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A Review of B^0 Mixing and Lifetimes

Intl. Workshop on Weak Interaction and Neutrinos

2002 Univ. of Canterbury

1978 Iowa State Univ.

E.I. Rosenberg

January 25, 2002

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Outline

- Mixing of neutral flavor states
- Measuring the mixing
- Mixing in the Standard Model
- Measuring the lifetimes
- What lies ahead

Many summary plots and combined fits can be found at:
B-Lifetimes Working Group: http://claires.home.cern.ch/claires/lepblife.html
B-Oscillations Working Group: http://lepbosc.web.cern.ch/LEPBOSC/
Last updated for 2001 summer conferences

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Where the data come from

- Υ_{4s} Symmetric e^+e^- Colliders:
  Argus, CLEO
  - B_d only
  - produced ~at rest
  - 9 x 10^6 events

- Z^0 Pole e^+e^- Colliders:
  LEP expts., SLD
  - B_d and B_s
  - boost
  - ~1 x 10^6 pairs/LEP expt.
  - ~1 x 10^5 SLD + pol. beam

- Hadron Colliders: CDF, D0
  - B_d and B_s
  - boost
  - several million events
  - trigger issues
  - Run II in progress

- Υ_{4s} Asymmetric e^+e^- Colliders:
  BABAR, BELLE
  - B_d only
  - boost
  - 3x10^7 pairs and counting

Mixing of Neutral Flavor States

- **Neutral flavor states (K, D, B mesons) are produced in strong interaction flavor eigenstates $B^0, \overline{B^0}$**
- **They decay in eigenstates of definite mass and lifetime**

$$\left|B^0_\pm(t)\right\rangle = e^{-\Gamma_\pm t/2} e^{-im_\pm t} \left|B^0_\pm\right\rangle$$

If CP is conserved: $\mathrm{CP}\left|B^0_\pm\right\rangle = \pm\left|B^0_\pm\right\rangle$

$$\left|B^0_\pm\right\rangle = \frac{1}{\sqrt{2}}\left\{\left|B^0\right\rangle \mp \left|\overline{B^0}\right\rangle\right\}; \quad \left|B^0\right\rangle = \frac{1}{\sqrt{2}}\left\{\left|B^0_+\right\rangle + \left|B^0_-\right\rangle\right\}$$

$$\left|\left\langle \overline{B^0}(t)\middle|B^0\right\rangle\right|^2 = \frac{1}{4}\left(e^{-\Gamma_+ t} + e^{-\Gamma_- t} - 2\cos(\Delta m\ t)\right);$$

$$= \frac{e^{-\bar{\Gamma} t}}{2}\left(\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\Delta m\ t)\right)$$

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Time-integrated B Mixing Measurements

$$\chi^{B^0\to\overline{B^0}} = \chi^{\overline{B^0}\to B^0} = \frac{\int_0^\infty \left|\left\langle \overline{B^0}(t)\middle|B^0(t)\right\rangle\right|^2 dt}{\int_0^\infty \left|\left\langle \overline{B^0}(t)\middle|B^0(t)\right\rangle\right|^2 dt + \int_0^\infty \left|\left\langle B^0(t)\middle|B^0(t)\right\rangle\right|^2 dt} = \frac{(\Delta m\,\tau)^2 + \left(\frac{\Delta\Gamma\,\tau}{2}\right)^2}{2\left(1+(\Delta m\,\tau)^2\right)} \approx \frac{(\Delta m\,\tau)^2}{2\left(1+(\Delta m\,\tau)^2\right)}$$

x_d

Most recent measurement of this type:

CLEO (Phys. Lett. B490: 36-44, 2000)
Uses 9.6 x 10^6 events (9.1 fb^{-1})

One B is flavor tagged by partially reconstructing: $\overline{B^0} \to D^{*+}\pi^-$ or $D^{*+}\rho^-$

The other B is tagged by high-p_T lepton in: $B \to Xl\nu$

$$\chi_d = \frac{B^0B^0 + \overline{B^0}\,\overline{B^0}}{B^0B^0 + \overline{B^0}\,\overline{B^0} + B^0\overline{B^0} + \overline{B^0}B^0} = 0.198 \pm 0.013 \pm 0.014$$

Measuring the B Mixing Oscillations

$$\frac{\Delta\Gamma}{\Delta m} \approx O\left(\frac{m_b^2}{m_t^2}\right) \sim 5x10^{-3}; \text{ for } B_d, \frac{\Delta\Gamma}{\bar{\Gamma}} < 1\%$$

from lattice QCD

we are measuring terms proportional to

$$\frac{e^{-\bar{\Gamma}t}}{2}\left(1 \pm \cos(\Delta m\, t)\right)$$

No flavor change

Flavor change

- **Need to flavor tag both initial and final state**
- **Need to reconstruct both primary and decay vertices to measure decay length: $t = mL/p = L/\beta\gamma$**

beam spot, vertexing from tracks, intrinsic detector resolution

$$\sigma_t = \left(\frac{\sigma_l m}{p}\right) \oplus t\left(\frac{\sigma_p}{p}\right)$$

decaying B momentum or good estimator needed (boost)

BABAR: $\delta(\beta\gamma)/\beta\gamma = 0.1\%$

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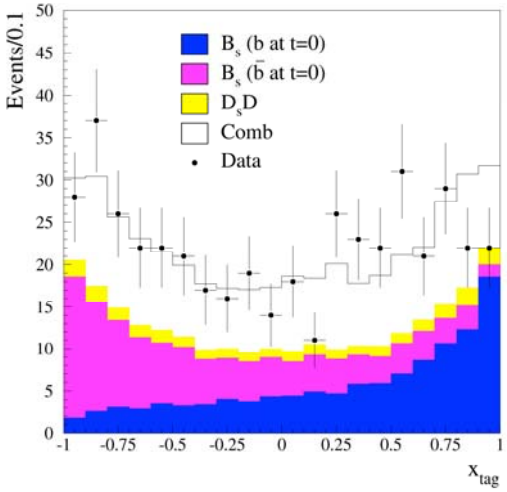
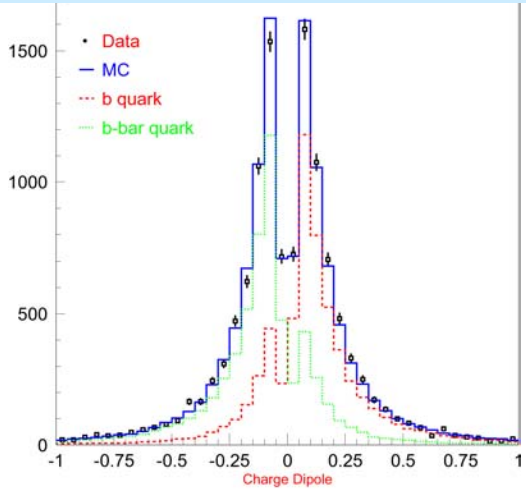
Tagging Methods

- **Initial State:**
  - **can tag same side or opposite side**
  - **side side: jet charge and topology**
  - **opposite side: techniques similar to final state tags**
- **Final State:**
  - **$b \rightarrow c \rightarrow s$ decays**
    - **charge of primary lepton in sl decay**
    - **charge of charm meson (fully or partially reconstructed)**
    - **charge of kaon**
  - **momentum-weighted jet charge**
  - **dipole charge between D and B**
  - **jet angles (polarized beams)**
  - **multivariate constraints (perhaps realized in a neural net)**
  - **full reconstruction**

DELPHI 9 Discr. variables:
5 opposite side; 3 same side uncorrelated with final state tag;1 both sides: polar angle



