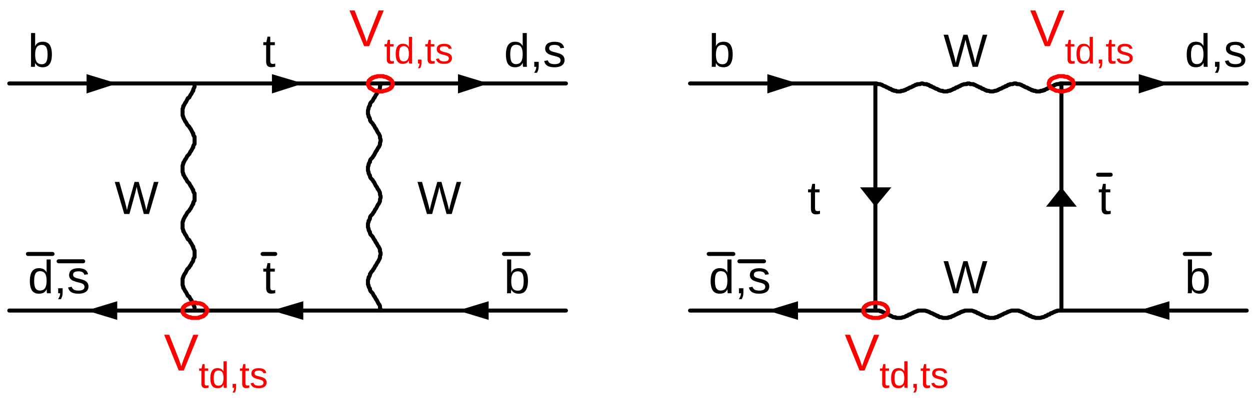
B_s Oscillation Results



Abstracts: 242 (OPAL), 250 (ALEPH), 478 (SLD), 587 (DELPHI)
new new new

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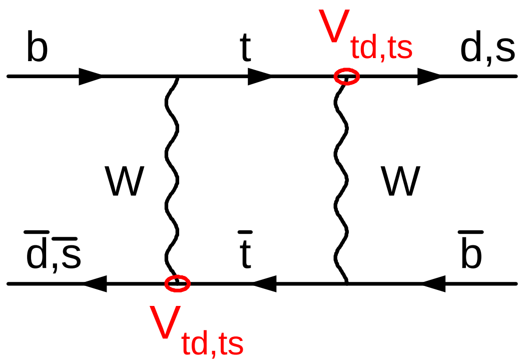
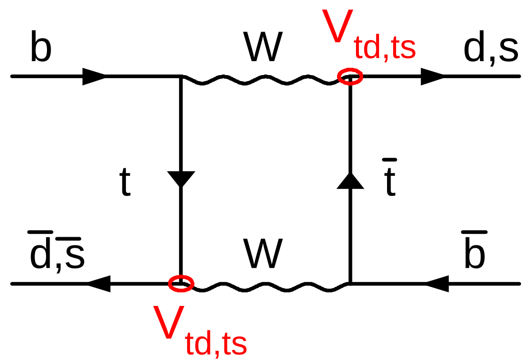
31st International Conference on High Energy Physics
Amsterdam
24-31 July 2002

Special thanks to D.Abbaneo, F.Parodi, O.Schneider, A.Stocchi

$B^0 - \bar{B}^0$ System (I)

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





- B_d^0 mixing frequency:

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_{B_d} m_t^2 \, F\!\left(\frac{m_t^2}{m_W^2}\right) B_{B_d} f_{B_d}^2 \eta_{QCD} \left| V_{tb}^* V_{td} \right|^2 = 0.503 \pm 0.006 \, \mathrm{ps}^{-1}$$

World average July 2002

But extraction of $|V_{td}|$ from Δm_d is affected by a 15 to 20% uncertainty

mostly due to theoretical uncertainty in $\sqrt{B_{B_d}} f_{B_d}$

→ reduced theoretical uncertainties and most precise determination of $|V_{td}|$

obtained by measuring $\Delta m_s / \Delta m_d$

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

S.Aoki BCP4

?

$(1.32 \pm 0.10)^2$

A.Kronfeld & S.Ryan

$B^0 - \overline{B}^0$ System (II)

Wolfenstein parameterization of the CKM weak quark mixing matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Measurements of the oscillations frequencies impose significant constraints on (ρ,η) = apex of unitarity triangle

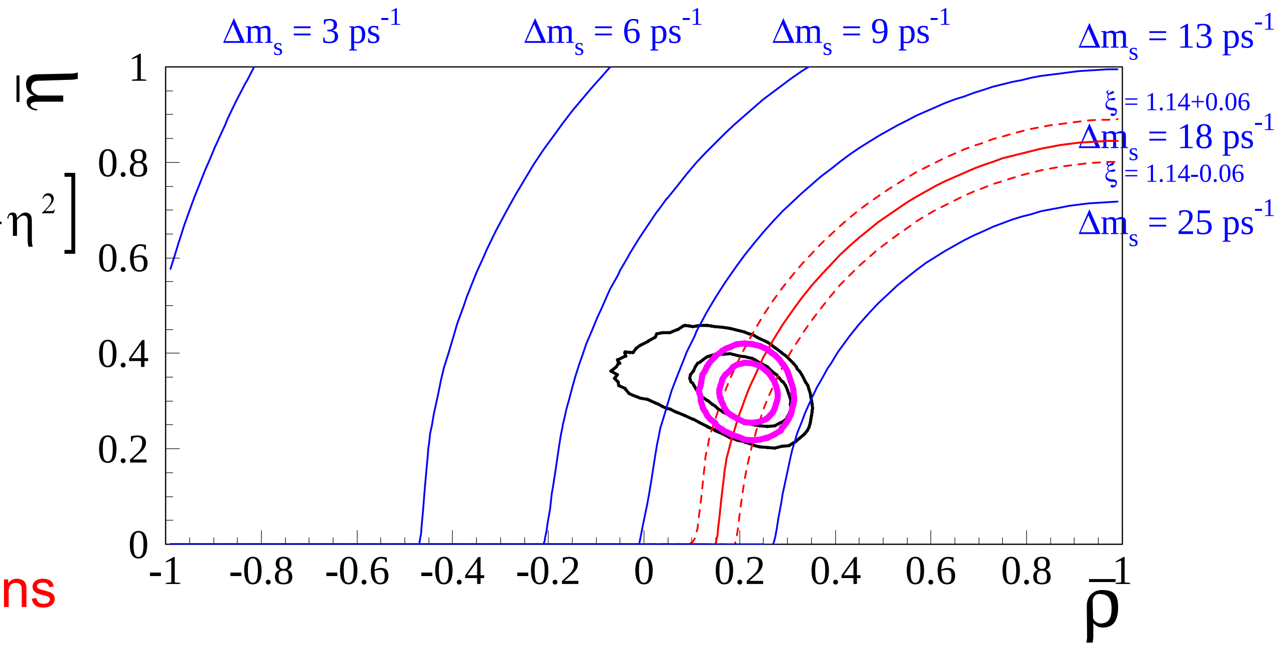
Lower limit on Δm_s → upper limit on $|V_{td}|$

$$\Delta m_s \propto |V_{ts}|^2 = A^2\lambda^4$$

$$\Delta m_d \propto |V_{td}|^2 = A^2\lambda^6 \left[(1-\rho)^2 + \eta^2 \right]$$

$$\Rightarrow \quad \frac{\Delta m_s}{\Delta m_d} \approx O\left(\frac{1}{\lambda^2}\right) = 20$$

→ *fast* B_s oscillations

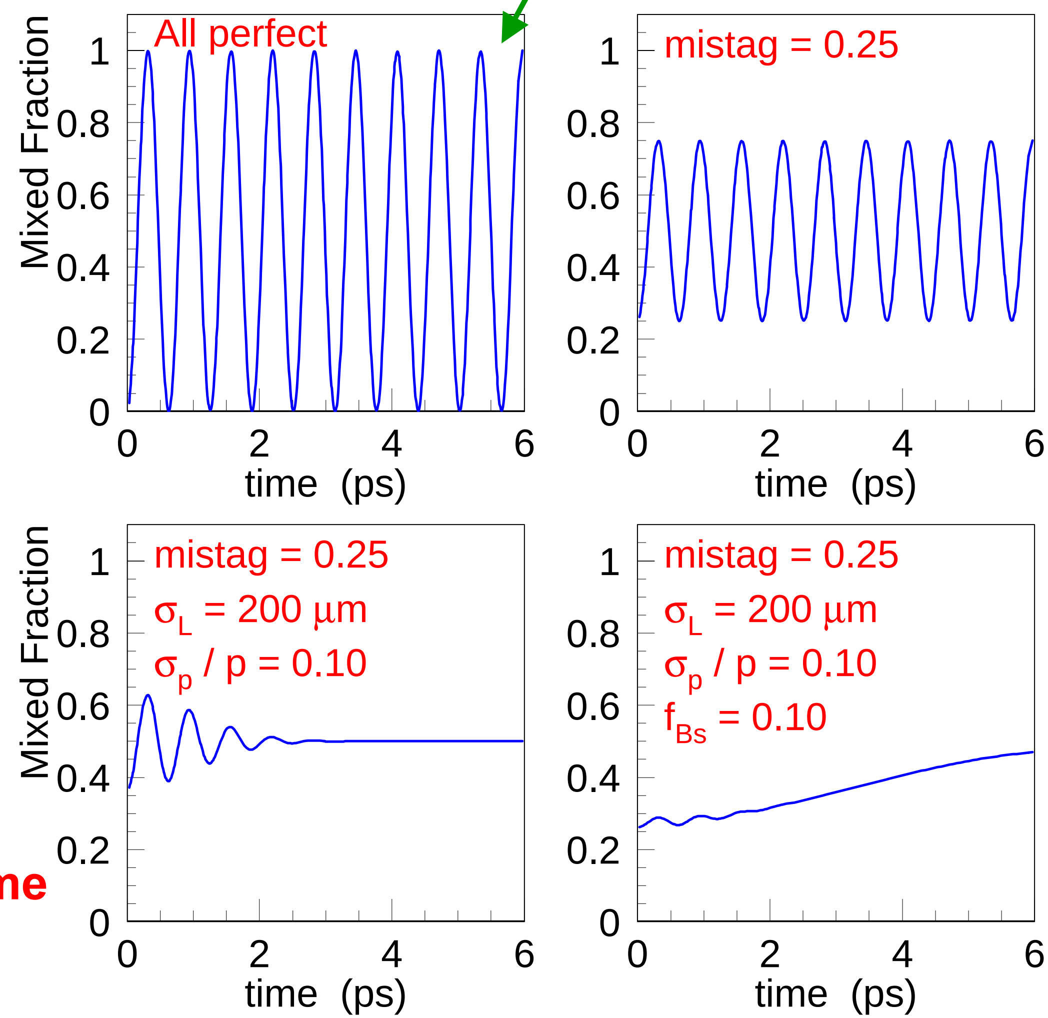


Mixing Ingredients (I)

