B physics from LEP and SLD
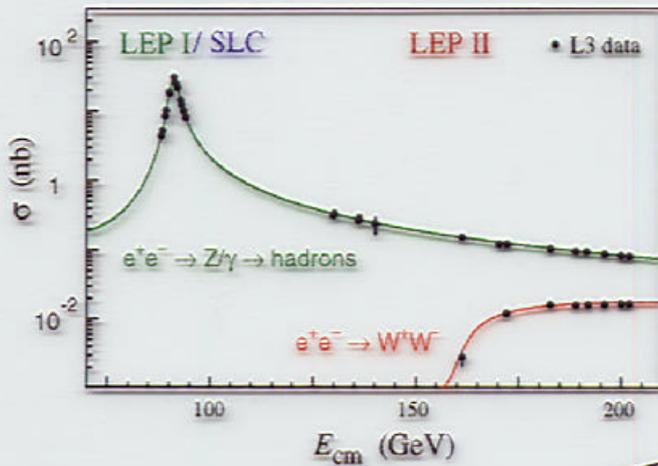
Roger Forty, CERN

The era of the B factories is just beginning,
taking over from the Z factories

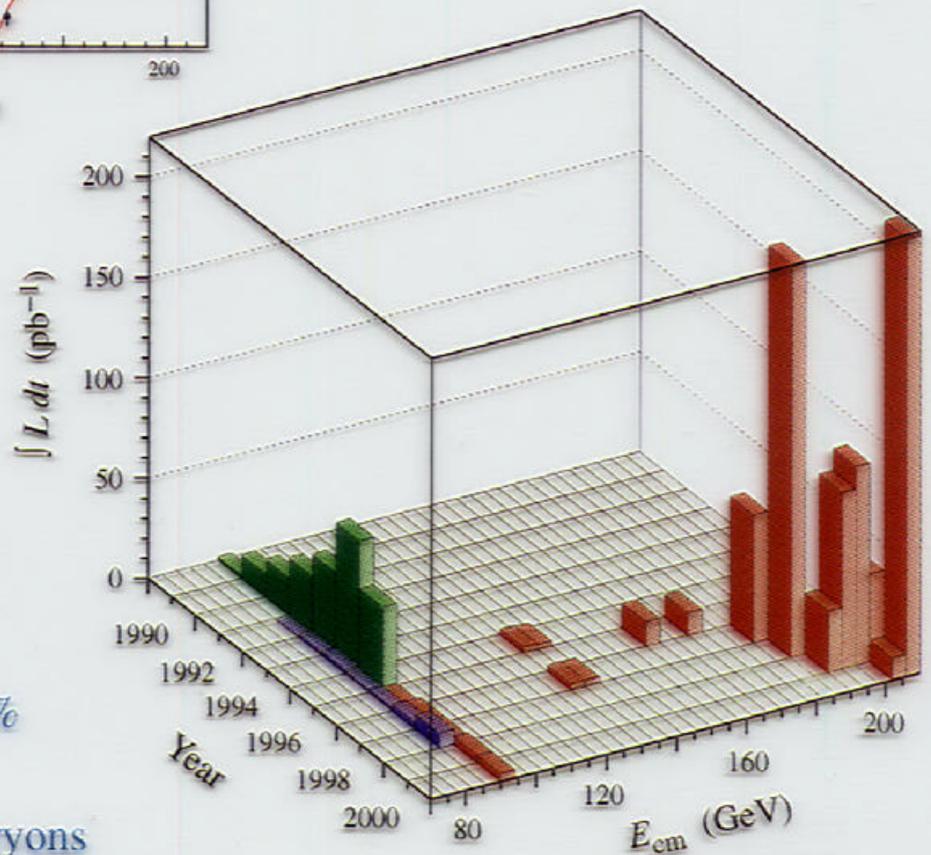I will concentrate on B decay properties
rather than production/electroweak