SLD sign(QD-QB)*separation



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Improvement in Detection

Statistical Significance

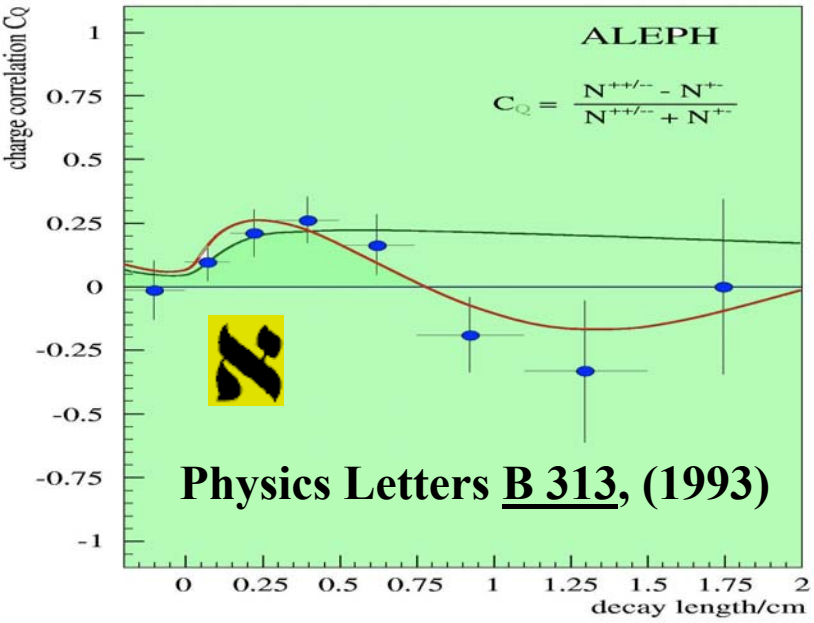
σ_t more important for large Δm

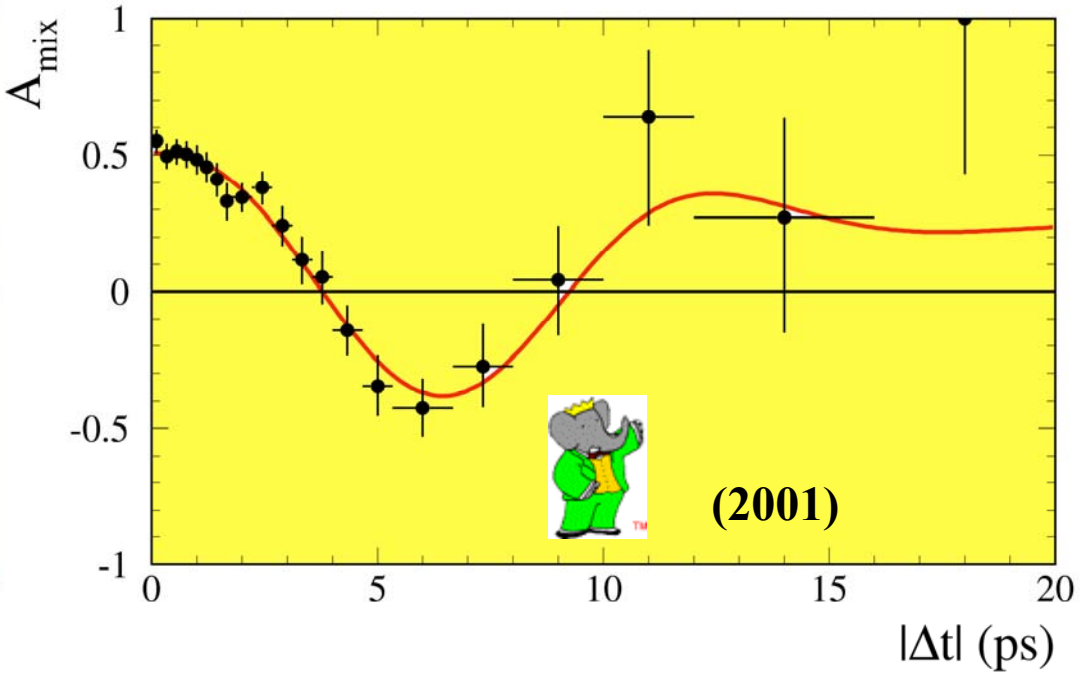
$$S \approx \sqrt{\frac{N}{2}} f (1-2w) e^{-\frac{1}{2}(\Delta m \sigma_t)^2}$$

Likelihood fit to:

$$\Gamma e^{-\Gamma t}\left(1 \pm (1-2w)\cos(\Delta m t)\right) \otimes res$$

w is mistag fraction; $(1-2w)=(1-2w_i)(1-2w_f)$





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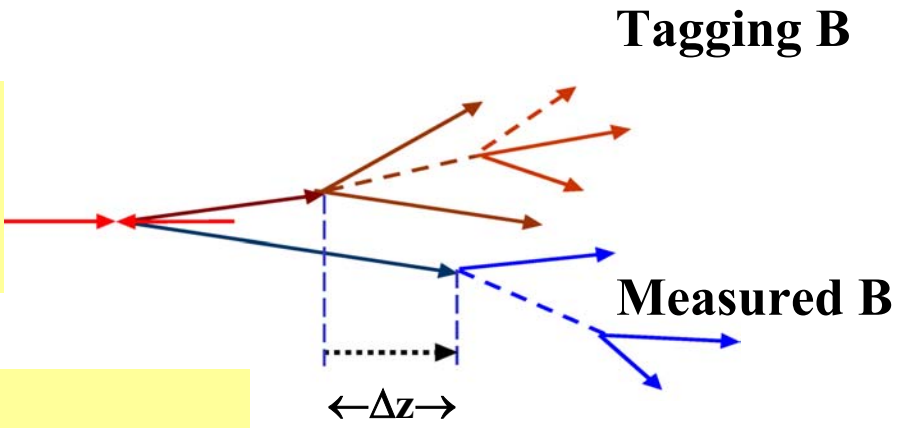
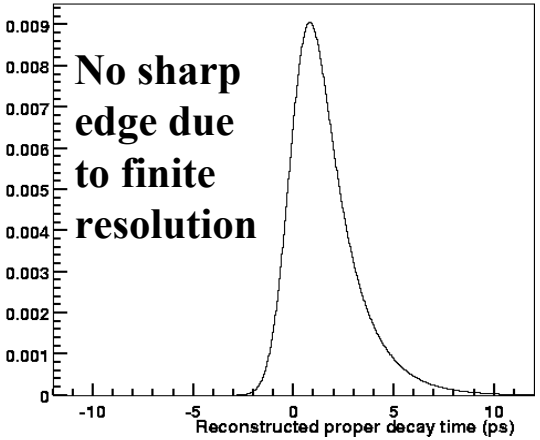
What's different about the Asymmetric B-factories

Coherent Production with boost: finding flavor of one B fixes the flavor of the second B at the same time

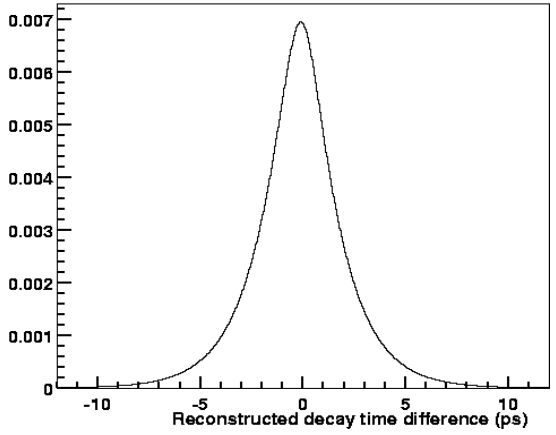


Either the tagging B or the reconstructed B can decay first, Δz (or Δt, proper time) can be < 0

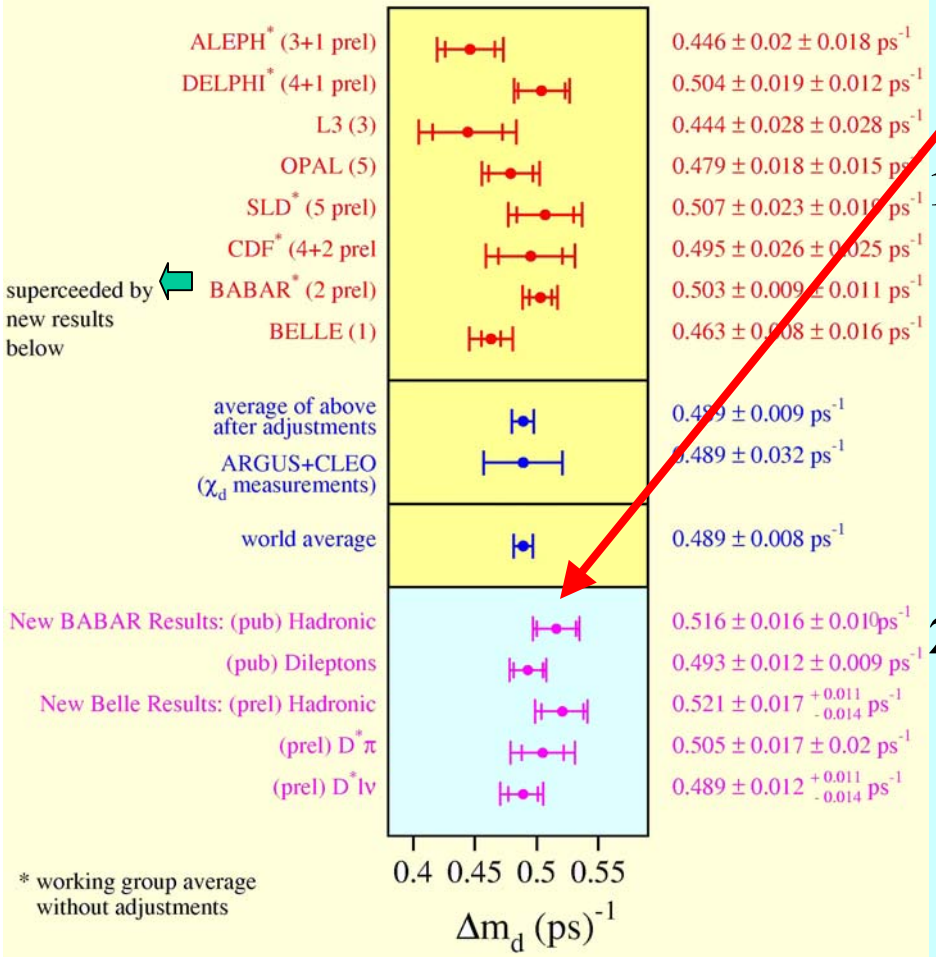


←LEP/SLD
←CDF

Belle/BaBar→ Present results vs. t or |t|



Update to July 2001 WG Summary



New Results:

1. **BABAR (submitted for publication):**
   Inclusive Dilepton Events (20.7 fb^{-1})
   Fully reconstructed hadronic events (29.7 fb^{-1})
   Both update preliminary results in WG summary

2. **BELLE (3 preliminary results) in Nov based on 29.1 fb^{-1}:**
   Fully reconstructed hadronic events
   Partial D*π reconstruction
   Partial D*lν reconstruction

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Asymmetric B-factories Analyses

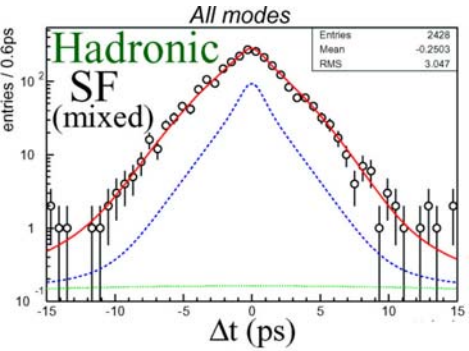
Full Reconstruction Analyses: Hadronic Decay Modes

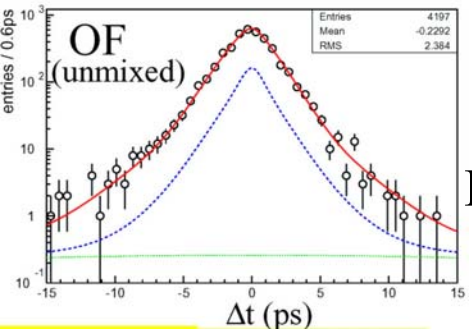
BELLE $D^{(*)-}\pi^+; D^{*-}\rho^+$

$D^{(*)-}\pi^+; D^{(*)-}\rho^+; D^{(*)-}a_1^+; J/\psi K^{*0}$

Simultaneous Maximum Likelihood Fit to mixed and unmixed events

$$\Gamma e^{-\Gamma\Delta t}\left(1\pm(1-2w)\cos(\Delta m\Delta t)\right)\otimes res$$