1. Reconstruct B decay vtx & proper time
2. Tag B^0 or $\overline{B}^0$ flavor at production
3. Tag B^0 or $\overline{B}^0$ flavor at decay

$\Delta m_s = 10\ ps^{-1}$

Mixed Fraction = Nmixed / (Nmixed + Nunmixed)



Significance of 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

$$\sigma_t^2 = \left(\frac{\sigma_L\, m_B}{p}\right)^2 + \left(\frac{\sigma_p}{p}\, t\right)^2$$

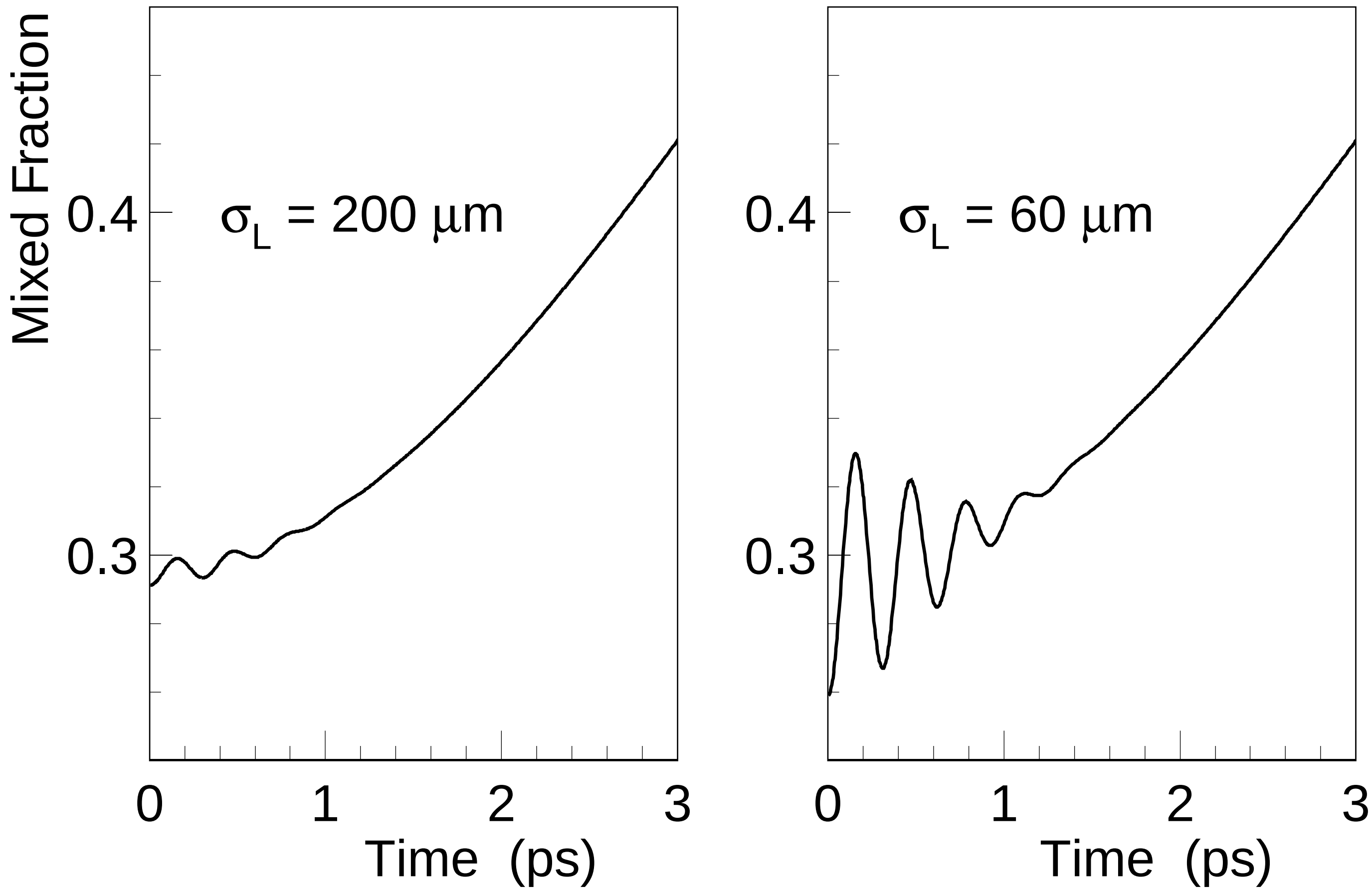
⇒ σ_t significantly increases with time for most analyses

(except for exclusive reco analyses that have small enough σ_p / p)

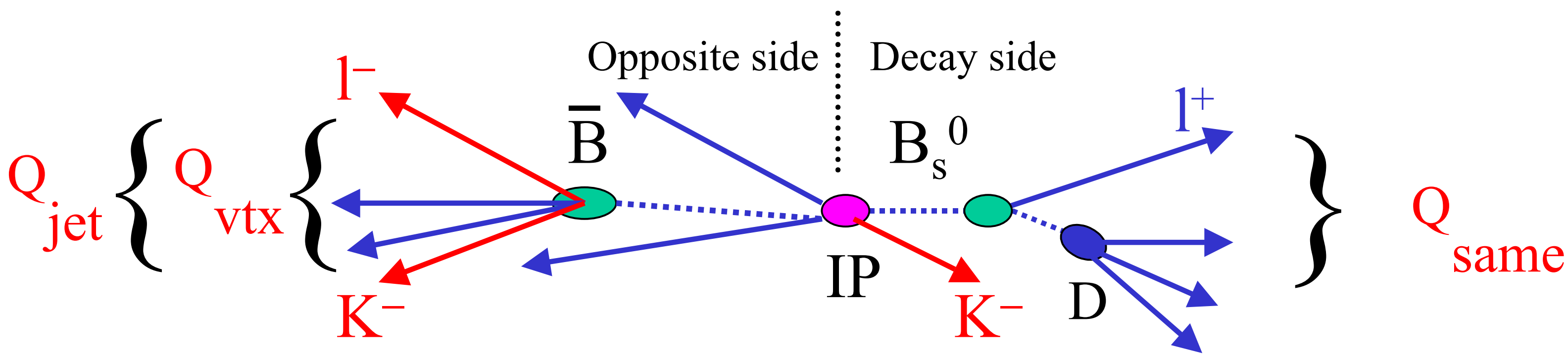
Mixing Ingredients (II)

Need excellent decay length resolution to detect high-frequency oscillations

Example: B_s mixing with Δm_s= 20 ps^{-1}, w = 0.25, σ_p / p = 0.10, f_{Bs} = 0.18



Initial State (Production) Tagging (I)



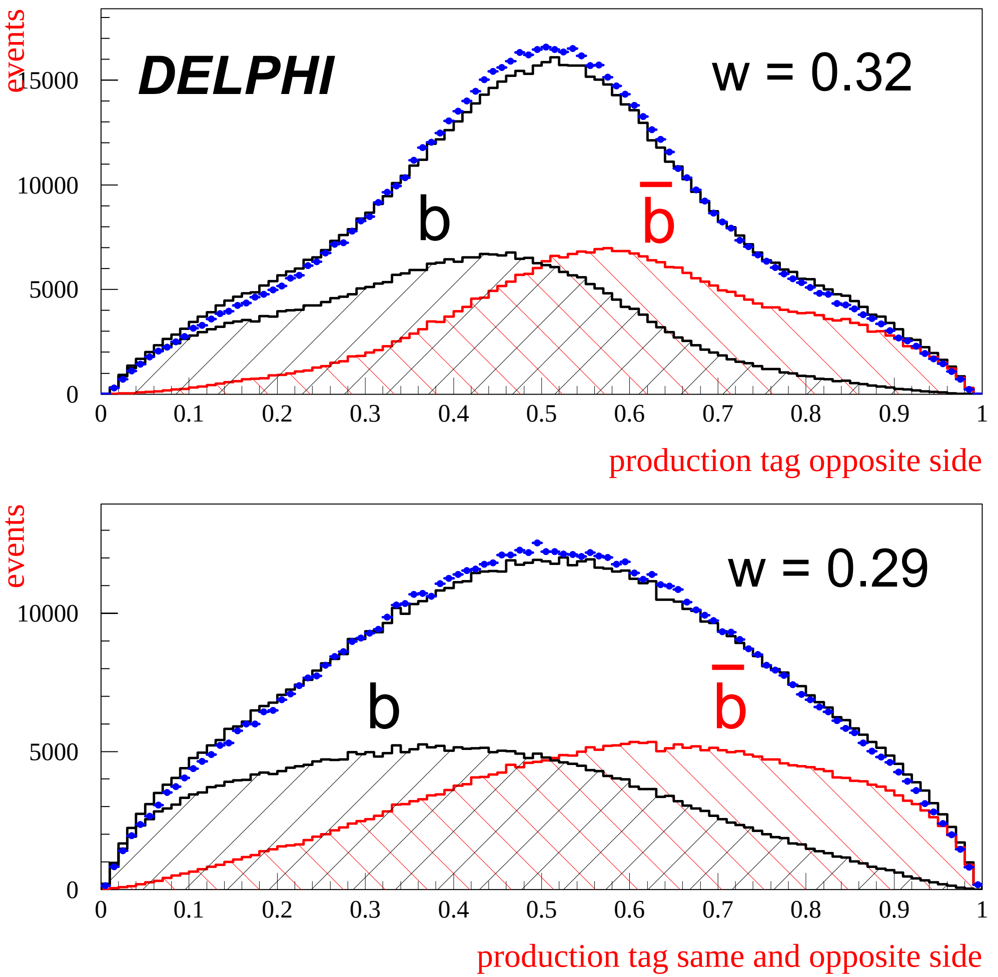
- Polarized Forward-Backward Asymmetry (SLD only)
  Left- (right-) polarized e^- tags forward hemisphere quark as b ($\bar{b}$)
- Opposite Side Tags
  Lepton charge $b \rightarrow l^-$
  Kaon charge $b \rightarrow c \rightarrow s$ (i.e. K^-)
  Jet Charge $\Sigma_{tracks} Q_i |p_i . T|^\kappa$
  Secondary vtx charge Q_{vtx}
- Same Side Tags
  Jet Charge
  Fragmentation kaon: $B_s(\bar{b}\ s)$ produced with accompanying $K^-(\bar{s}\ u)$

