13% (D_s + hadrons)

final state mistag = 5% (D_s + lepton)



D_s+tracks Amplitude Fit

95% CL sensitivity 3.3 ps^{-1}

(was 1.4 ps^{-1} last year)

Excluded regions

at 95% CL:

$\Delta m_s < 0.48$ ps^{-1}

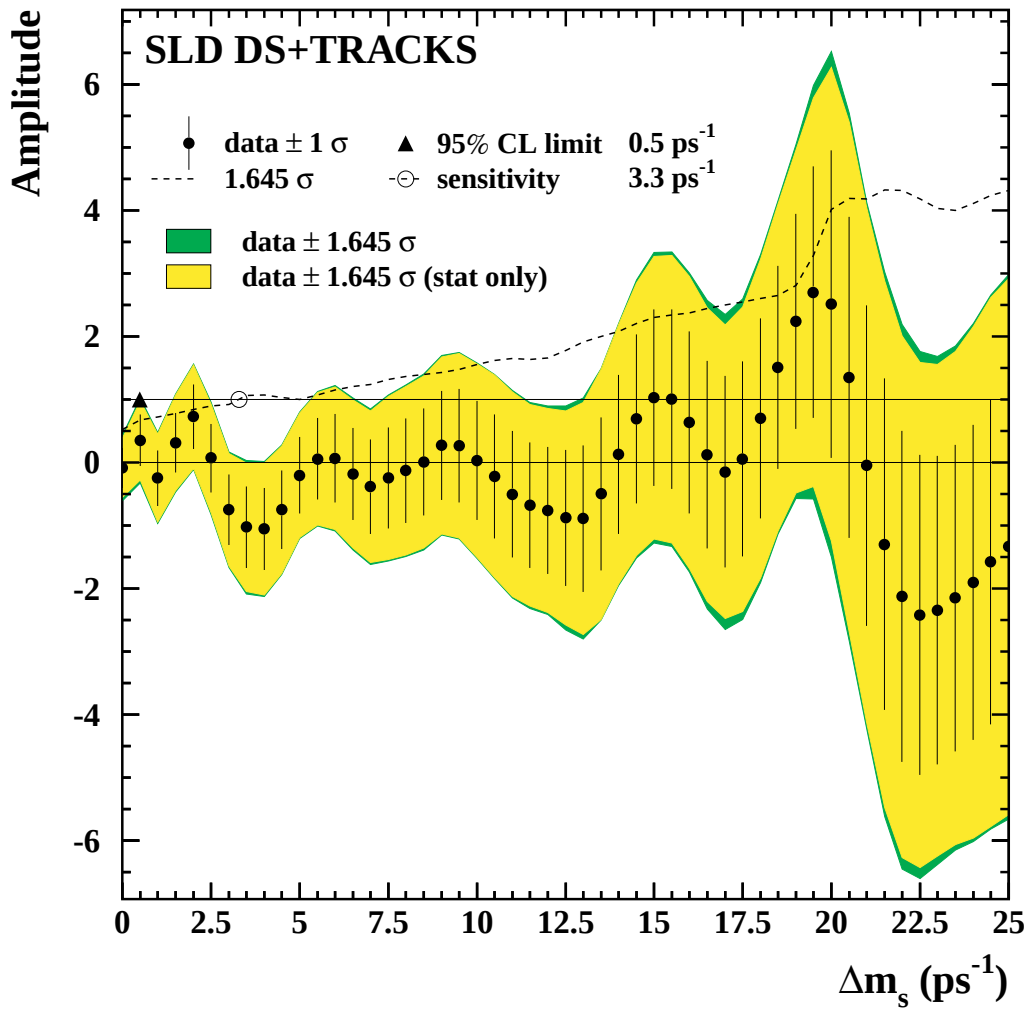
$0.5 < \Delta m_s < 1.4$ ps^{-1}

$2.5 < \Delta m_s < 5.3$ ps^{-1}

TO DO:

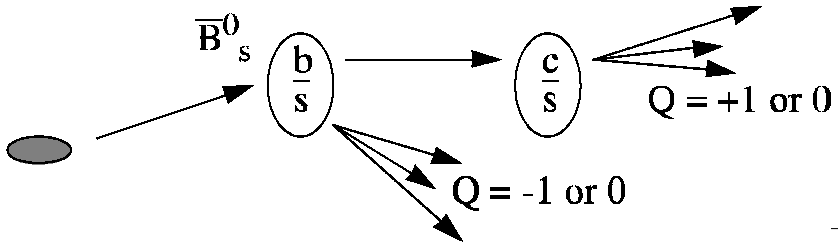
Finalize systematics

Finish paper



Charge Dipole Analysis

- FULLY inclusive reconstruction



Reconstruct sec. and tert. vertices

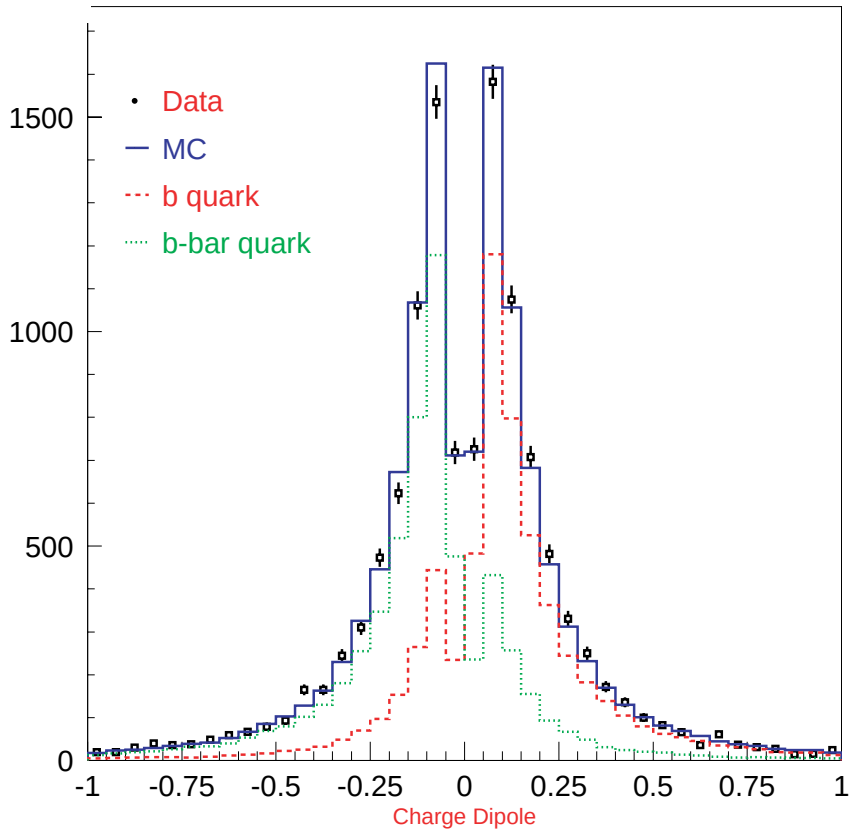
Tag flavor with "charge dipole"