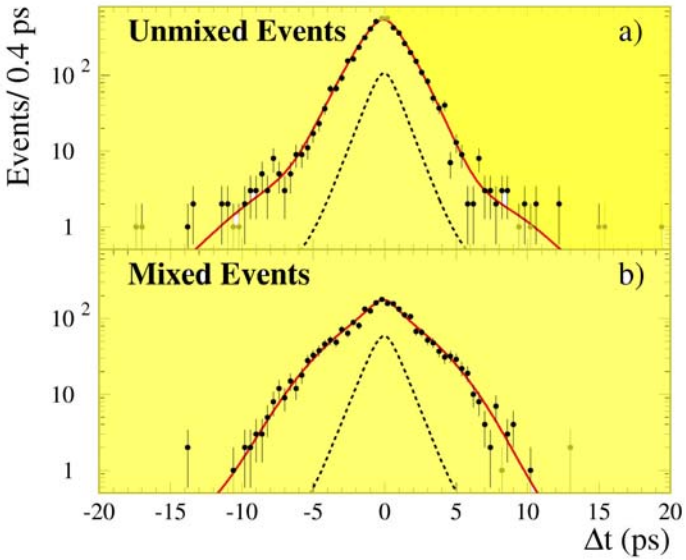


Output is Δm; *w* (mistag rates), and resolution parameters for signal and background (44 total for BABAR); τ_{Bd} fixed at PDG value (1.548 ps)

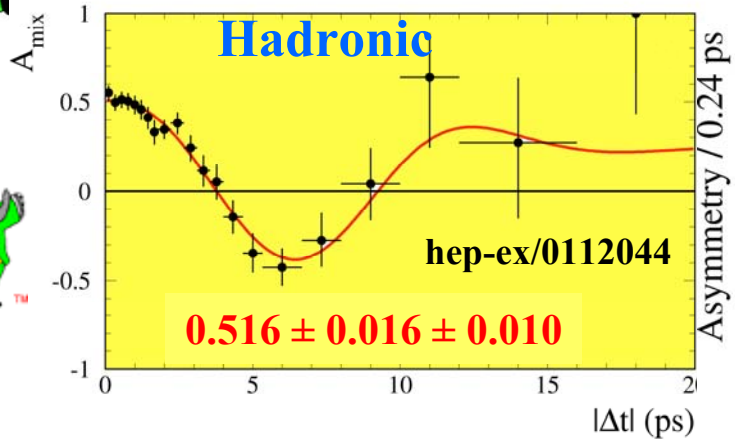
Other analyses: dilepton events

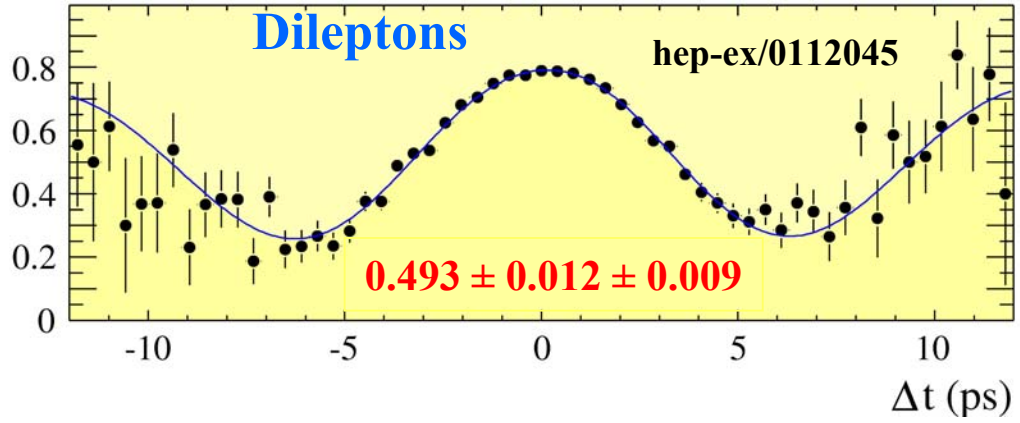
Belle: D*lν

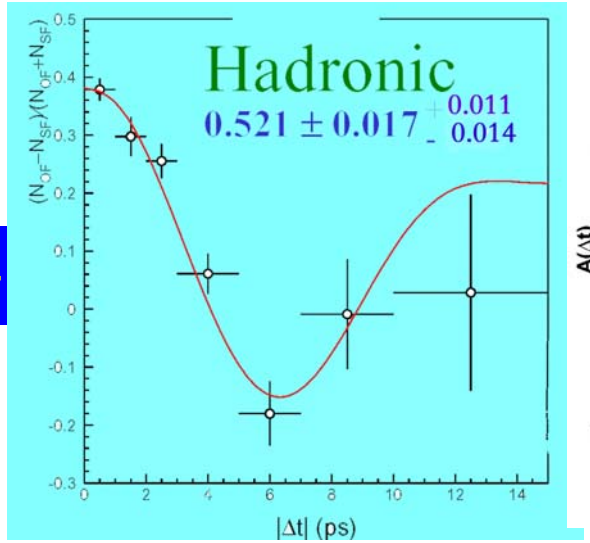
D*⁺π partial reconstruction (high and low p π's)

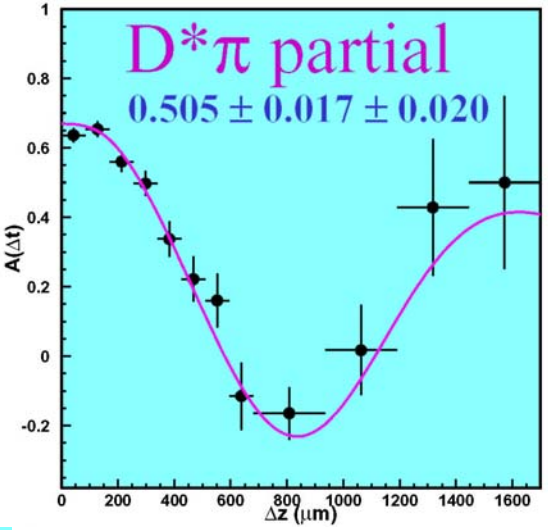


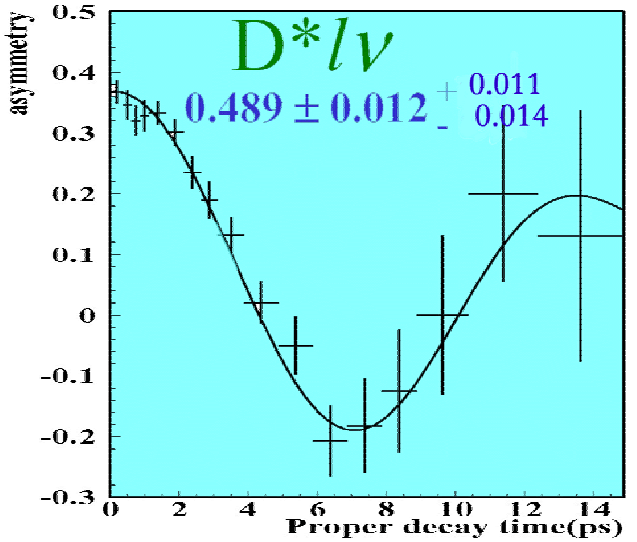
Δm_d New Results





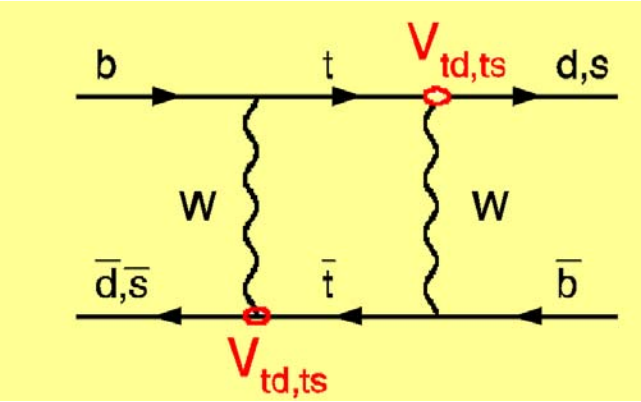


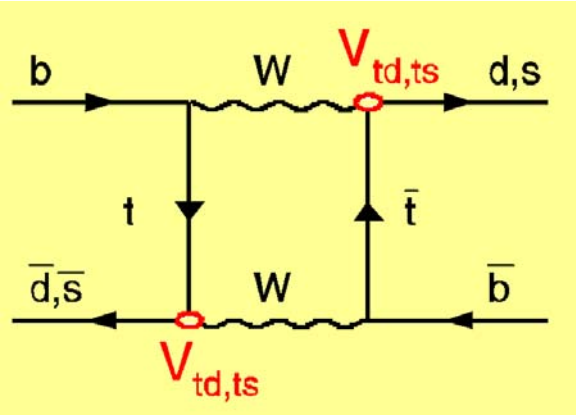




$B^0 \Leftrightarrow \overline{B^0}$ Mixing and the Standard Model

In the Standard Model, the transformation takes place via box diagrams and gives us information on V_{td} (B_d mesons) and V_{ts} (B_s mesons)





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

QCD correction

Decay constant

Bag parameter

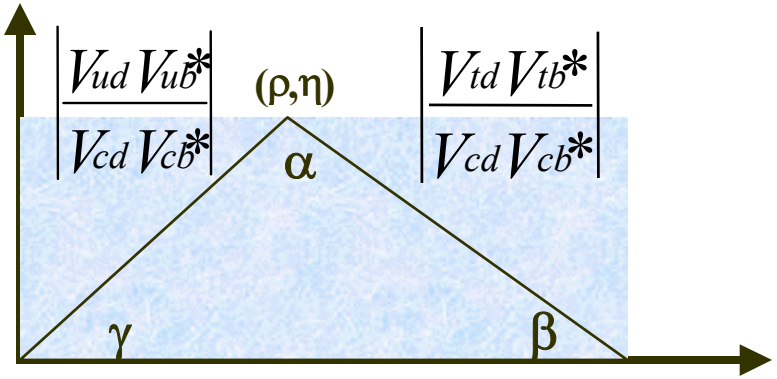
Standard Model and Mixing

$$\begin{pmatrix} u \\ d \end{pmatrix}\begin{pmatrix} c \\ s \end{pmatrix}\begin{pmatrix} t \\ b \end{pmatrix}$$

- The flavor eigenstates of the quarks are not the weak interaction eigenstates--there are transitions between the families.