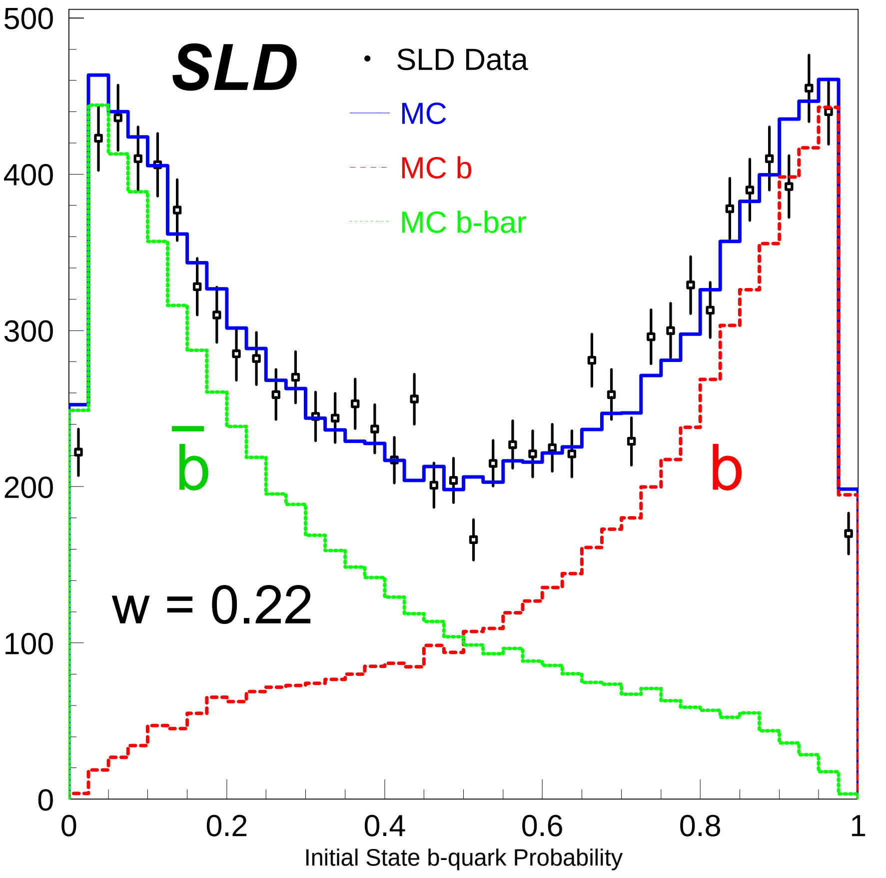
Avg mistag rates $w \approx 0.28$ (LEP)
0.22 (SLD)

→ Tags combined in most analyses + event-by-event mistag probabilities

Initial State (Production) Tagging (II)

1992-2000 data





b-quark probability

Reconstruction Methods

→ Reconstruct B decay to determine proper time and B^0 / $\bar{B}^0$ decay flavor

Efficiency ↑ ↓ Purity

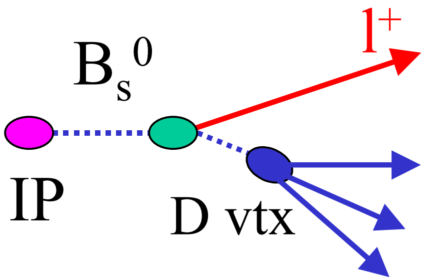
1) Inclusive

Fully inclusive: reconstruct $B_s \to D_s^- X$ cascade structure

DELPHI, SLD

Semileptonic decays: lepton + topological D vtx

ALEPH, DELPHI, OPAL, SLD



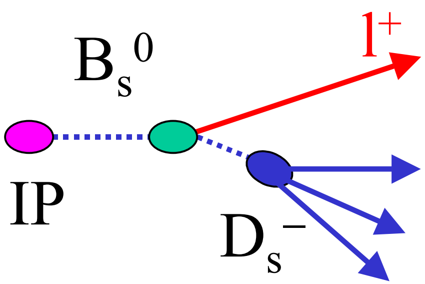
2) Semi-exclusive

Partial reconstruction: $B_s \to D_s^- l^+$ or $B_s \to D_s^-$ (hadrons)$^+$

with full or partial reconstruction of D_s decay

$D_s^- \to \phi\pi^-, K^{*0}K^-, K^0_sK^-, \ldots$ ALEPH, DELPHI, OPAL, SLD

$D_s^- \to \phi h^- X$ CDF

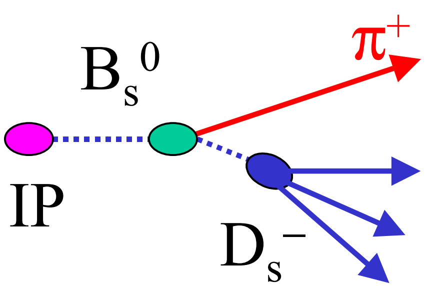


3) Exclusive

Full reconstruction: $B_s \to D_s^- h^+$, $\bar{D}^0 K^- h^+$ (h= π, ρ, a_1)

with fully reconstructed D_s and $\bar{D}^0$ decays

ALEPH, DELPHI



→ Total of 13 different analyses (8 updated since Feb. 2002)

Inclusive Methods (I)

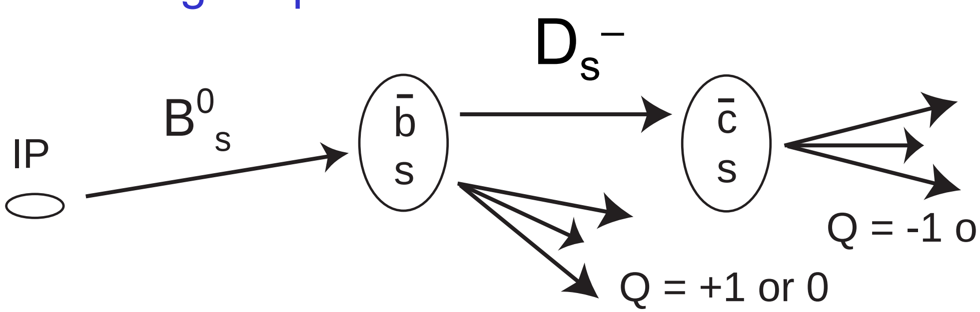
- **Fully Inclusive Analyses** DELPHI, SLD

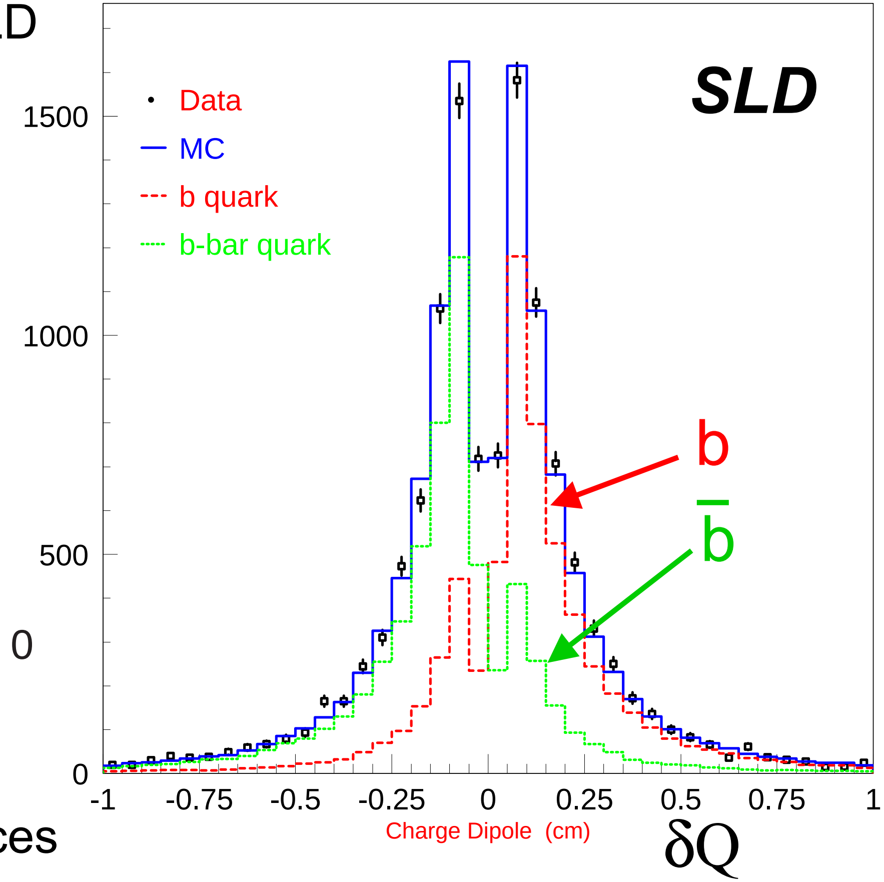
SLD Charge Dipole (400 K Z^0)

CCD Pixel Vertex Detector

$\Rightarrow$ superb decay length resolution

Charge Dipole:





Reconstruct both secondary and tertiary vertices

Tag flavor with $\delta Q = (Q_D - Q_B) * \text{Distance}_{B \text{ to } D}$

Decay flavor mistag = 0.22 overall

= 0.10 for $B_s \rightarrow$ single D_s X

= 0.46 for $B_s \rightarrow D_s D X$

11,462 selected decays

$f_{Bs} = 0.16$

σ_L = 78 μm (60%) & 304 μm (40%)

Inclusive Methods (II)

DELPHI inclusive analysis (4 M Z^0)

155,023 soft lepton events

Q_{lepton} for decay flavor tag with mistag probability w = 0.31

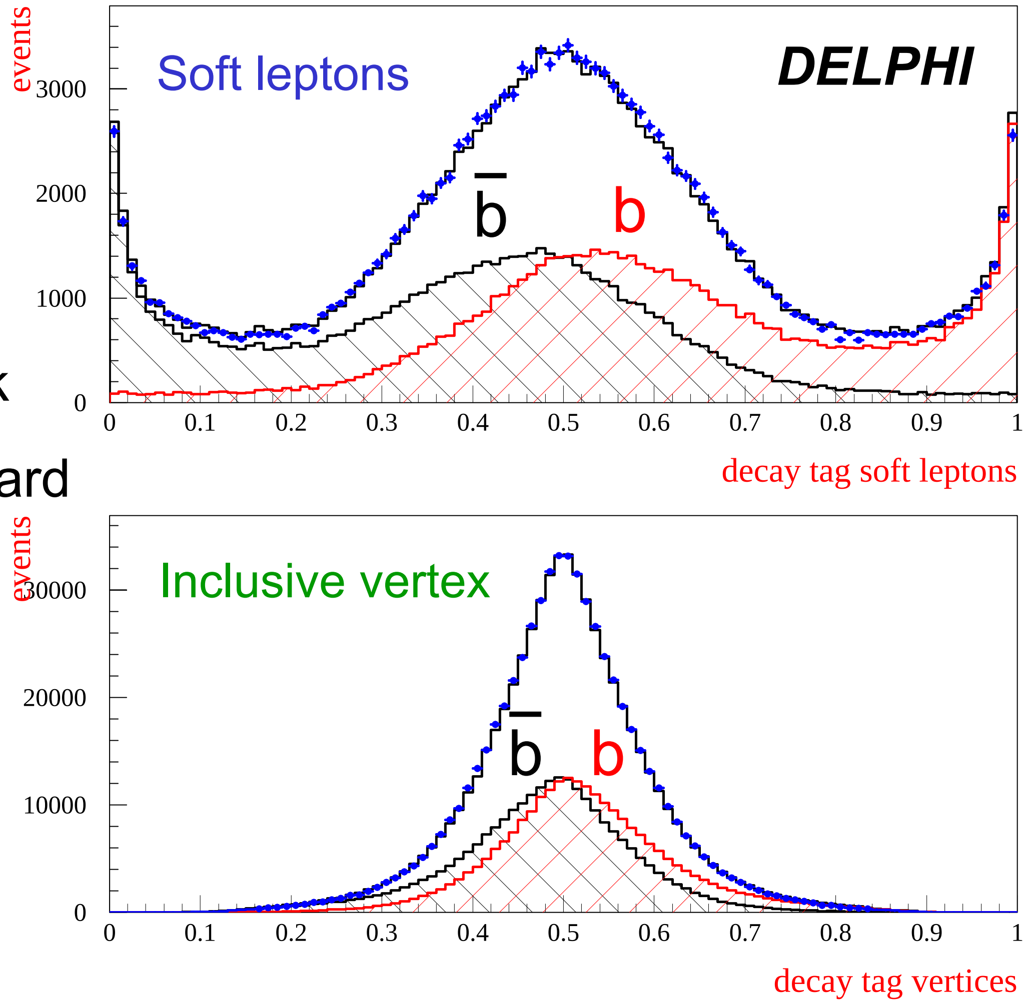
614,577 inclusive vertex events

"Dipole charge" formed from track information in forward and backward hemispheres of the B rest frame

⇒ decay flavor tag with w = 0.42

(mistag increases slightly after calibration from data)

1992-2000 data



Inclusive Methods (III)

- **Inclusive Lepton Analyses** ALEPH, DELPHI, OPAL, SLD

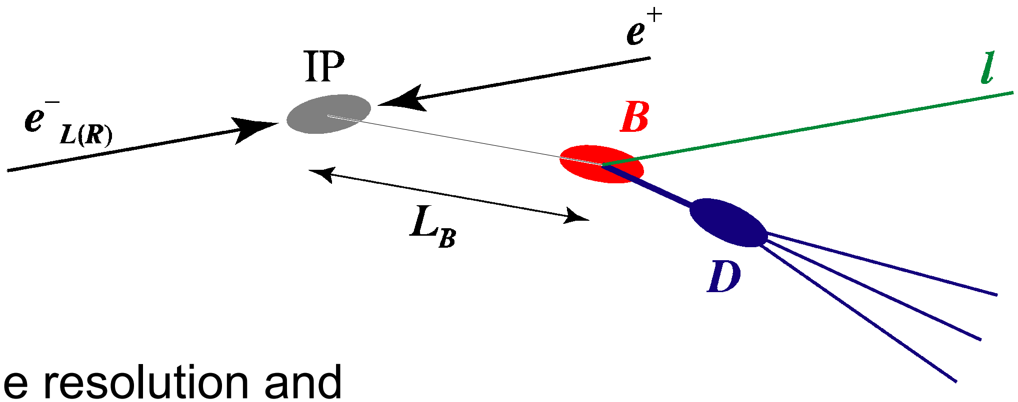
Select high-p_T lepton to suppress ($b \to c \to l^+$)

$\to$ lepton charge tags decay flavor ($b \to l^-$) with mistag as low as w = 0.04 (SLD)

Reconstruct D meson inclusively (decay vertex topology & kinematical info)

$\to$ B vtx = intersection of lepton trajectory and D vtx "track"

vertexing also includes "B track" formed with particles in jet



Pros: large statistics

Cons: worse proper time resolution and lower B_s purity than more exclusive methods

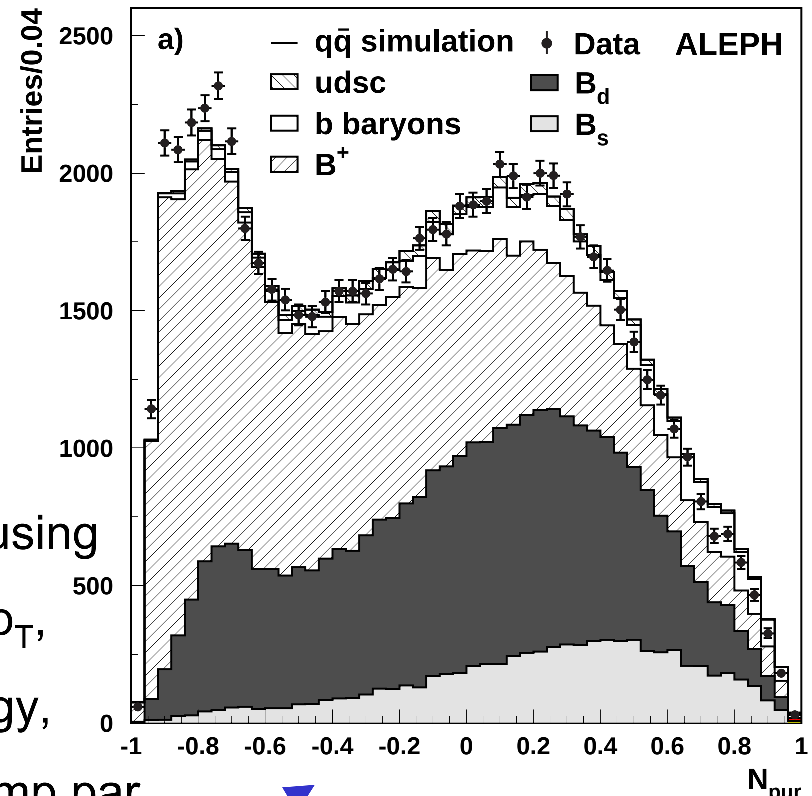
$\Rightarrow$ Include variables sensitive to proper time resolution, mistag probabilities and B_s purity on an event-by-event basis

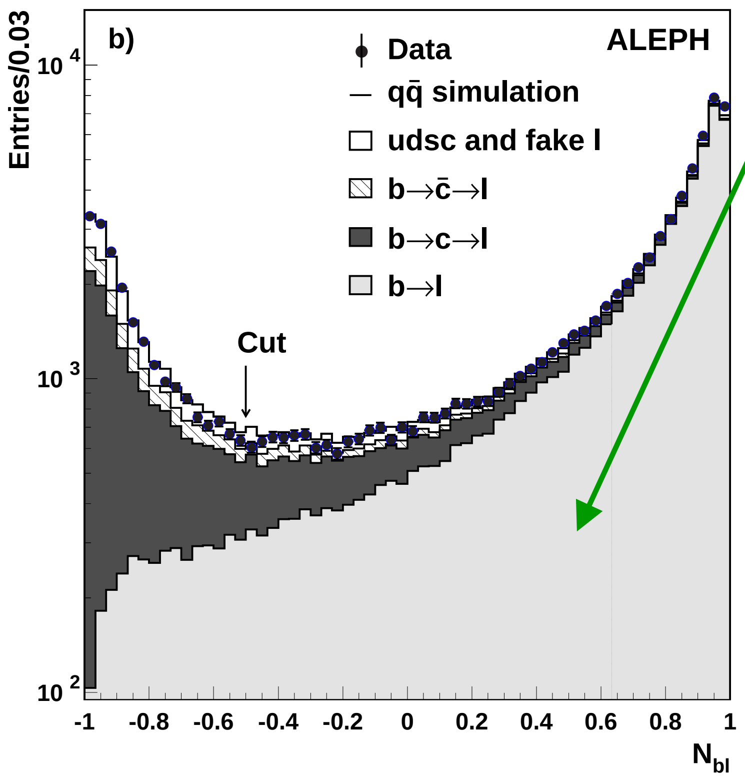
Inclusive Methods (IV)

- **ALEPH Inclusive Lepton** (4M Z^0)

Most sensitive B_s mixing analysis: 74026 events

Avoid hard cuts and incorporate information on an evt-by-evt basis for mistag probability, B_s purity and proper time resolution





NN for $b \to l$ using lepton p and p_T, Eν, jet topology, lepton-D vtx imp.par.