$\delta q = \text{sign}\,(Q_D - Q_B) * \text{Distance}_{B \text{ to } D}$

New event selection: higher eff. & higher B_s purity

Select 11462 neutral decays

Final state mistag = 22%



Amplitude fit results

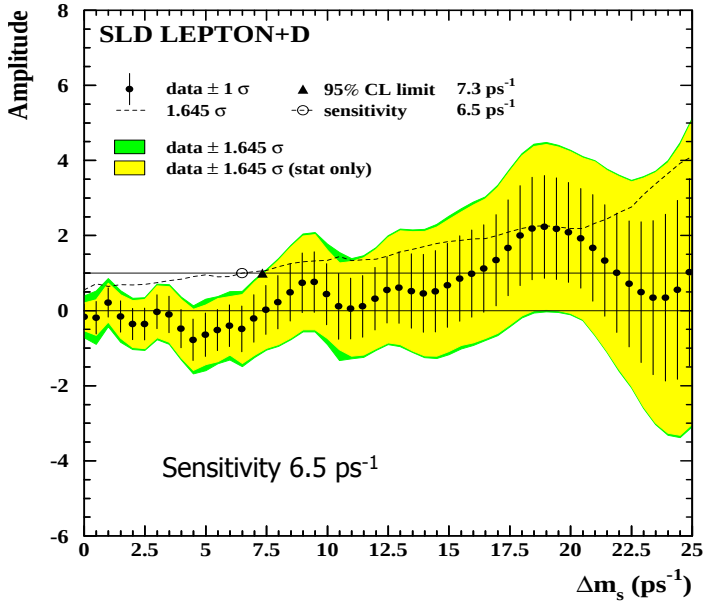
Oscillation amplitude A at fixed Δm_s

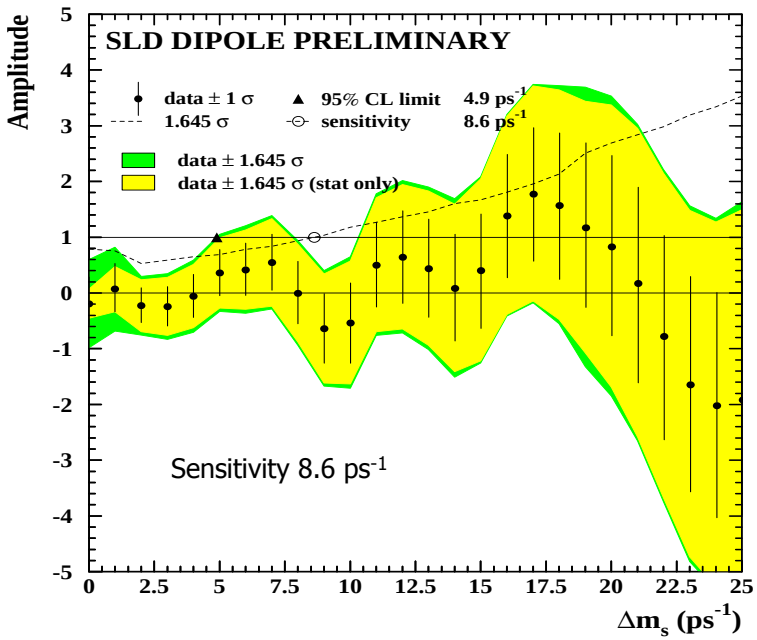
$$P_{\text{mix,unmixed}} = \frac{1}{2}\Gamma e^{-\Gamma t}\left(1 \mp A\cos\Delta m_s t\right)$$

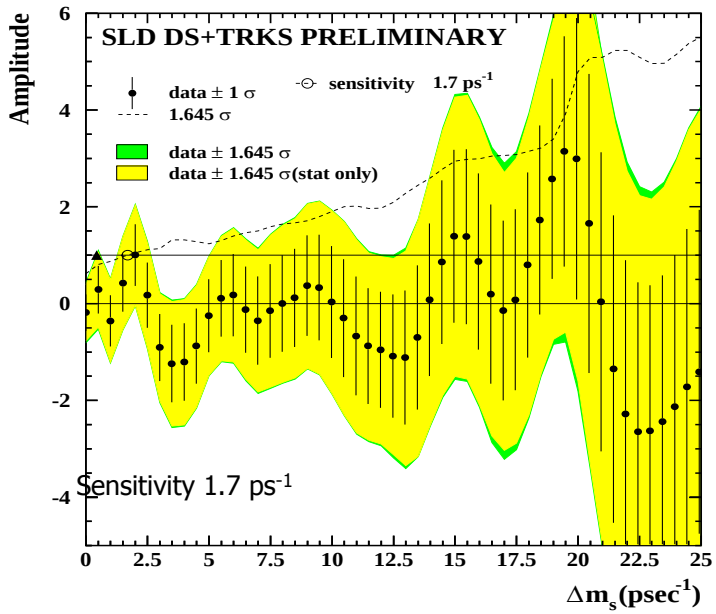
Expect **A = 1** for freq = true Δm_s

A = 0 for freq ≠ true Δm_s

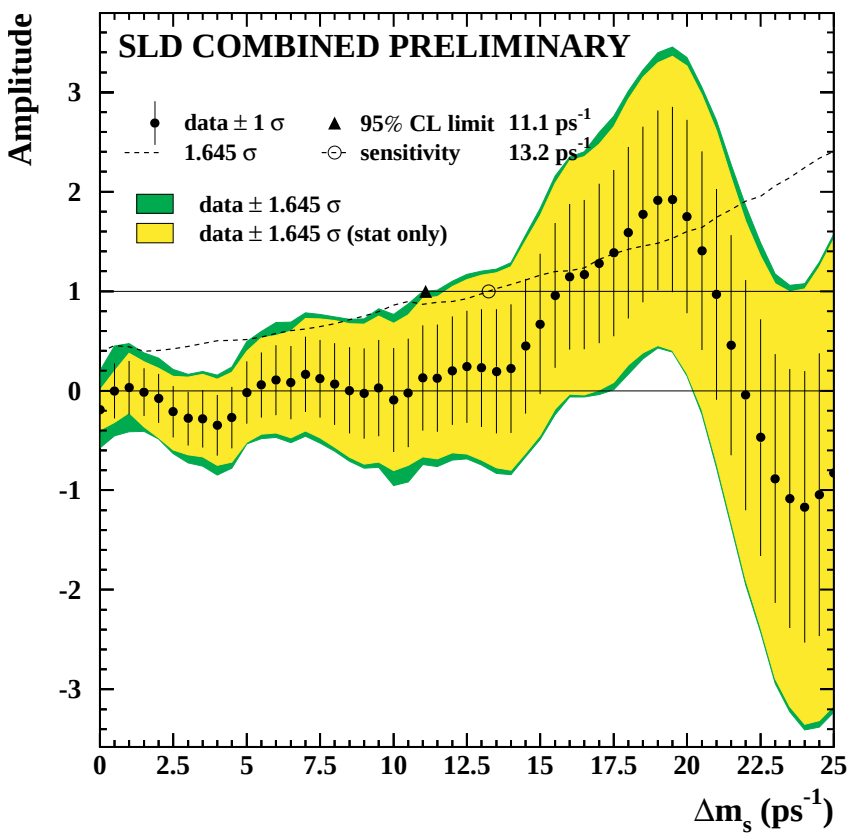
Sensitivity: Δm_s value with 1.645 σ_A= 1