- This mixing is described by the CKM Matrix. Where the three diagonal elements V_{ud}, V_{cs}, and $V_{tb} \approx 1$, family is almost a good quantum number.

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



- The CKM matrix is unitarity which can be expressed as:
  $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

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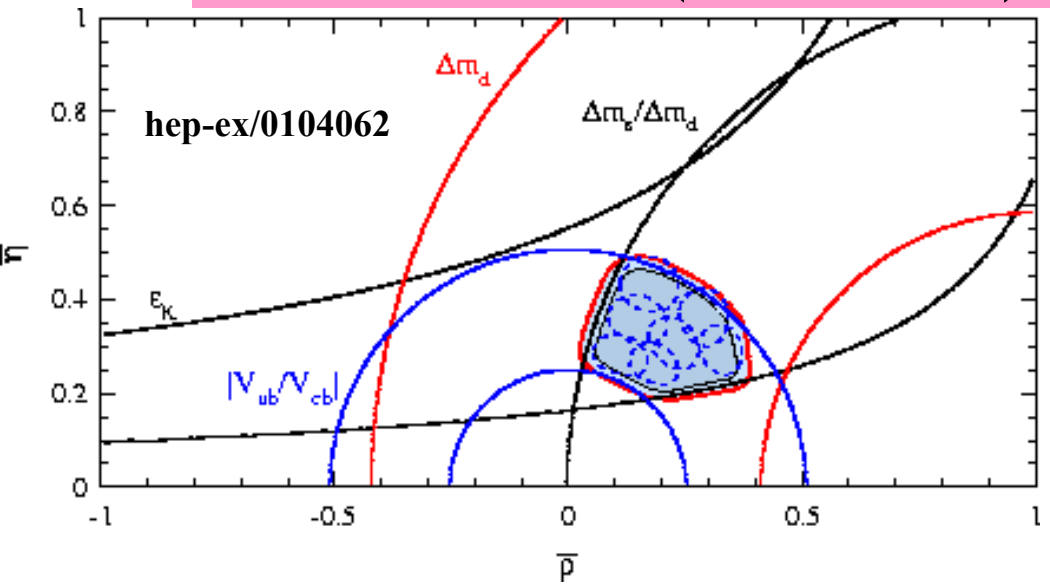
Constraining the Unitarity Triangle

- **Lattice QCD calculations: uncertainty in $B_{B_d} \otimes f_{B_d}$ ~20%**
  $\Rightarrow$ limits extraction of V_{td} from Δm_d
- **Ratio $\Delta m_s/\Delta m_d$ gives us a better limit**

$$\Delta m_d \propto |V_{td}|^2 = A^2\lambda^6\left((1-\rho)^2+\eta^2\right);\ \Delta m_s \propto |V_{ts}|^2 = A^2\lambda^4$$



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

Lattice QCD: "known" to ~ 5%

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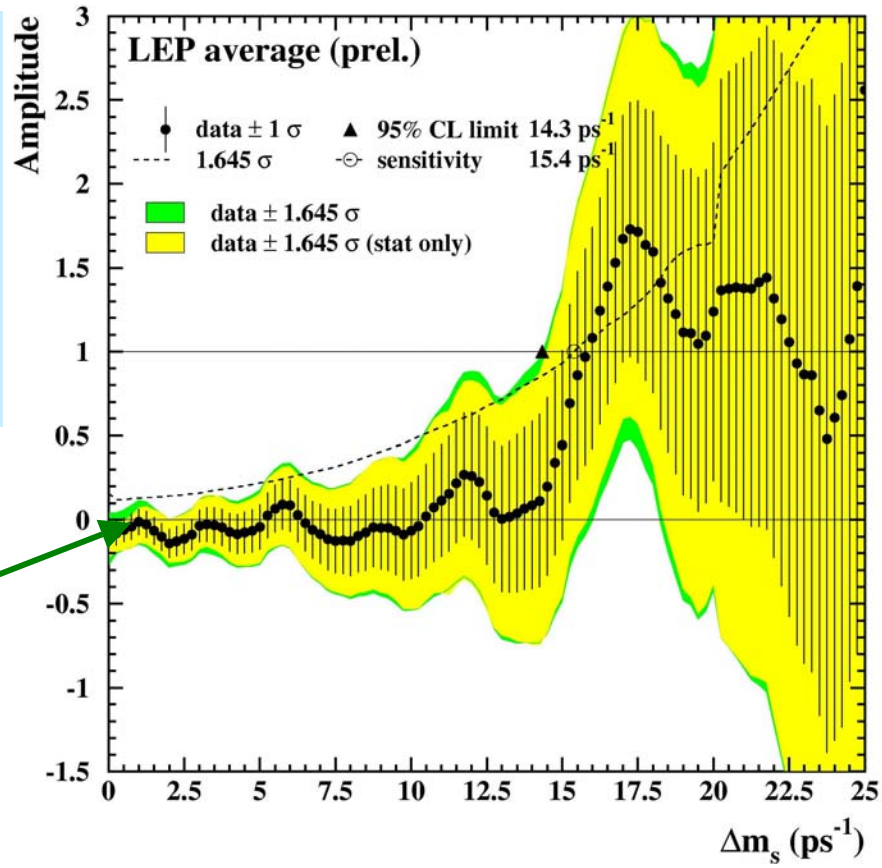
B^0_s Mixing

- **Oscillations not yet observed**
- **Express results as Amplitude $\mathcal{A}$ of oscillations as a function of Δm_s by a likelihood fit for fixed value of Δm_s to**

$$\overline{\Gamma} e^{-\overline{\Gamma} t}(1 \pm \mathcal{A} \cos \Delta m_s t)$$

Bands show 95% C.L. Limits

LEP/SLD and CDF provide data



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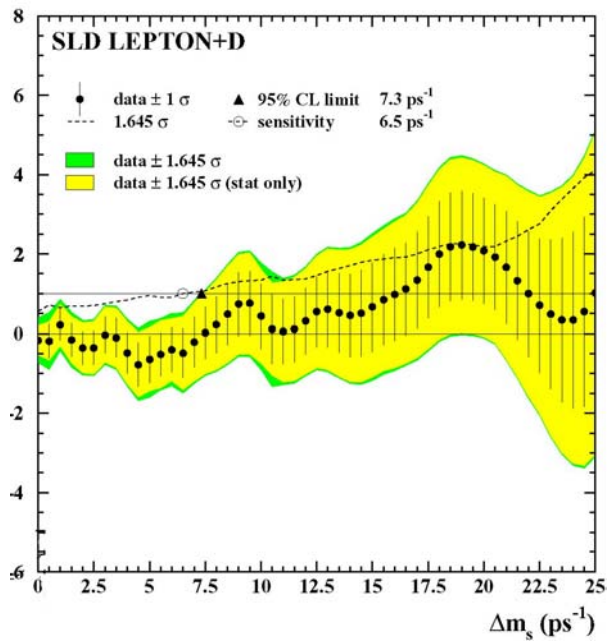
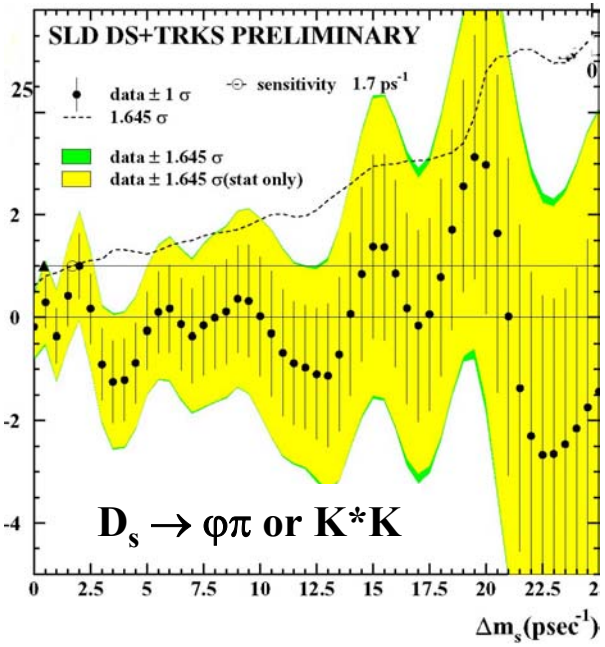
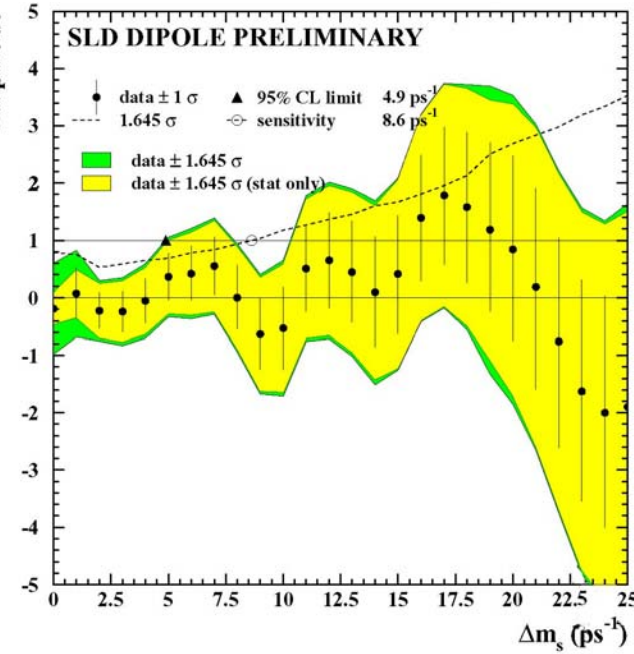
New Results from SLD

Same initial state tag: Pol. A_{FB} or NN multivariate using opposite side var.