1. Lifetimes
2. Semileptonic BR
3. V_{cb} and V_{ub}
4. Oscillations
5. CKM constraints

Dataset

LEP II

~ 10^4 W⁺W⁻ events / experiment

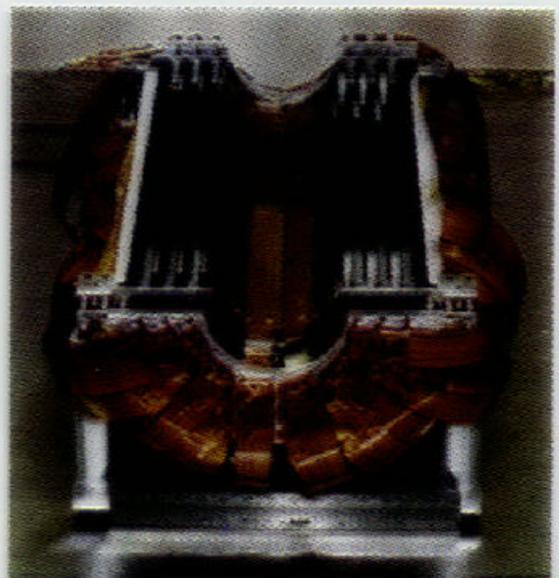but few B's

finally switched off end-2000

LEP I

~ 5×10^6 Z → *hadron*

events / experiment

× 4 experiments

× $R_b = (21.64 \pm 0.08)\%$

⇒ ~ 10^7 b-hadrons

~ 10% B_s, 10% b-baryons

SLD

~ 0.5×10^6 Z → *hadron* events

Rely on unique features to be

competitive:

1. Polarized e⁻ beam

2. Precise beam spot ~ (2×1) μm

3. Beautiful vertex detector
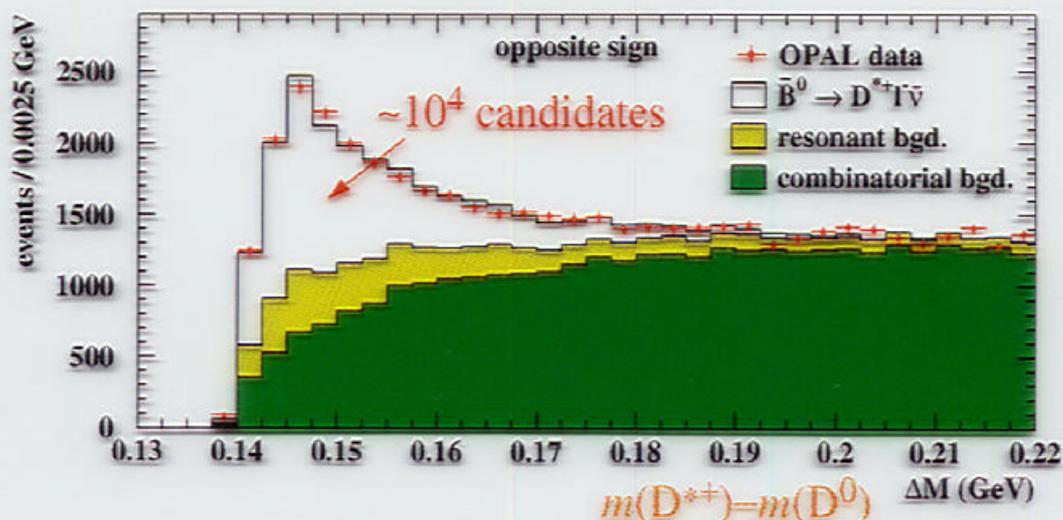 3×10^8 pixels, (20×20) μm

1. Lifetimes

Inclusive, topological vertexing techniques give most precise $\tau(B^+)$