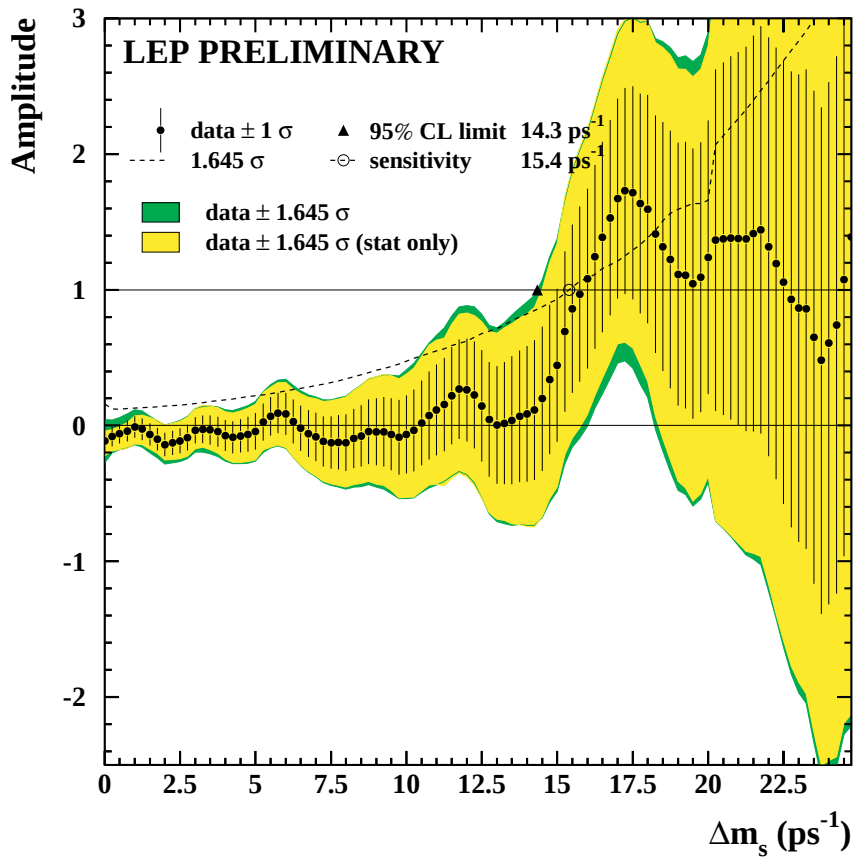






B_s Oscillation Amplitude: SLD and LEP





SLD 400K Z^0: Sensitivity = 13.2 ps^{-1}

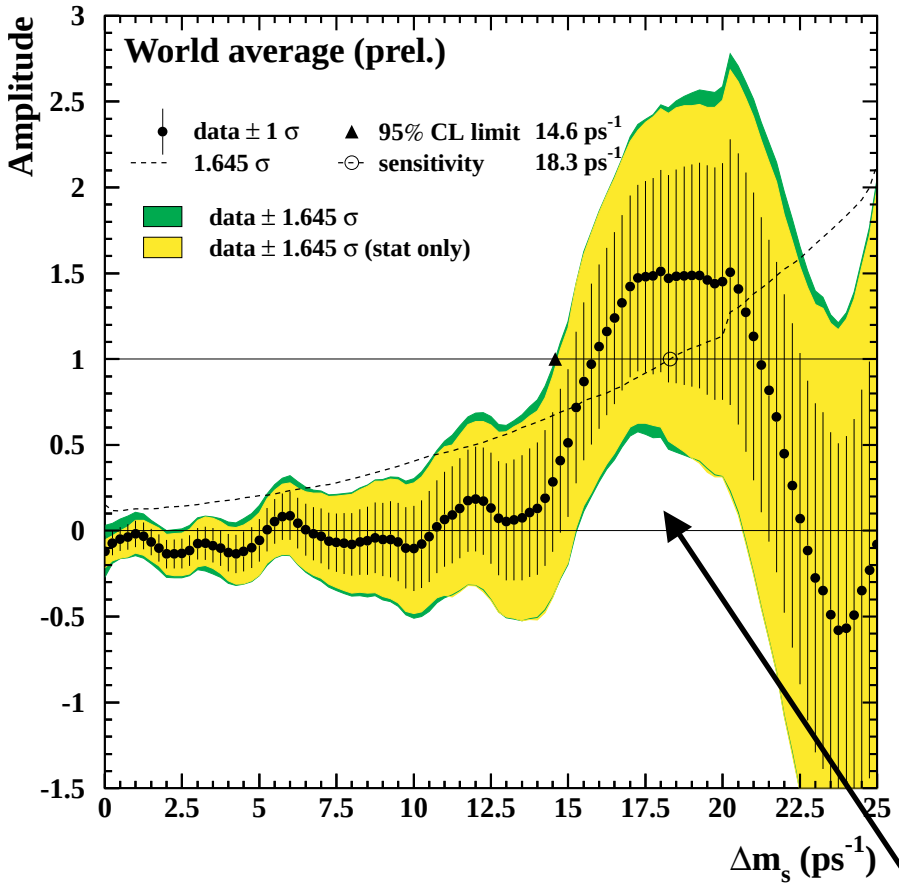
LEP 12M Z^0: Sensitivity = 15.4 ps^{-1}