Three different final state tags – hierarchical to remove overlaps:
Lepton + topological D $B_s \rightarrow D_s X$; D_s reconstructed Dipole Charge







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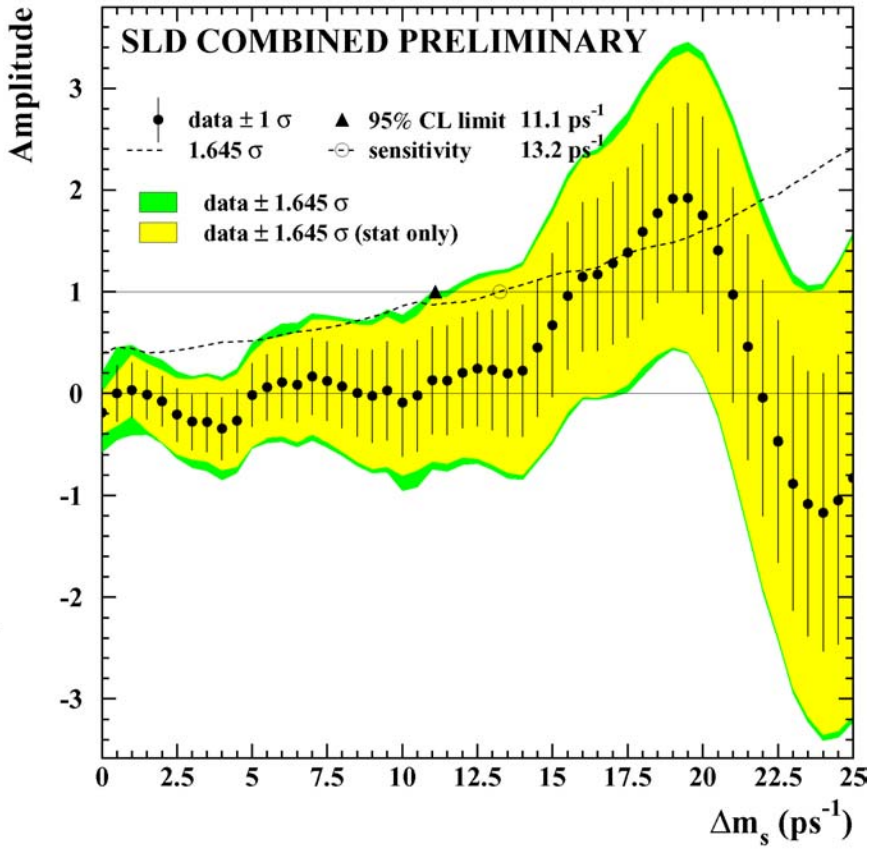
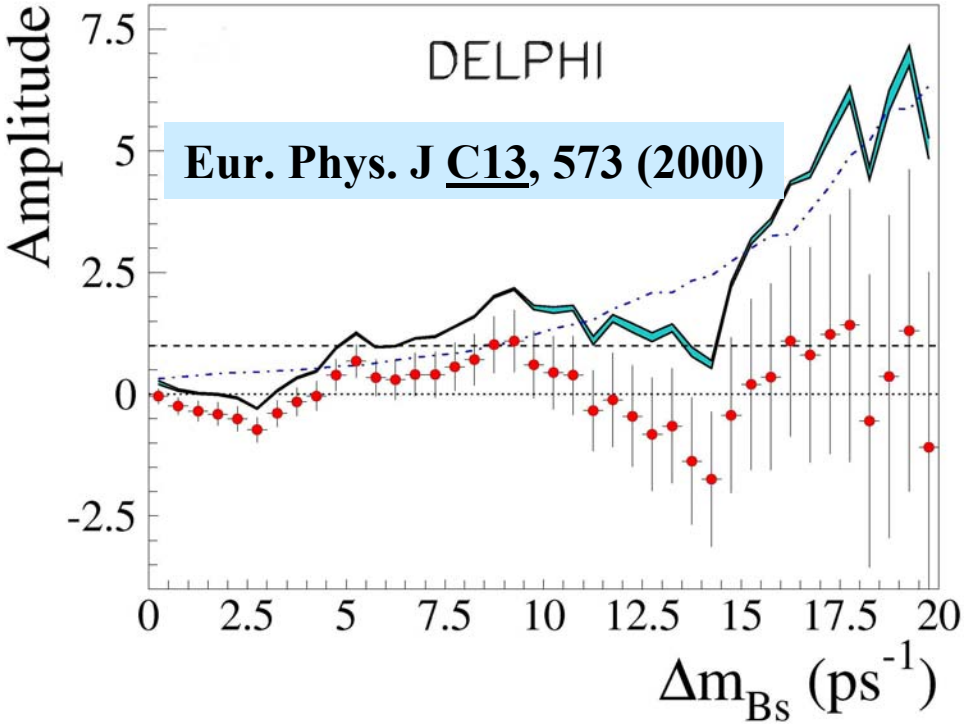
New Δm_s Limits

$$B_s^0 \to D_s^- \pi^+, D_s^- a_1^+, \overline{D^0} K^- \pi^+, \overline{D^0} K^- a_1^+$$

Complete D reconstruction
also exclusive D_s and high-p_T hadron

SLD





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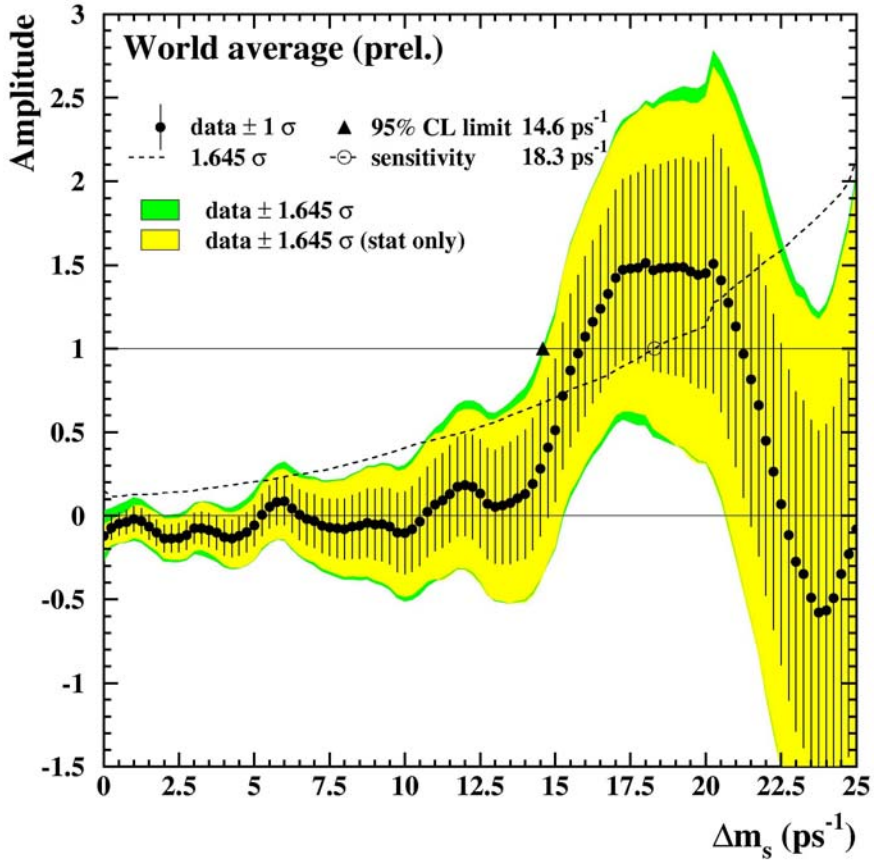
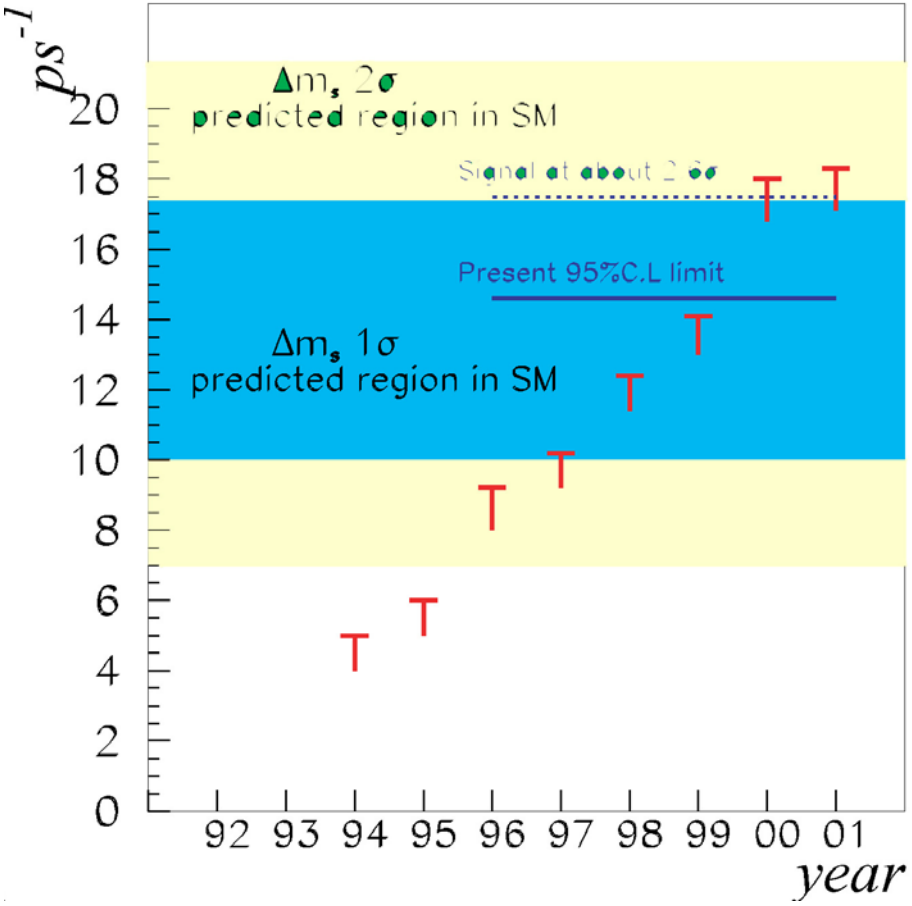
Current Status of B_s Mixing