B_s purity determined with NN using Q_{tot}, # D vtx trks, #($K^0 + K^+$) from fragmentation and D vtx, $Q_{lepton} * Q_{kaon}$

Amplitude Fit Method

- Time-dependent mixing generates periodic signal

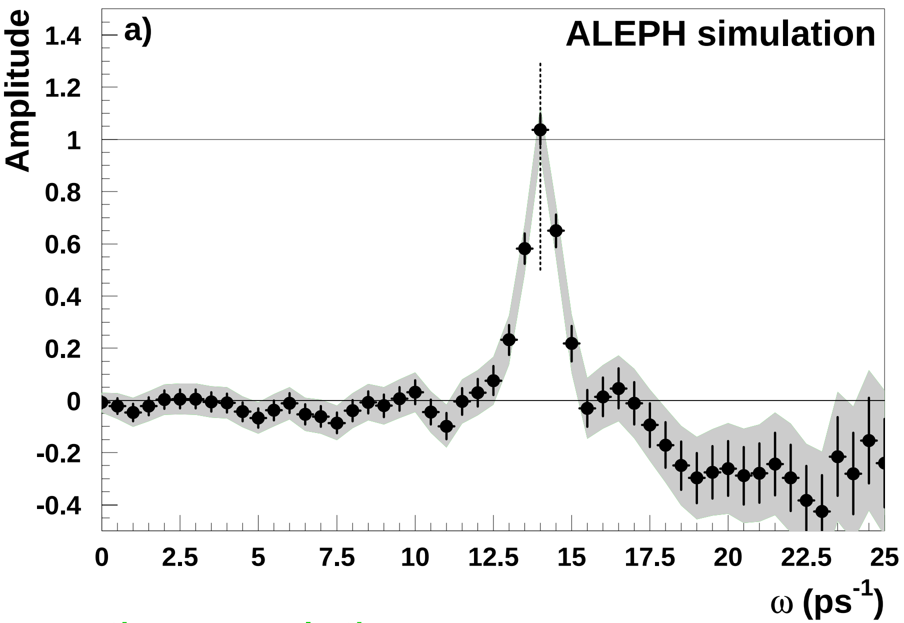
  ⇒ ideally suited for Fourier Analysis *pioneered by ALEPH* NIM A384, 491 (1997)

  ⇒ measure oscillation amplitude A at fixed frequency Δm_s

$$\text{Prob}\,(B_s^0 \to B_s^0) = \tfrac{1}{2}\Gamma e^{-\Gamma t}\left(1 + A\cos\Delta m_s t\right)$$

$$\text{Prob}\,(B_s^0 \to \overline{B}_s^0) = \tfrac{1}{2}\Gamma e^{-\Gamma t}\left(1 - A\cos\Delta m_s t\right)$$

MC generated with $\Delta m_s = 14\ \text{ps}^{-1}$



Expect A = 1 for frequency = true Δm_s

A = 0 for frequency ≠ true Δm_s

95% C.L. limit:

Δm_s values for which $A + 1.645\,\sigma_A < 1$

Sensitivity:

Δm_s value for which $1.645\,\sigma_A = 1$

→ σ_A increases with Δm_s due to limited proper time resolution

Inclusive Methods (V)

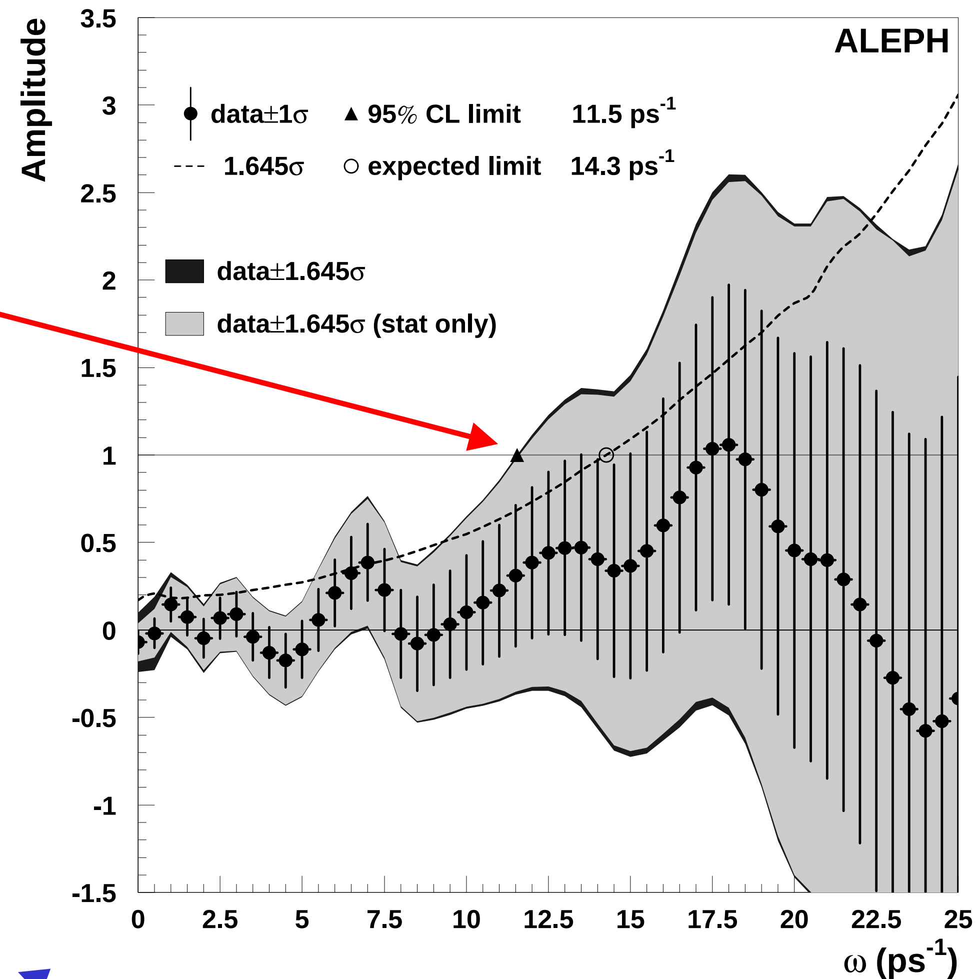
- **ALEPH Inclusive Lepton**

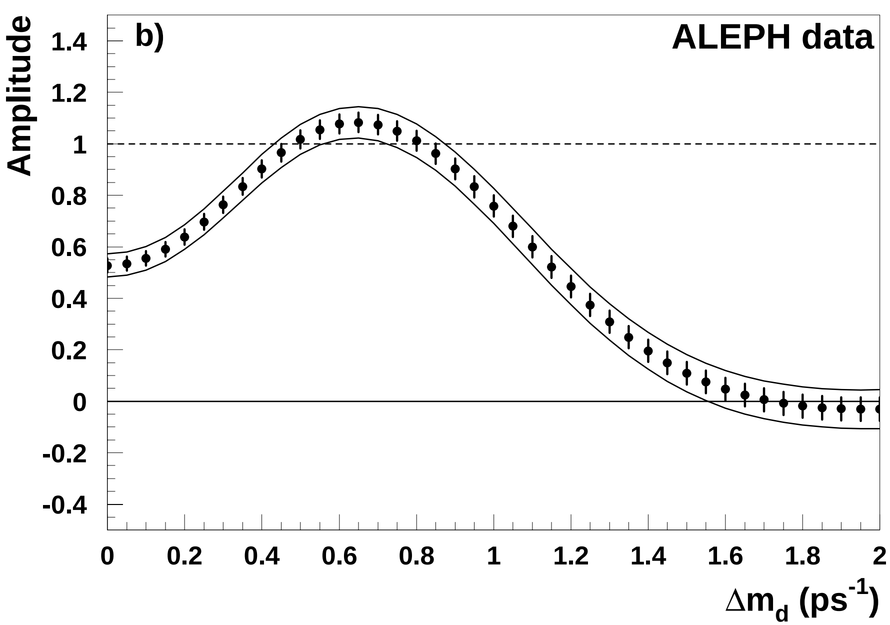
Amplitude fit for B_s mixing

$\Delta m_s > 11.5\ ps^{-1}$ (95% C.L.)

Sensitivity = $14.3\ ps^{-1}$

(assuming B_s prod frac = 10.7%)

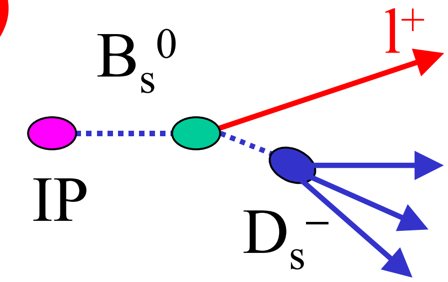




Amplitude fit for B_d mixing

$\Delta m_d = 0.55\ ps^{-1}$ ($\sigma_{syst} = 0.08\ ps^{-1}$)

Semi-exclusive Methods (I)