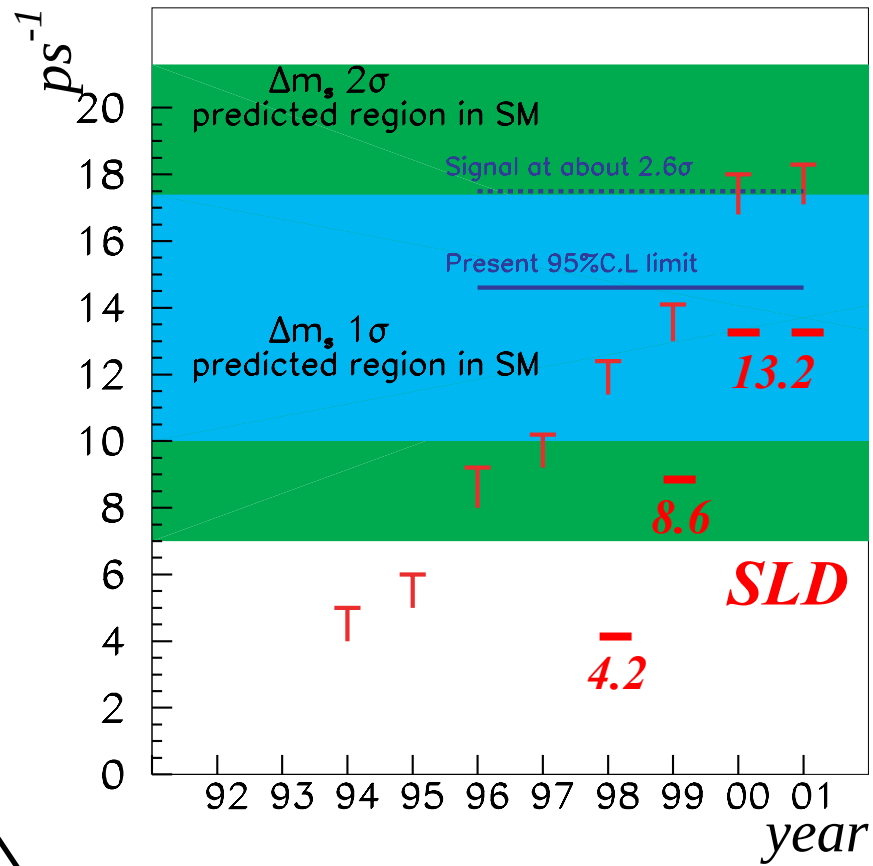
Excluded at 95% C.L.:

$\Delta m_s < 11.1\ ps^{-1}$

$\Delta m_s < 14.3\ ps^{-1}$

B_s Oscillation Amplitude: SLD, LEP, CDF





WORLD Sensitivity = 18.3 ps^{-1}

Excluded at 95% C.L.:

$\Delta m_s < 14.6\ ps^{-1}$

World sensitivity as a function of t

Prob of stat fluctuation ~ 3%

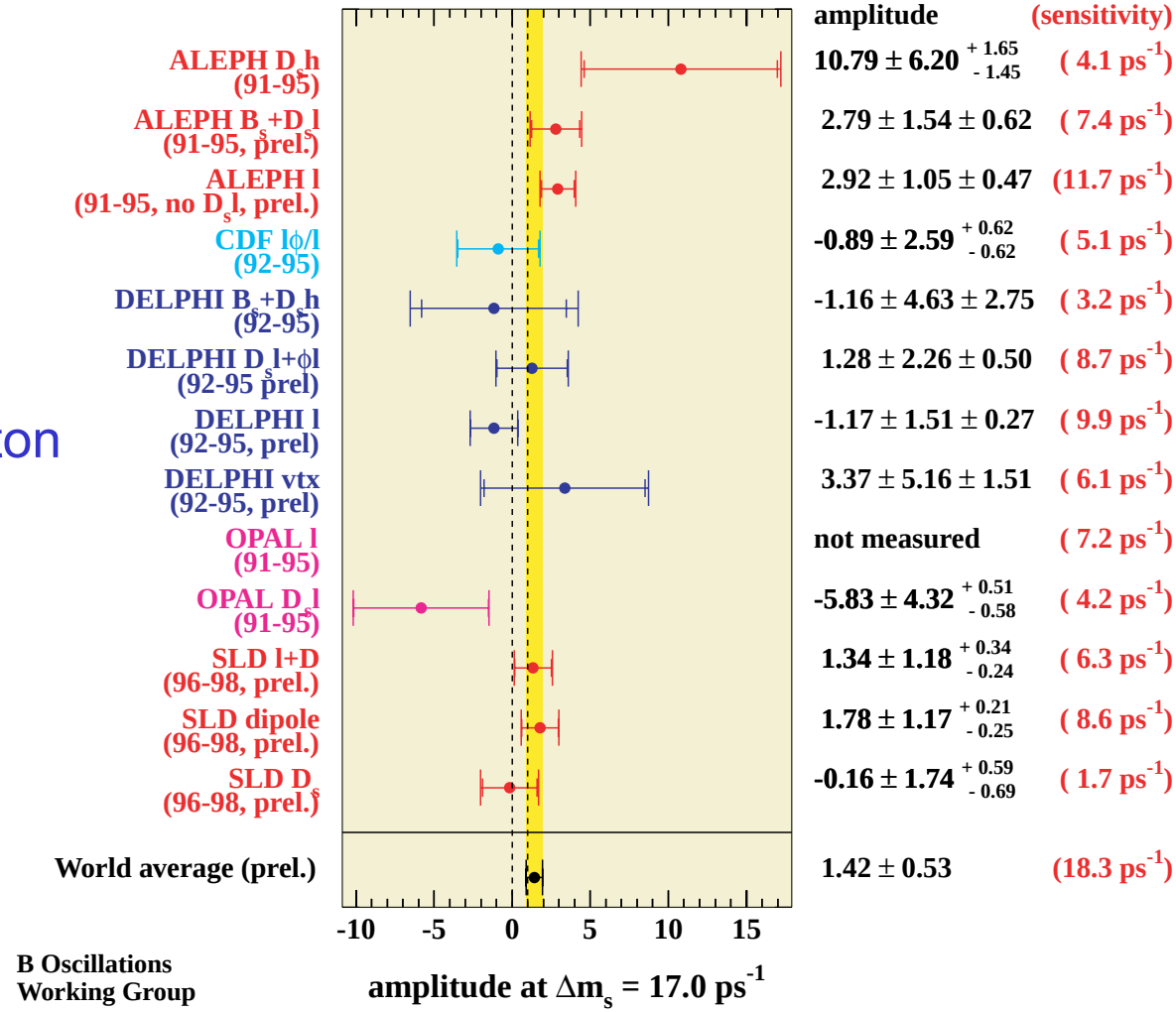
21

Individual B_s Oscillation Amplitude Measurements

Compare measured amplitude at
$\Delta m_s = 17.0\ ps^{-1}$

Most sensitive
(smallest σ_A):