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Lifetime Measurements

$$\left|\left\langle \overline{B^0}(t)\middle|B^0\right\rangle\right|^2 = \frac{e^{-\bar{\Gamma}t}}{2}\left(1-\cos(\Delta m\ t)\right)$$

$$\left|\left\langle B^0(t)\middle|B^0\right\rangle\right|^2 = \frac{e^{-\bar{\Gamma}t}}{2}\left(1+\cos(\Delta m\ t)\right)$$

- Tag event as B
- Measure B momentum
- Measure Decay length

Exclusive Event Tagging

$B \rightarrow D^* l\nu$ (X); reconstruct D*

$B \rightarrow DX$

$B \rightarrow J/\psi K$

Inclusive

Topology:

Displaced vertex; event shape

Full reconstruction (new)

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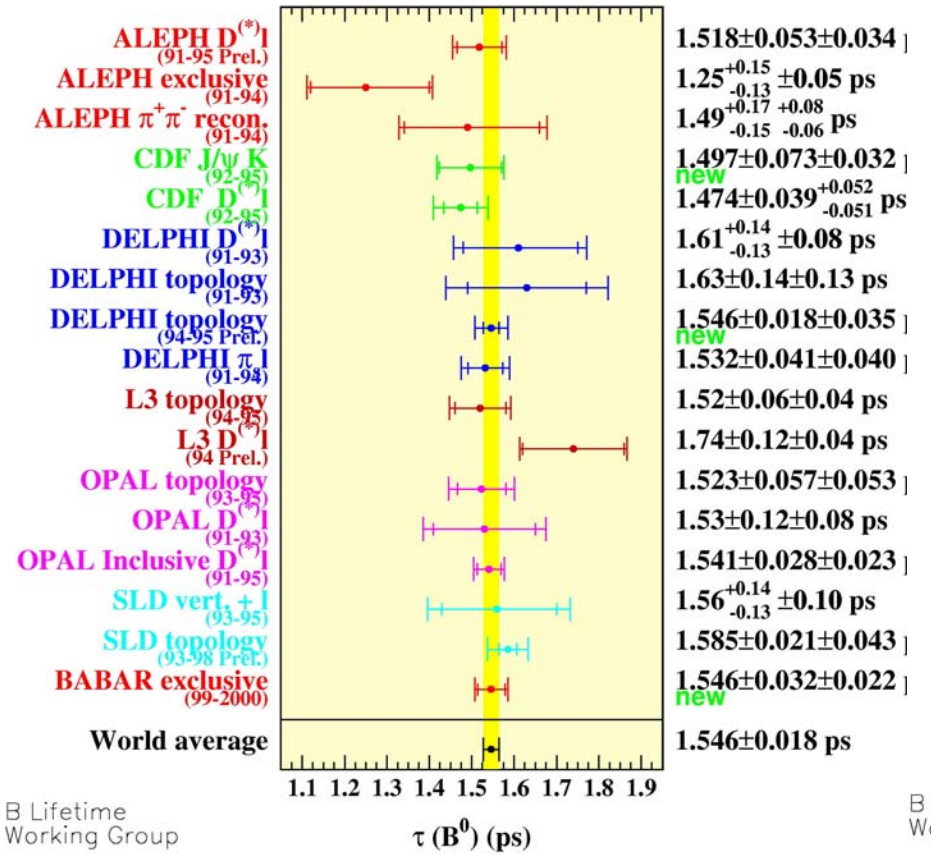
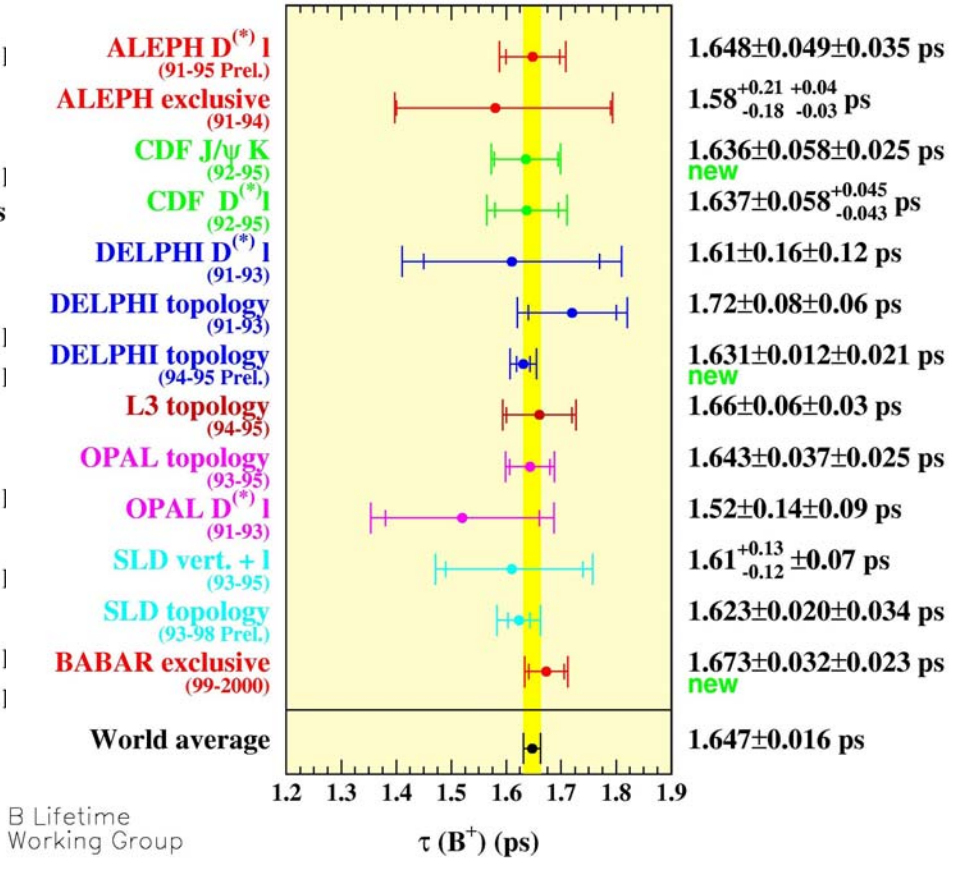
Working Group Summary





Belle (new) 1.554 ± 0.030 ± 0.019 ps

Belle (new) 1.695± 0.026 ± 0.015 ps

PRL 87 201803 (2001)