- **Ds-Lepton Analyses** ALEPH, DELPHI, OPAL, CDF

Partial reconstruction of $B_s \to D_s^- l^+ \nu_l$

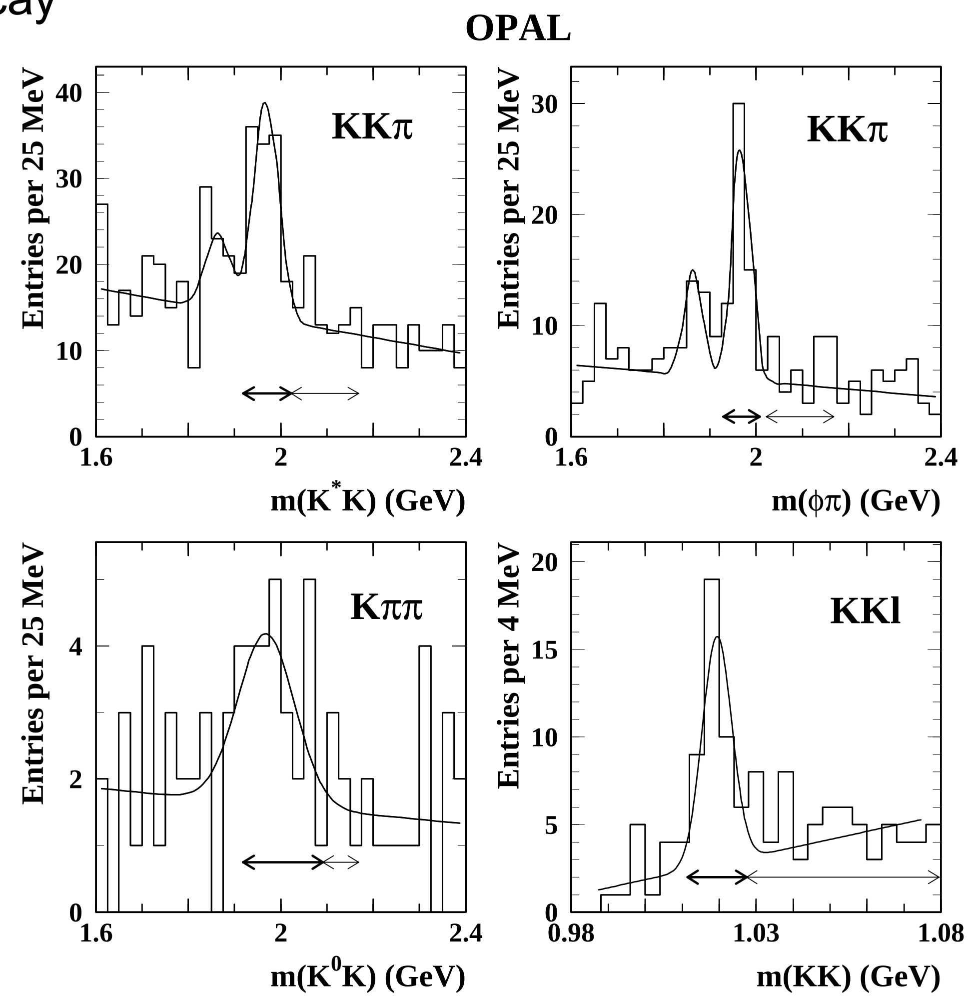
with full or partial reconstruction of D_s decay

$D_s^- \to \phi\pi^-, K^{*0}K^-, K^0_sK^-, \ldots \phi h^- X$

use dE/dx (and RICH @ DELPHI)

Pros: high B_s purity, good proper time resolution

Cons: low statistics



Semi-Exclusive Methods (II)

- **DELPHI Ds-Lepton** (3.5 M Z^0)

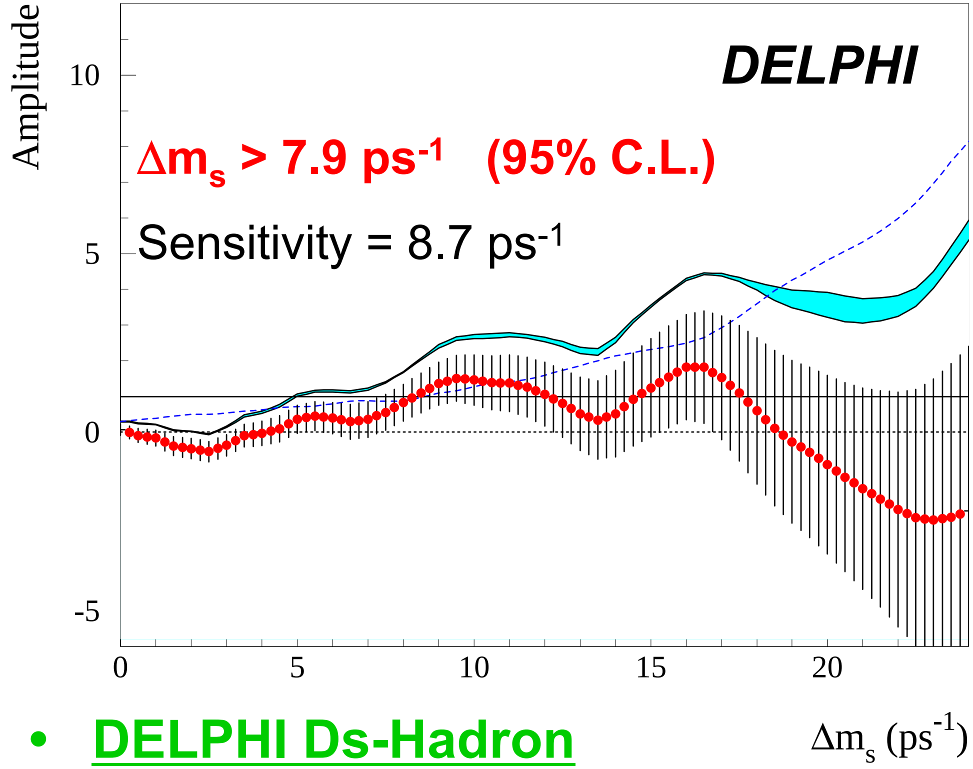
  436 D_s l candidates

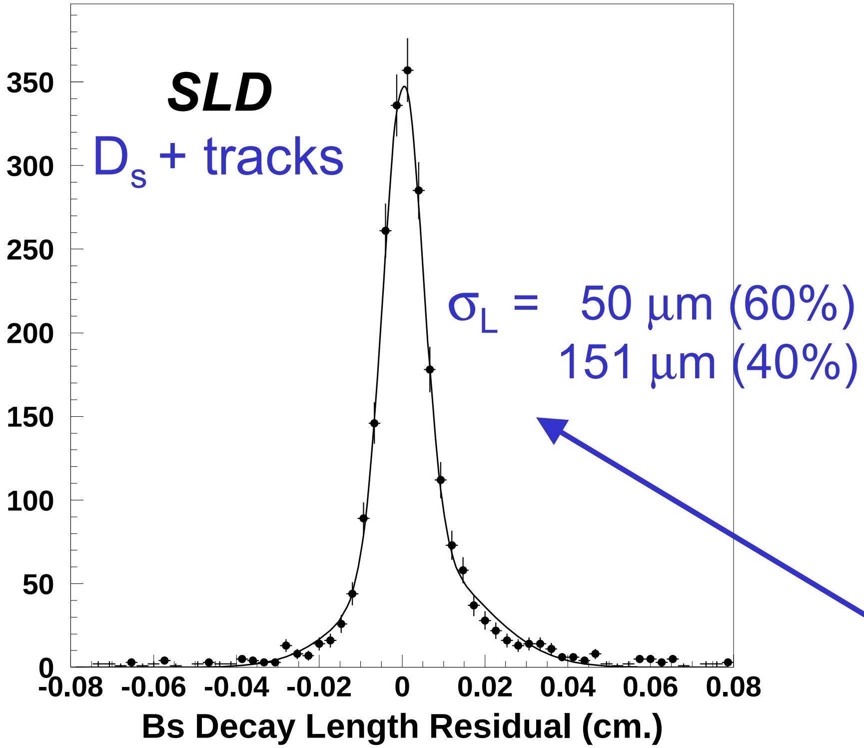
  230 ± 18 from $B_s \to D_s\, l\, \nu_l$

  σ_L = 200 μm (82%) & 740 μm (16%)

  σ_p / p = 0.07 (82%) & 0.16 (16%)

  now includes evt-by-evt resolution





- **DELPHI Ds-Hadron**

  Higher efficiency but less sensitive than D_s-lepton due to worse resolution and lower B_s purity

- **SLD Ds-Tracks** (lepton or hadrons)

  Good B_s purity (40%) and best resolution

Exclusive Method

- **ALEPH+DELPHI** (4.4+3.5 M Z^0)

Full reconstruction of

$B_s \to D_s^- \pi^+$, $D_s^- a_1^+$

$\bar{D}^0 K^- \pi^+$, $\bar{D}^0 K^- a_1^+$

with fully reconstructed D_s and $\bar{D}^0$ decays

Also sensitive to modes with

photons: $D_s^{*-} \pi^+$, $D_s^{(*)-} \rho^+$, $D_s^{*-} a_1^+$

$\to$ satellite peak if missed photon(s)

B_s signal in main peak:

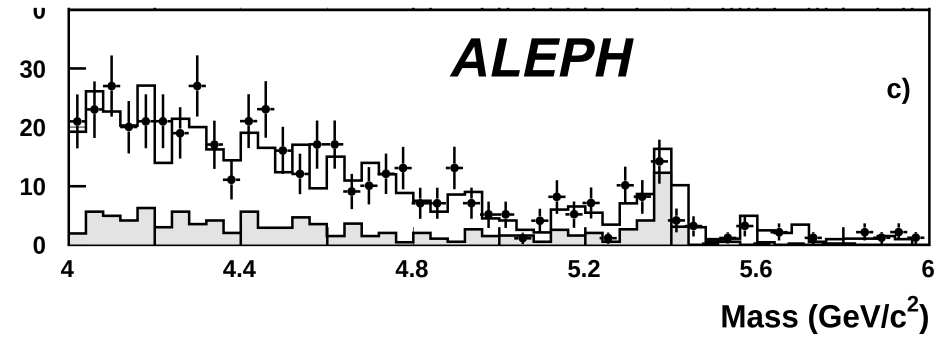
14 (ALEPH) + 8 (DELPHI)