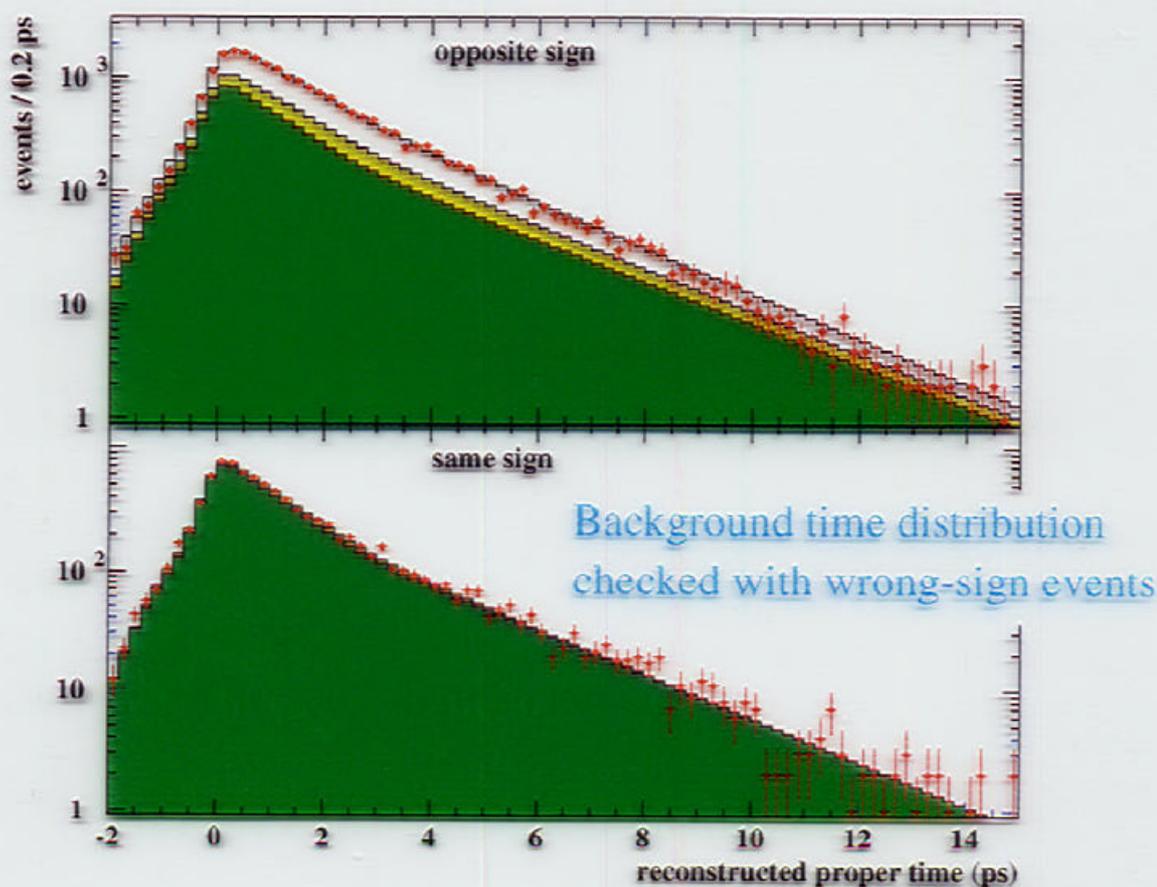
Limited for B^0 by contamination from the other neutrals: B_s, Λ_b
$\rightarrow$ select B^0 decays using partial reconstruction of $\overline{B}^0 \rightarrow D^{*+} l^- \bar{\nu}$