New Results on Lifetime

110 pb^{-1} J/ψK

2.1 M Z→hadrons topology tag

Fully reconstructed hadrons

20.0 fb^{-1}

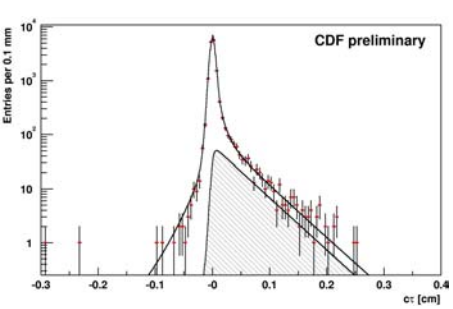
29.1 fb^{-1}

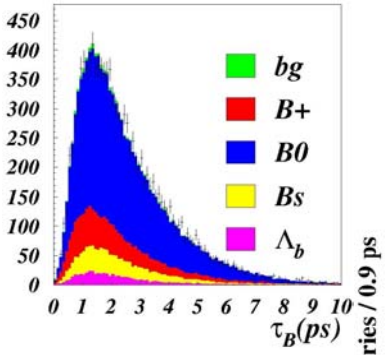
1.497 ± 0.073± 0.033 ps

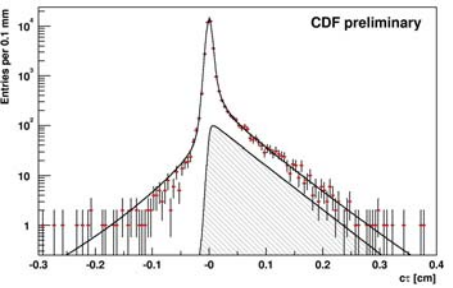
1.546 ± 0.018 ± 0.035 ps

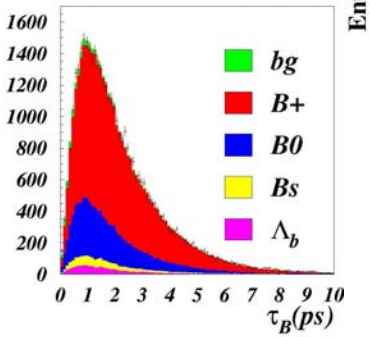
1.546 ± 0.032 ± 0.022 ps

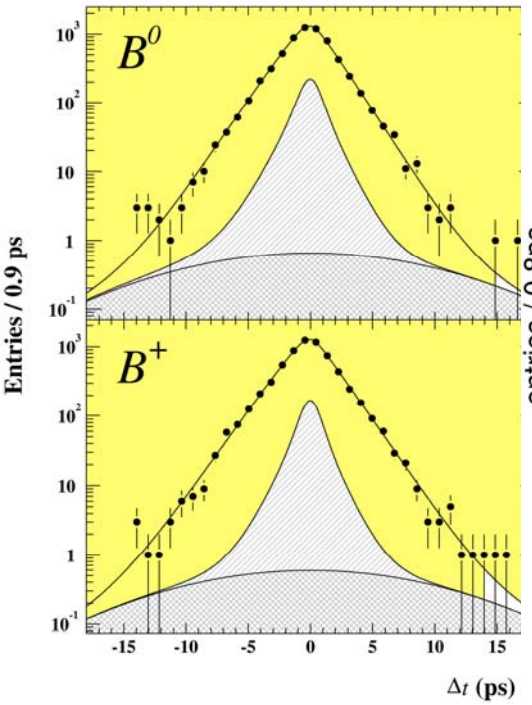
1.554 ± 0.030 ± 0.019 ps

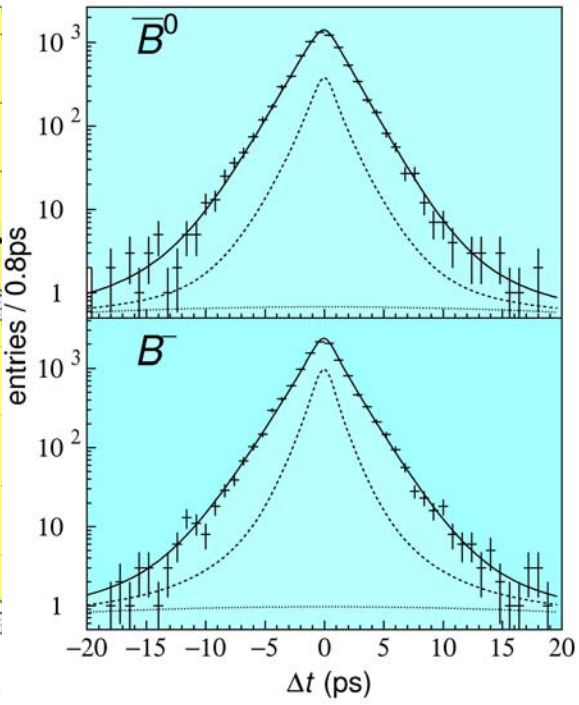












1.636± 0.058 ± 0.025 ps

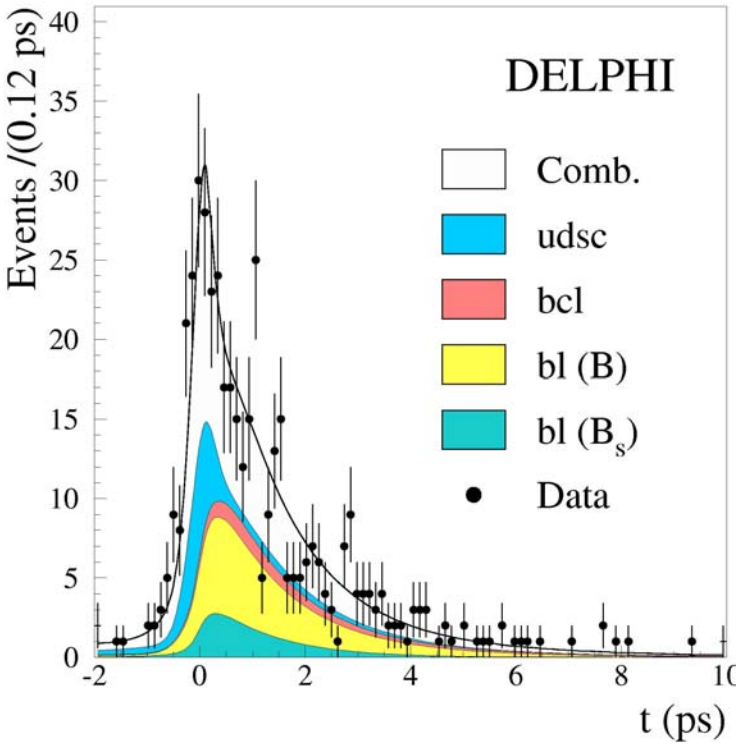
1.631 ± 0.012 ± 0.021 ps

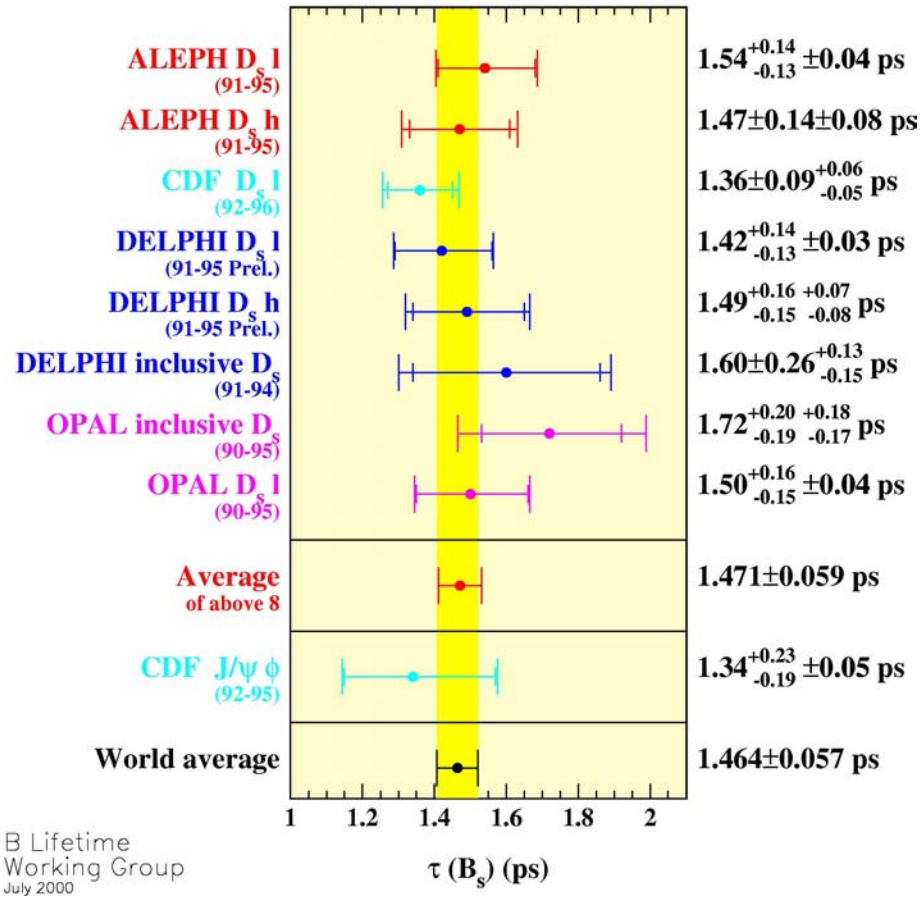
1.673 ± 0.032 ± 0.023 ps

1.695 ± 0.026± 0.015ps

B_s Lifetime

DELPHI: $D_s l \rightarrow \phi l h$





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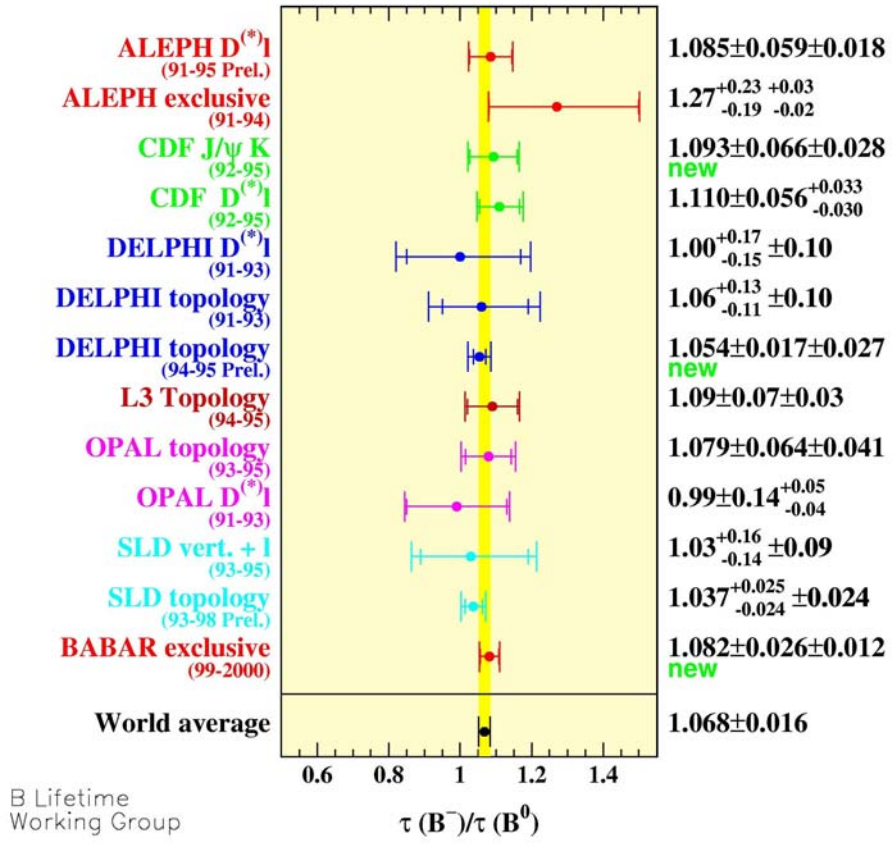
Lifetime Ratios