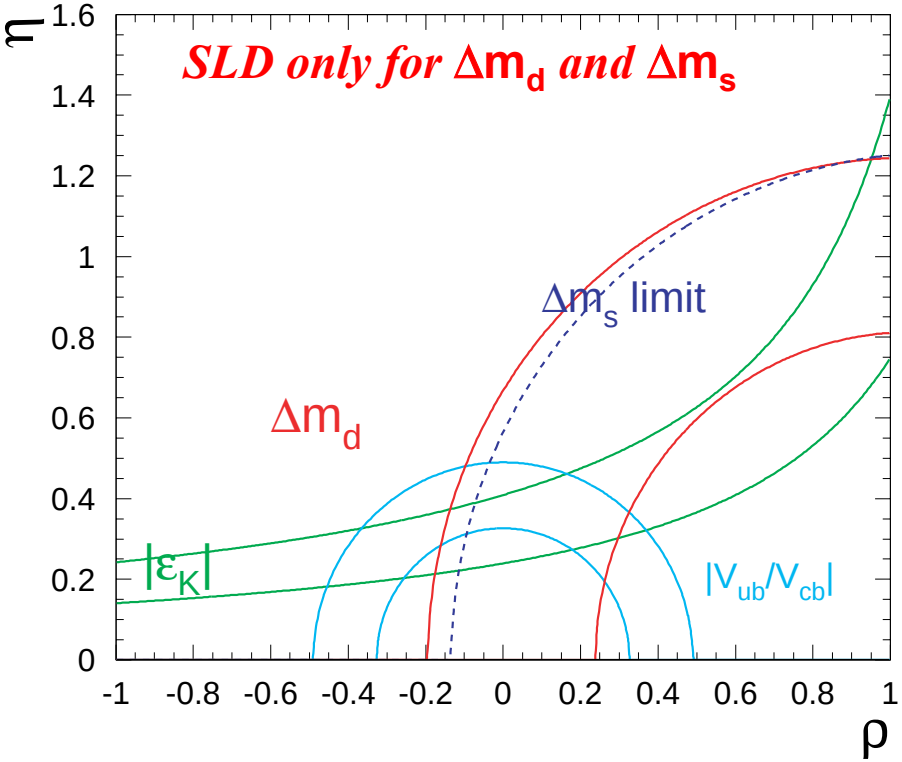
1. ALEPH inclusive lepton
2. SLD charge dipole
3. SLD lepton + D

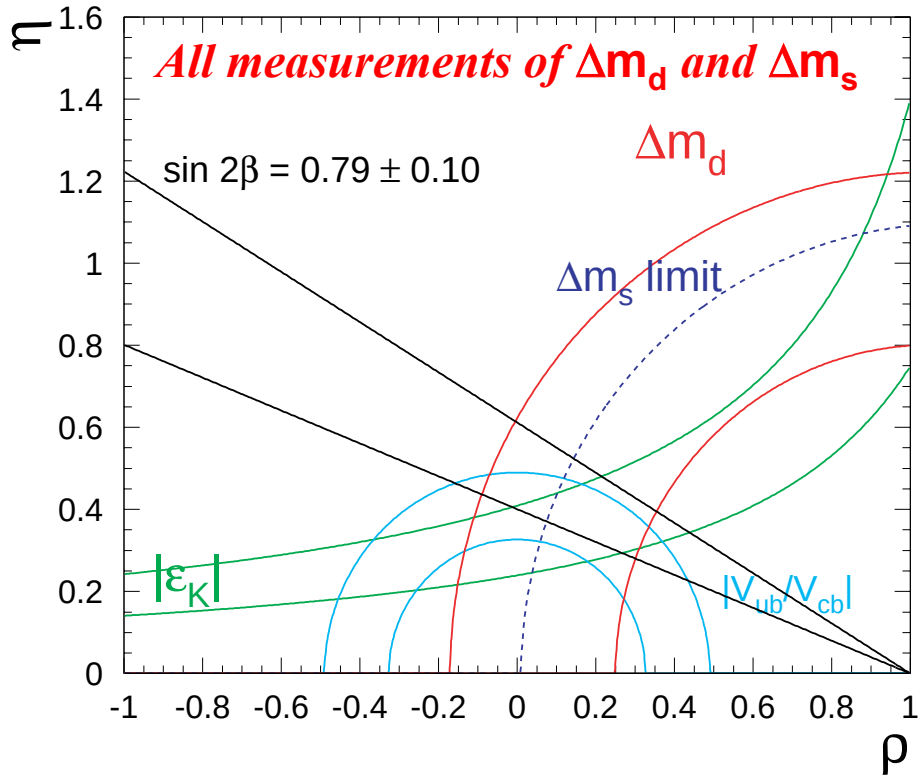


Impact on Unitarity Triangle

Contributions from V_{cb}, V_{ub}, Δm_d, Δm_s, ε_K and sin2β

+ theory input for hadronic matrix elements (lattice QCD)