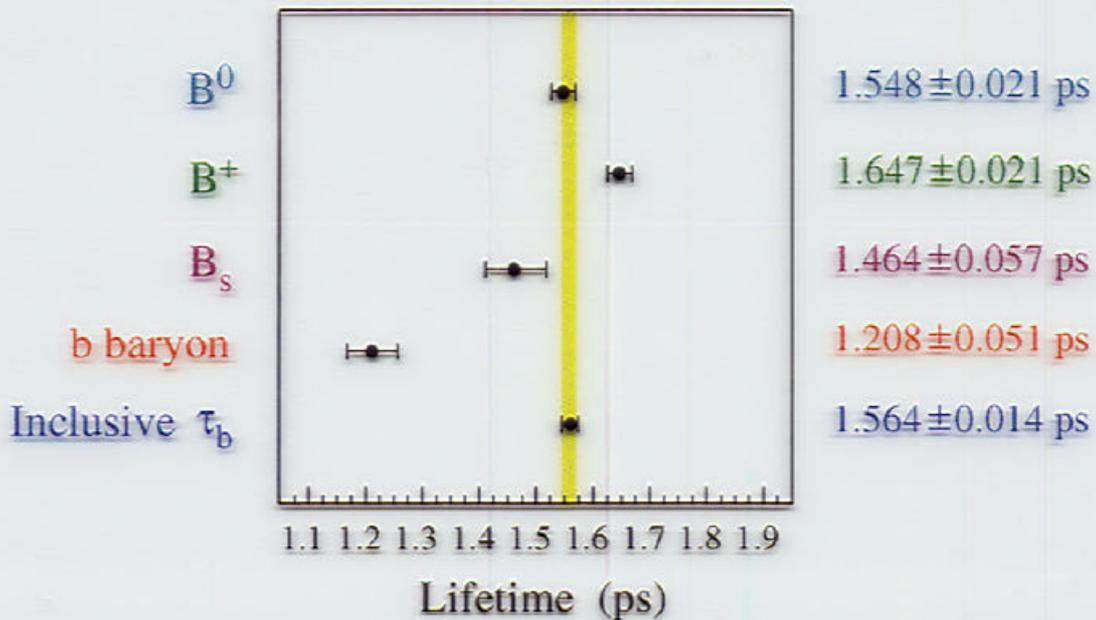
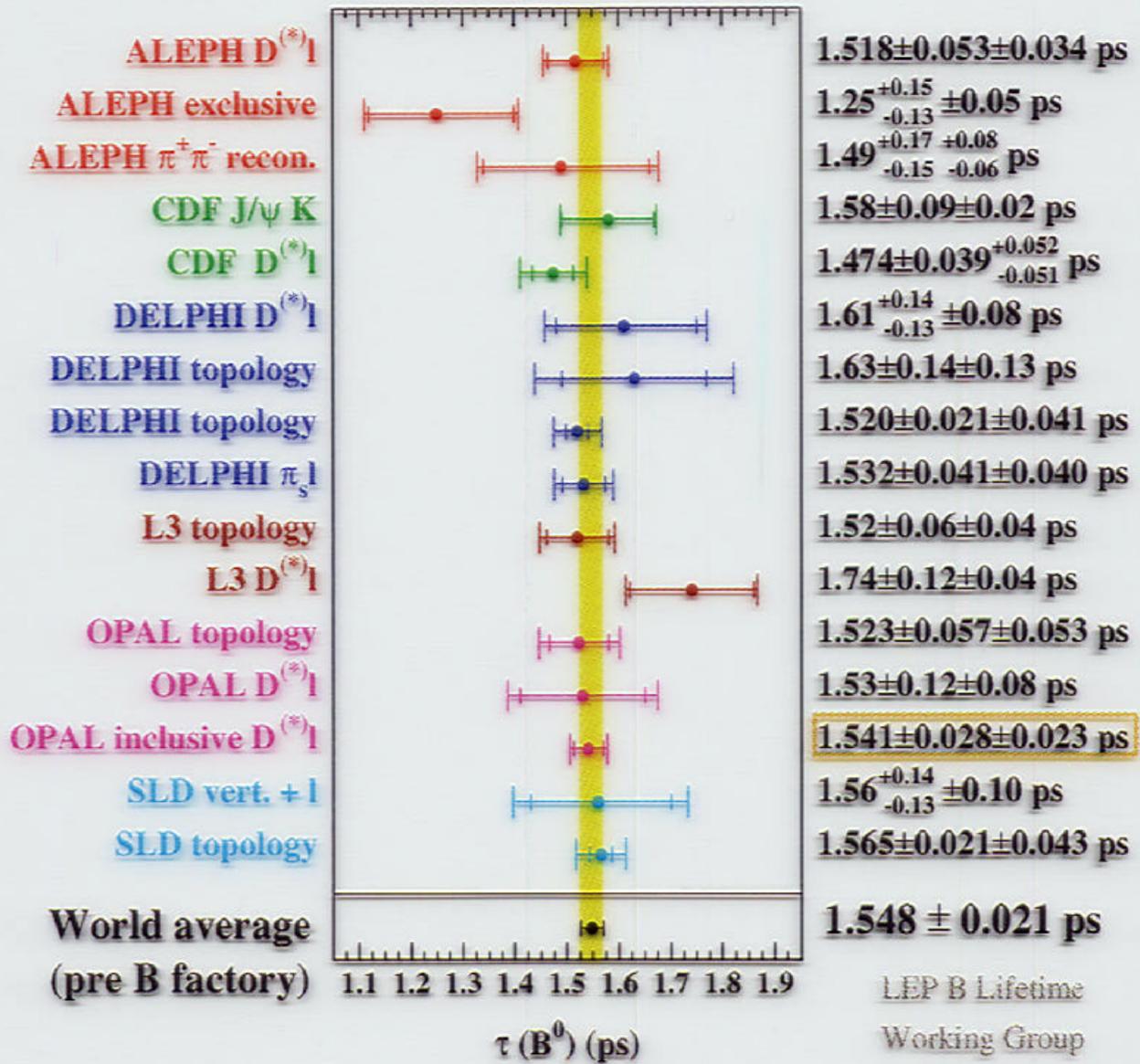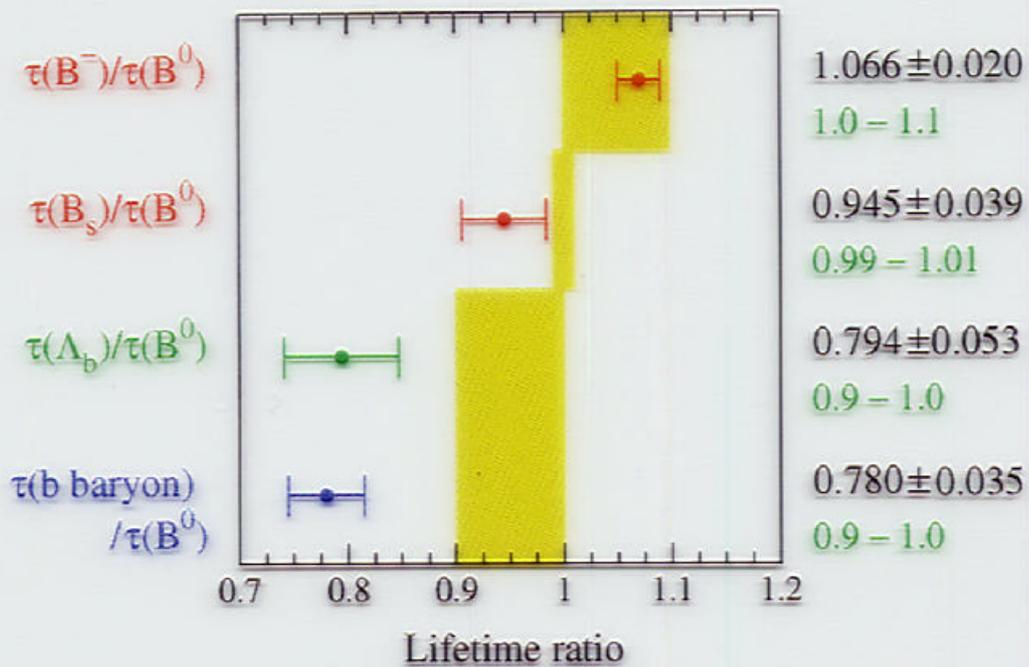New OPAL analysis [CERN–EP–2000–090]
$\hookrightarrow D^0 \pi^+$