baryon/ meson

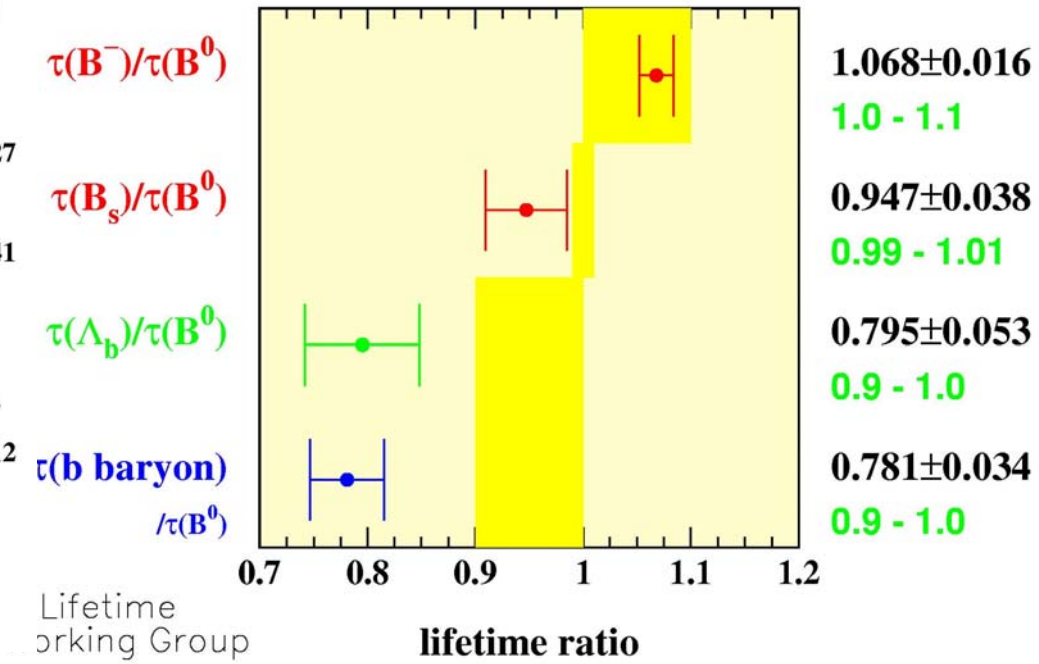
meson/meson

Spectator process

$$\Gamma \approx \frac{G_F^2 m^5}{129\pi^3}\left(A_1 + \frac{A_2}{m^2} + \frac{A_3}{m^3} + O\left(\frac{1}{m^4}\right)\right)$$



Belle (new) 1.091±0.023±0.014



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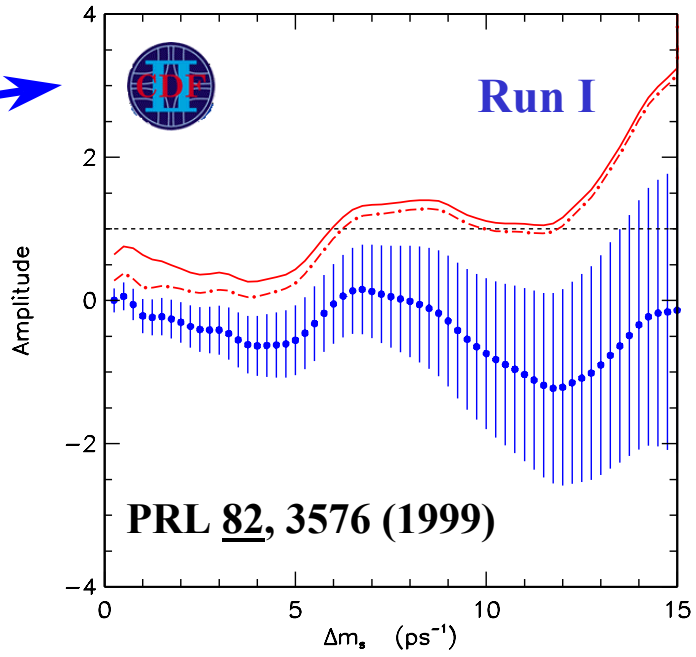
What lies ahead?

- **BABAR and Belle:**

  30 fb^{-1} → 300 fb^{-1} 2004
  - **Go beyond Δm: ΔΓ**
  - **CP effects: ε (|q/p|)**

$$|B_{\pm}\rangle = p|B^0\rangle \mp q|\overline{B^0}\rangle$$

- **CDF/D0 100 pb^{-1} → 2 fb^{-1} 2004**
  - **probe B_s mixing to $x_s \approx 30$ with semileptonic decays** ($x_s = \Delta m_s/\Gamma_s$)
  - **probe B_s mixing to $x_s \approx 60$ in hadronic mode**
  - **Precision lifetime ratios (B_s/B^0)**



CDF Expectations

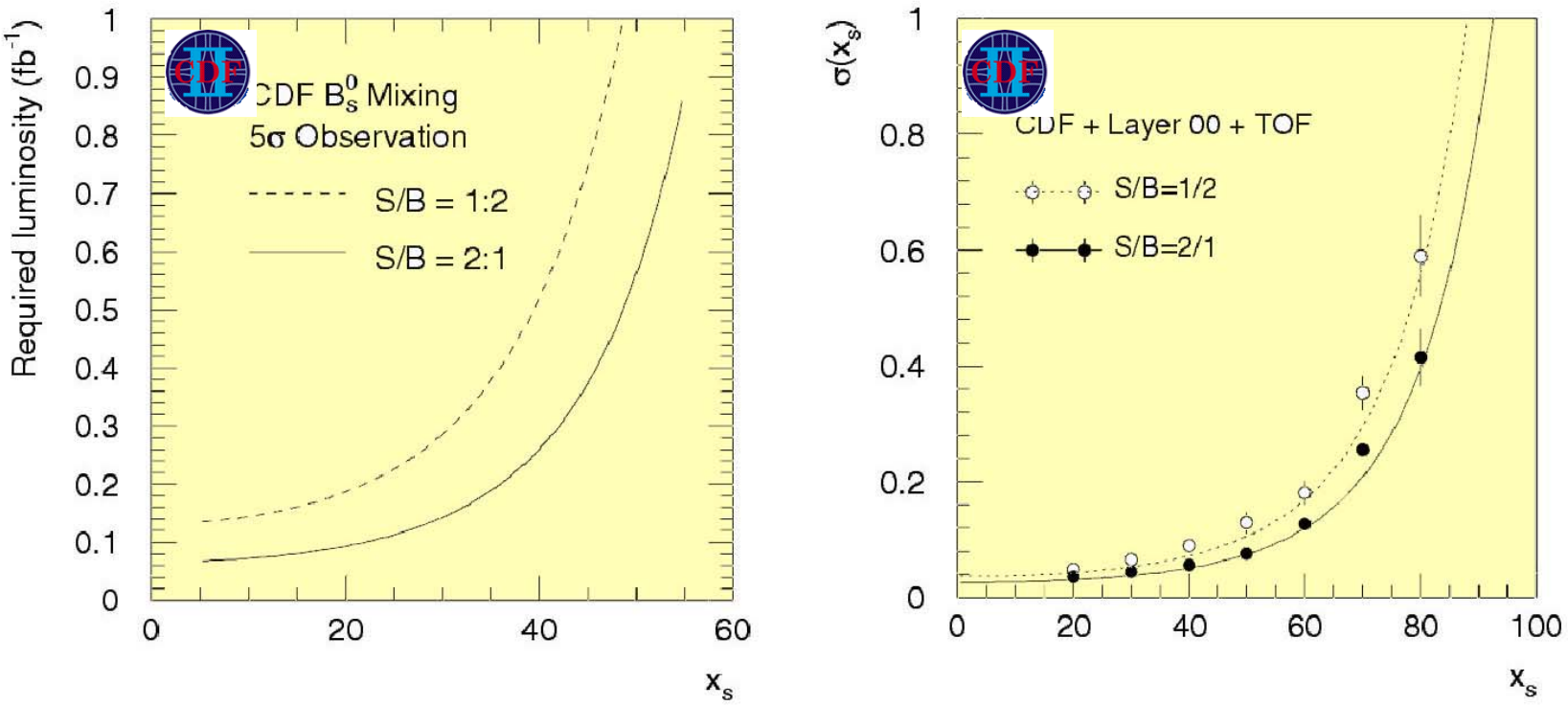


Figure 1: *Left: Required luminosity to measure at 5σ x_s as function of x_s. Right: Error on x_s as function of x_s.*

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And much later ……

LHC start in 2006?

	ATLAS	CMS	LHCb
Channels used:			
B_s^0 decay channels	$D_s^-\pi^+$ $D_s^-a_1^+$	$D_s^-\pi^+$	$D_s^-\pi^+$
D_s^- decay channels	$\phi\pi^-$	$\phi\pi^-$ $K^{*0}K^-$	$\phi\pi^-$ (see text)
ϕ decay channel	K^+K^-	K^+K^-	K^+K^-
a_1^+ decay channel	$\rho^0\pi^+$		
K^{*0} decay channel		$K^+\pi^-$	
Assumptions:			
$B(\bar{b} \to B_s^0)$	0.105	0.105	0.12
$B(B_s^0 \to D_s^-\pi^+)$	3.0×10^{-3}	3.0×10^{-3}	3.0×10^{-3}
$B(B_s^0 \to D_s^-a_1^+)$	6.0×10^{-3}	–	–
$B(D_s^- \to \phi\pi^-)$	0.036	0.036	
$B(D_s^- \to K^{*0}K^-)$	–	0.033	–
$B(D_s^- \to K^+K^-\pi^-)$	–	–	0.04
B_s^0 lifetime	1.54 ps	1.61 ps	1.57 ps
Analysis performance:			
Reconstructed signal events per year	3457	4500	86000
Rec. and tagged signal events per year	3457	4500	34500
B_s^0 purity of tagged sample	0.38	0.5	0.95
Wrong tag probability	0.22	0.22	0.30
Proper time resolution(Gaussian function(s))	50 fs (60.5%) 93 fs (39.5%)	65 fs	43 fs
ΔM_s reach after one year of running:			
Measurable values of ΔM_s up to	$30\,\text{ps}^{-1}$	$26\,\text{ps}^{-1}$	$48\,\text{ps}^{-1}$
95% CL excl. of ΔM_s values up to	–	$29\,\text{ps}^{-1}$	$58\,\text{ps}^{-1}$
$\sigma(\Delta m_s)$ for $\Delta m_s = 20\,\text{ps}^{-1}$	0.11	–	0.011
x_s reach after one year of running:			
Measurable values of x_s up to	46	42	75
95% CL excl. of x_s values up to	–	47	91

Table 22: Summary of the analyses and results for B_s^0 oscillation frequency measurements by the LHC experiments

start in 2008???