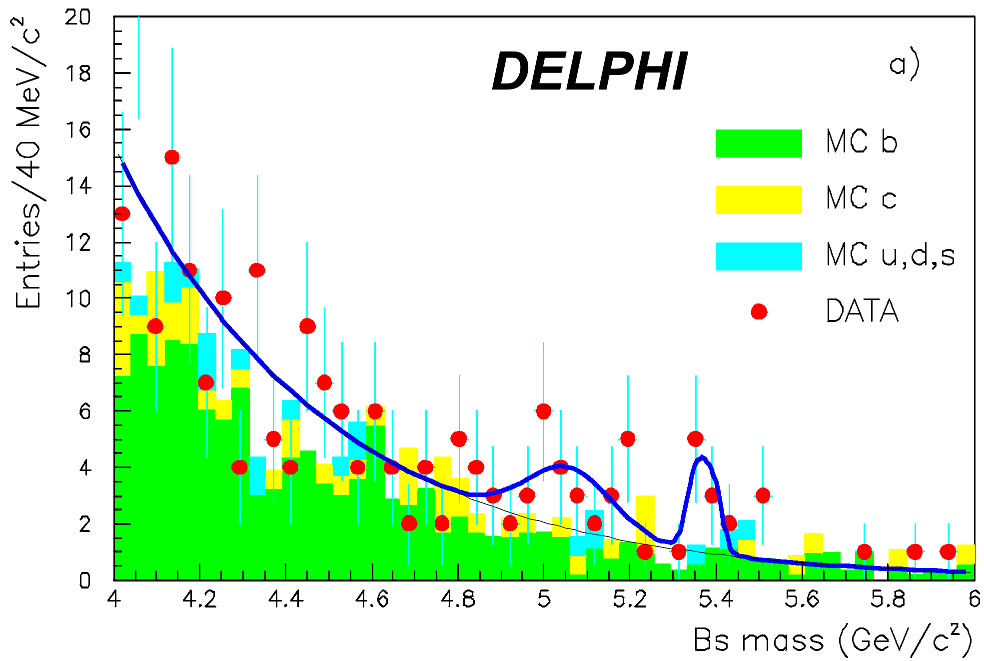
B_s signal in satellite peak:

14 (ALEPH) + 15 (DELPHI)

Excellent proper time resolution

$<\sigma_L>$ = 180 μm (ALEPH)





σ_L = 117 μm (58%) & 216 μm (42%) (DELPHI)

σ_p / p very small (0.5% ALEPH)

B_s Oscillation Amplitude: WORLD average

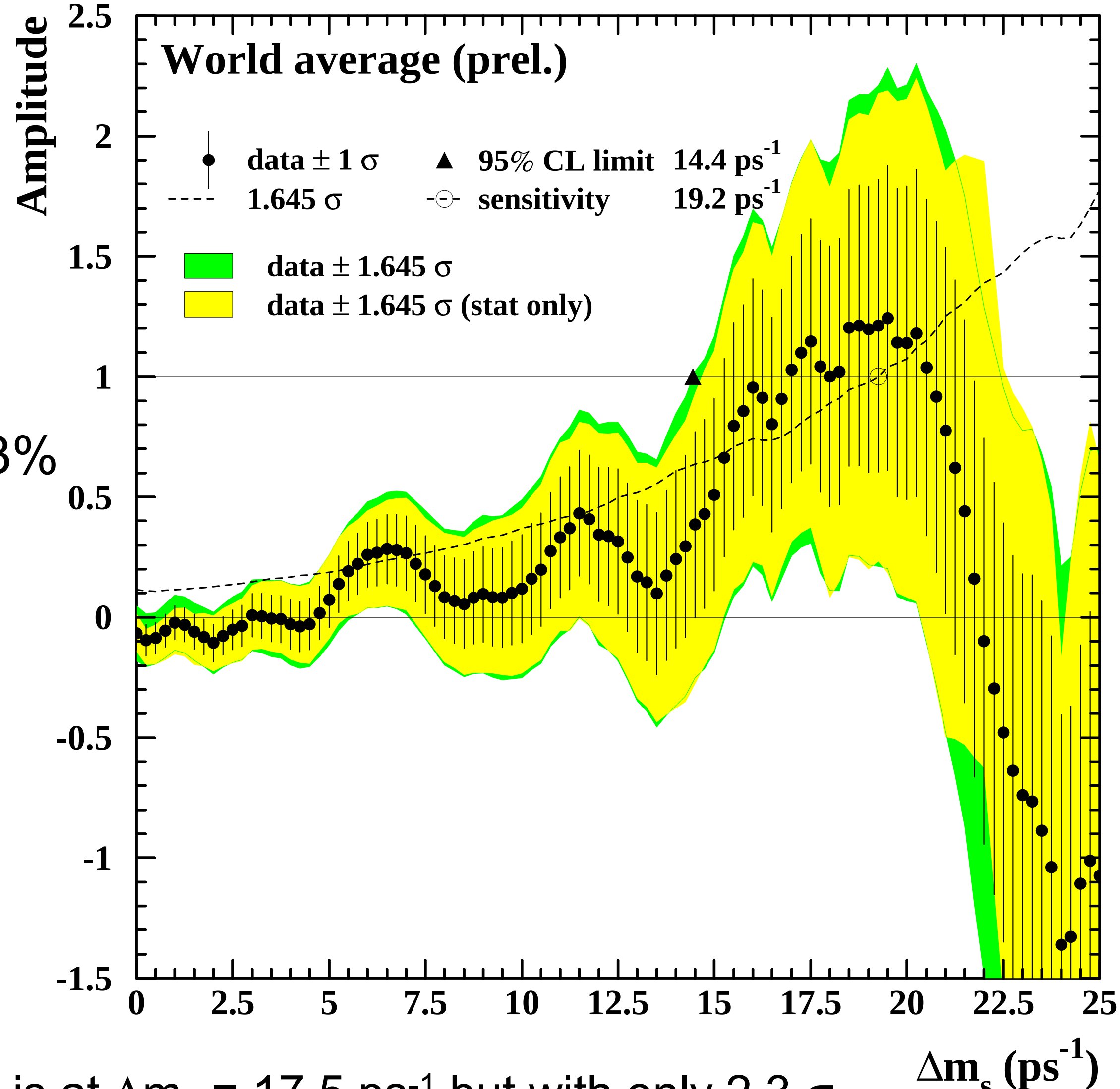
Combine measurements from ALEPH, CDF, DELPHI, OPAL and SLD

Rescale results to common set of input parameters:
e.g., B_s production fraction = 9.3%
$\rightarrow \sigma_A$ is rescaled for inclusive analyses

Sensitivity = 19.2 ps^{-1}

Lower limit at 95% C.L.:

$\Delta m_s >$ 14.4 ps^{-1}



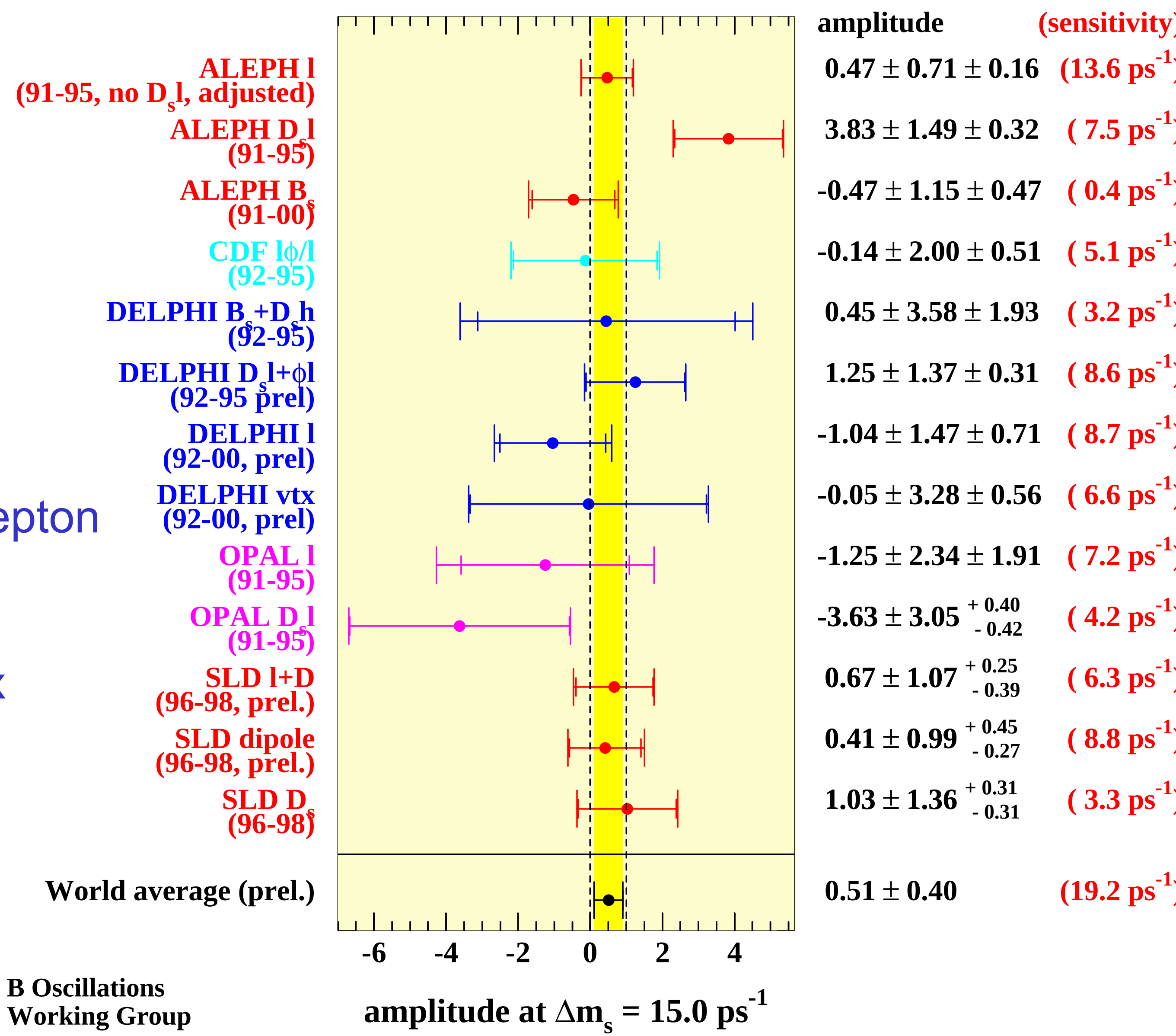
Most significant deviation from A=0 is at Δm_s = 17.5 ps^{-1} but with only 2.3 σ