Decay length measured by vertexing lepton and slow π^+

Background time distribution checked with wrong-sign events

Summary of results for the B^0 lifetime:

ALEPH $D^{(*)}l$	$1.518 \pm 0.053 \pm 0.034$ ps
ALEPH exclusive	$1.25^{+0.15}_{-0.13} \pm 0.05$ ps
ALEPH $\pi^+\pi^-$ recon.	$1.49^{+0.17}_{-0.15}{}^{+0.08}_{-0.06}$ ps
CDF $J/\psi\,K$	$1.58 \pm 0.09 \pm 0.02$ ps
CDF $D^{(*)}l$	$1.474 \pm 0.039^{+0.052}_{-0.051}$ ps
DELPHI $D^{(*)}l$	$1.61^{+0.14}_{-0.13} \pm 0.08$ ps
DELPHI topology	$1.63 \pm 0.14 \pm 0.13$ ps
DELPHI topology	$1.520 \pm 0.021 \pm 0.041$ ps
DELPHI $\pi_s l$	$1.532 \pm 0.041 \pm 0.040$ ps
L3 topology	$1.52 \pm 0.06 \pm 0.04$ ps
L3 $D^{(*)}l$	$1.74 \pm 0.12 \pm 0.04$ ps
OPAL topology	$1.523 \pm 0.057 \pm 0.053$ ps
OPAL $D^{(*)}l$	$1.53 \pm 0.12 \pm 0.08$ ps
OPAL inclusive $D^{(*)}l$	$1.541 \pm 0.028 \pm 0.023$ ps
SLD vert. $+ l$	$1.56^{+0.14}_{-0.13} \pm 0.10$ ps
SLD topology	$1.565 \pm 0.021 \pm 0.043$ ps
World average	1.548 ± 0.021 ps
(pre B factory)	

LEP B Lifetime
Working Group

$\tau\,(B^0)$ (ps)

1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9

B^0	1.548 ± 0.021 ps
B^+	1.647 ± 0.021 ps
B_s	1.464 ± 0.057 ps
b baryon	1.208 ± 0.051 ps
Inclusive τ_b	1.564 ± 0.014 ps

1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9

Lifetime (ps)

Comparison of measured lifetime ratios with predictions [Bigi]:

$\tau(B^-)/\tau(B^0)$ 1.066 ± 0.020 $1.0 - 1.1$

$\tau(B_s)/\tau(B^0)$ 0.945 ± 0.039 $0.99 - 1.01$

$\tau(\Lambda_b)/\tau(B^0)$ 0.794 ± 0.053 $0.9 - 1.0$

$\tau(b \text{ baryon})/\tau(B^0)$ 0.780 ± 0.035 $0.9 - 1.0$

Lifetime ratio

Predicted hierarchy confirmed, but long-standing discrepancy for Λ_b

However, may be resolved by theory: range of predictions for
reasonable choices of unknown hadronic matrix elements [Neubert]
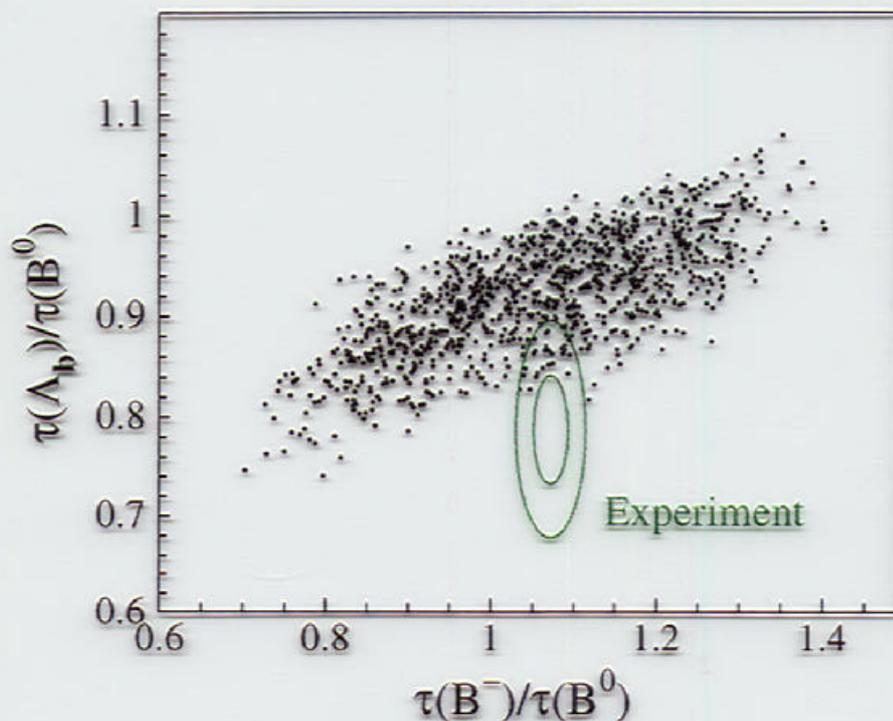
Recent analysis based on QCD sum-rules [Huang, Liu, Zhu]:

$$\tau(\Lambda_b)/\tau(B^0) = 0.83 \pm 0.04$$

2. Semileptonic BR

Two long-standing problems:
1. Discrepancy between measurements at LEP and $\Upsilon(4S)$
2. Predicted value somewhat higher than measured
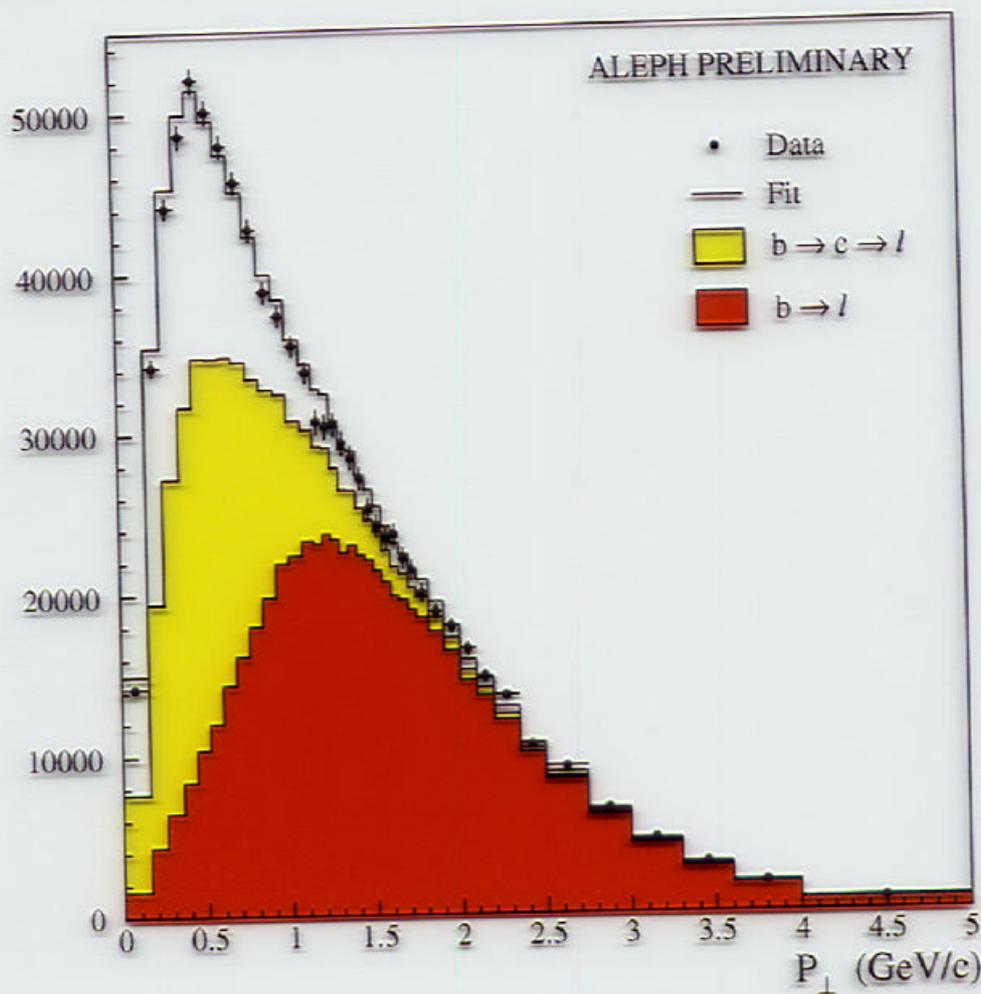
From the same review of Neubert [ICHEP 1997]:
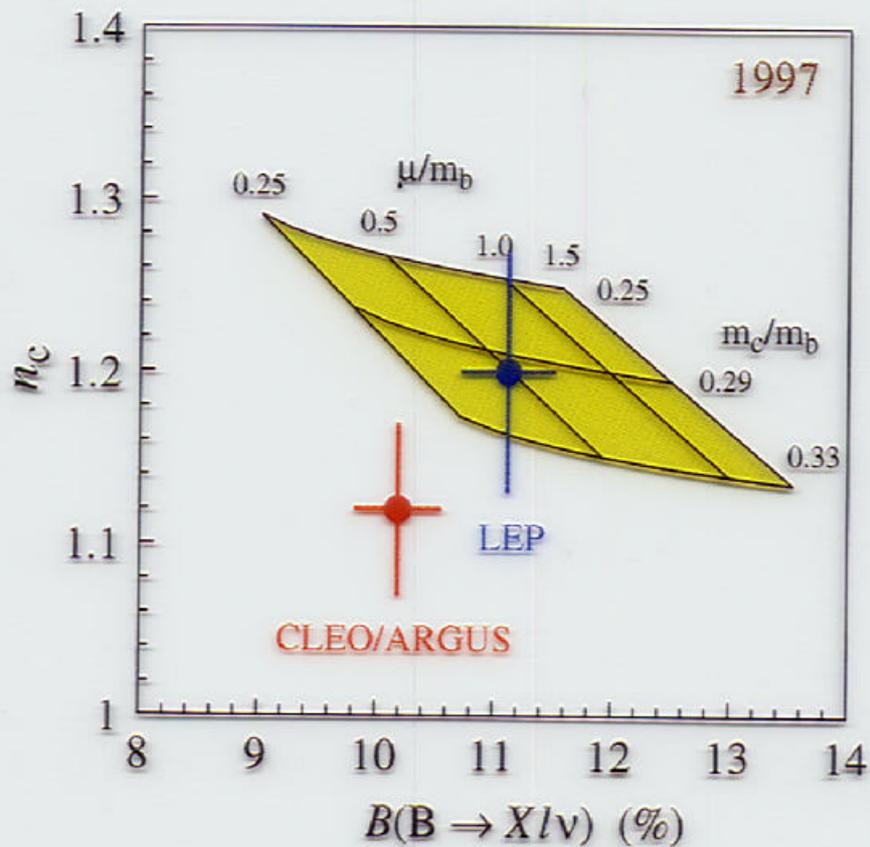
$$B(B \to Xl\nu) \ (\%)$$