B_s mixing results eliminate $\rho < 0$ and imply CP phase $\gamma < 90^o$

Last-Ever(!) B_s Mixing Projection

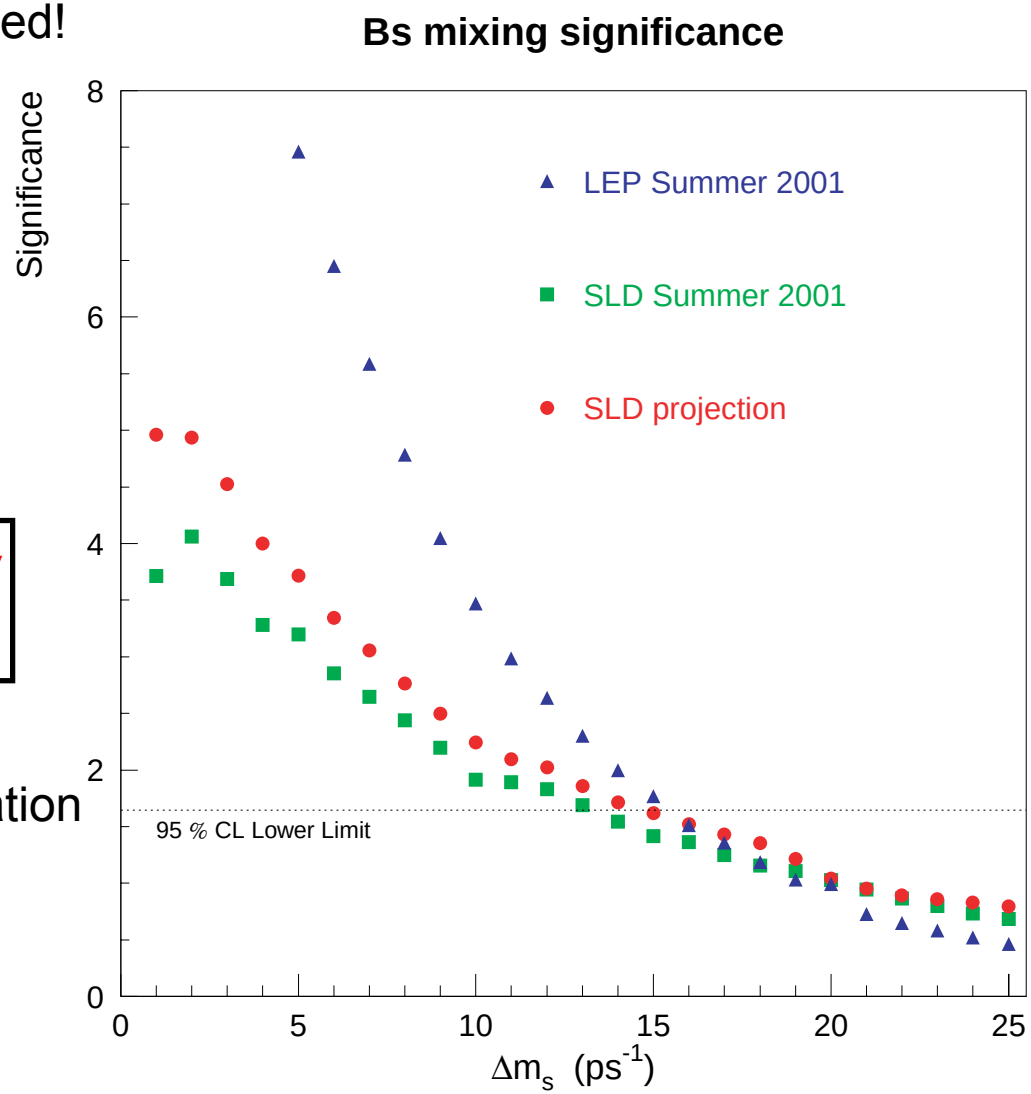
Are we done yet? No… stay tuned!

Final projection includes:

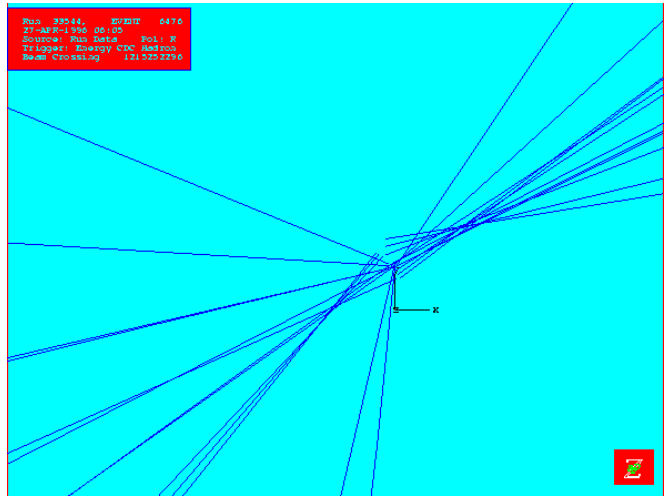
- latest version of lepton+D analysis
- (nearly) final D_s+tracks

→ **Expect final sensitivity of 15-16 ps^{-1}**

Plan to submit results for publication within 6 months



Summary



- SLD pioneered topological vertexing for average B lifetime, B^+ and B^0 lifetime measurements
- SLC/SLD strengths extremely well-suited to studies of time-dependent B^0, and particularly, B_s mixing

→ Beautifully illustrates power of small IP, CCD VXD, polarization and PID for B Physics

- It's been fun and rewarding!