Individual B_s Oscillation Amplitude Measurements

Compare measured amplitudes at $\Delta m_s = 15.0\ ps^{-1}$

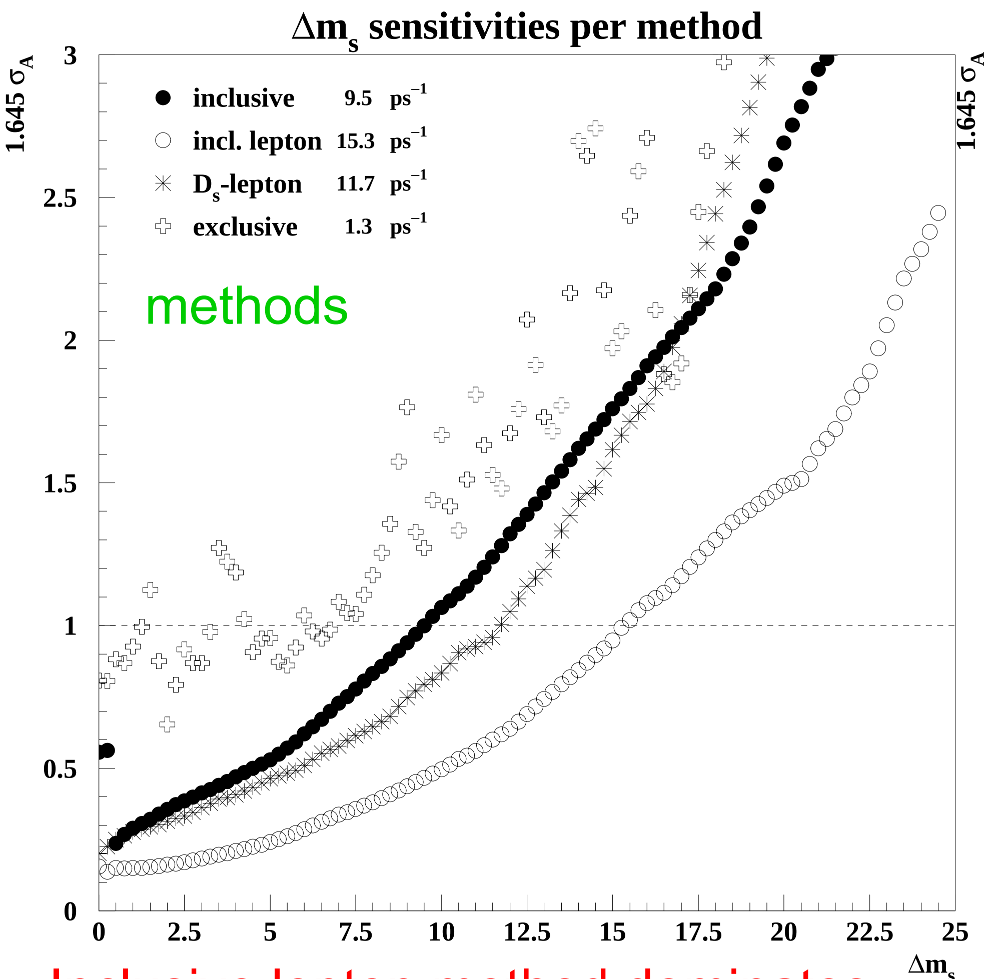
Most sensitive (smallest σ_A):

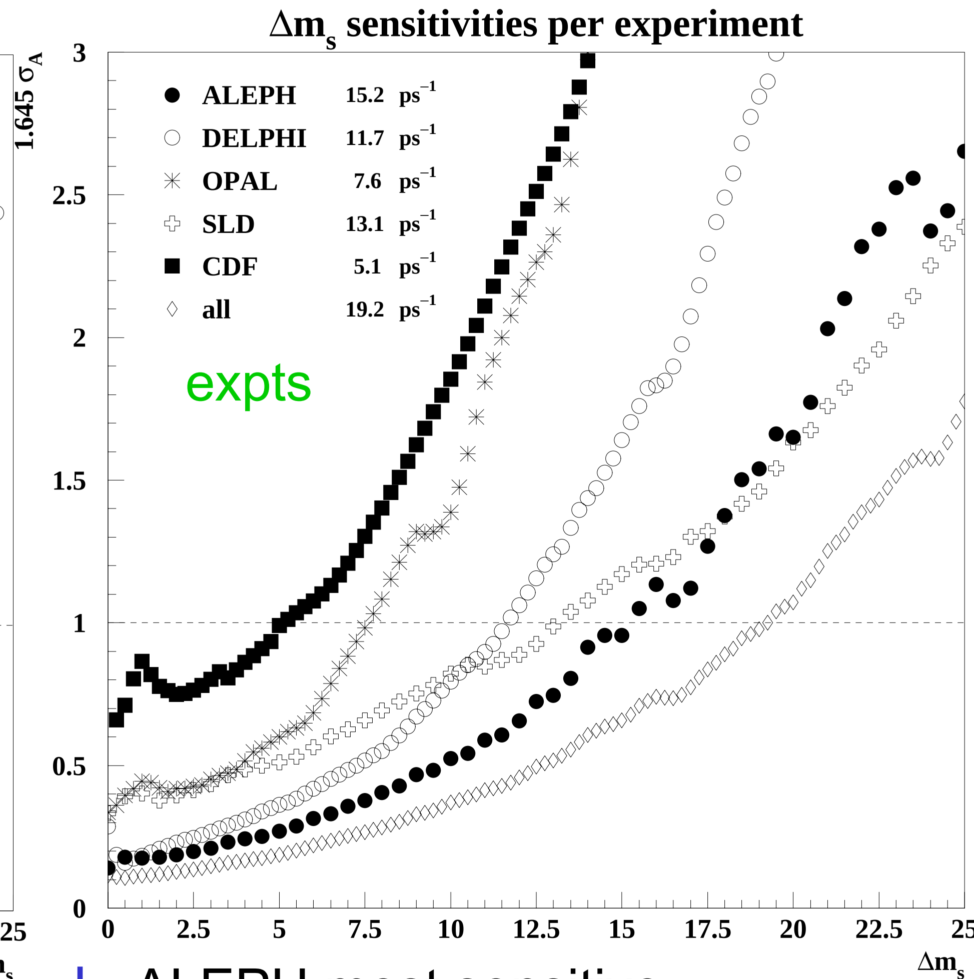
1. ALEPH inclusive lepton
2. SLD charge dipole
3. SLD lepton + D vtx



B_s Oscillation Sensitivity

Compare amplitude uncertainties (1.645 σ_A) as a function of Δm_s





Inclusive lepton method dominates

Exclusive method needs more statistics

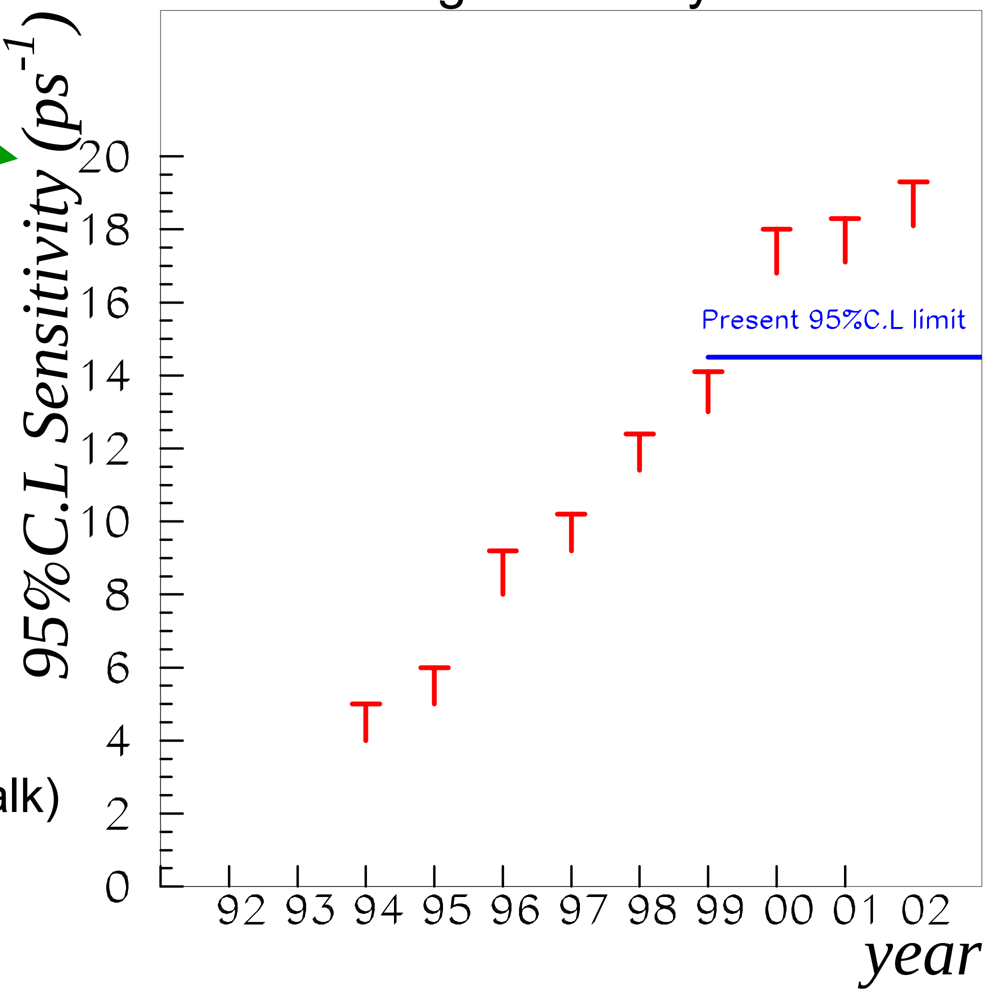
ALEPH most sensitive

SLD hi-resolution → smaller slope

B_s Oscillations Summary

The development of sophisticated analyses has provided steady increase in sensitivity

World avg sensitivity vs.



B_s oscillations yet to be observed

But current limit from ALEPH+CDF+DELPHI+OPAL+SLD:

$\Delta m_s > 14.4\ ps^{-1}$ (95% C.L.)

sets a powerful constraint on the unitarity triangle (see F. Parodi's talk)

LEP+SLD analyses nearly final

Look forward to 2nd generation expts (CDF, D0, LHCb, BTeV) to study B_s oscillations