Prediction for $B(B \to Xl\nu)$ is correlated to n_c
  the number of c or $\bar{c}$ quarks produced per b decay:

Increasing $B(b \to c\bar{c}s)$ $\begin{cases} \text{increases } n_c \\ \text{decreases } B(B \to Xl\nu) \end{cases}$

In this case, experiment has resolved the discrepancies

New ALEPH measurement of $B(b \to Xl\nu)$ from lepton p_T spectrum:

Uses latest fragmentation function $x_E = E_{\text{b-hadron}}/E_{\text{beam}}$

from $B \to D^*l\nu$ [ALEPH 2000–068] $\langle x_E \rangle = 0.730 \pm 0.008$

consistent with SLD result [SLAC–PUB–8316] 0.714 ± 0.009

but harder than traditional LEP value 0.702 ± 0.008

Second approach: use charge correlation between lepton and opposite hemisphere, reduces model-dependence

Final result: $B(b \to Xl\nu) = (10.55 \pm 0.09 \pm 0.32)\%$ [ALEPH 2000–069]

Latest LEP average: $(10.56 \pm 0.11 \pm 0.18)\%$ [Golutvin, ICHEP]

$B(B \to Xl\nu) = B(b \to Xl\nu) \times \tau(B)/\tau(b) = (10.79 \pm 0.25)\%$

in good agreement with value from $\Upsilon(4S)$ $(10.45 \pm 0.21)\%$

New SLD measurement of n_c from topological vertexing:
Fit number of reconstructed vertices and vertex separation distances
with Monte Carlo functions for decays with 0, 1 and 2 charm vertices
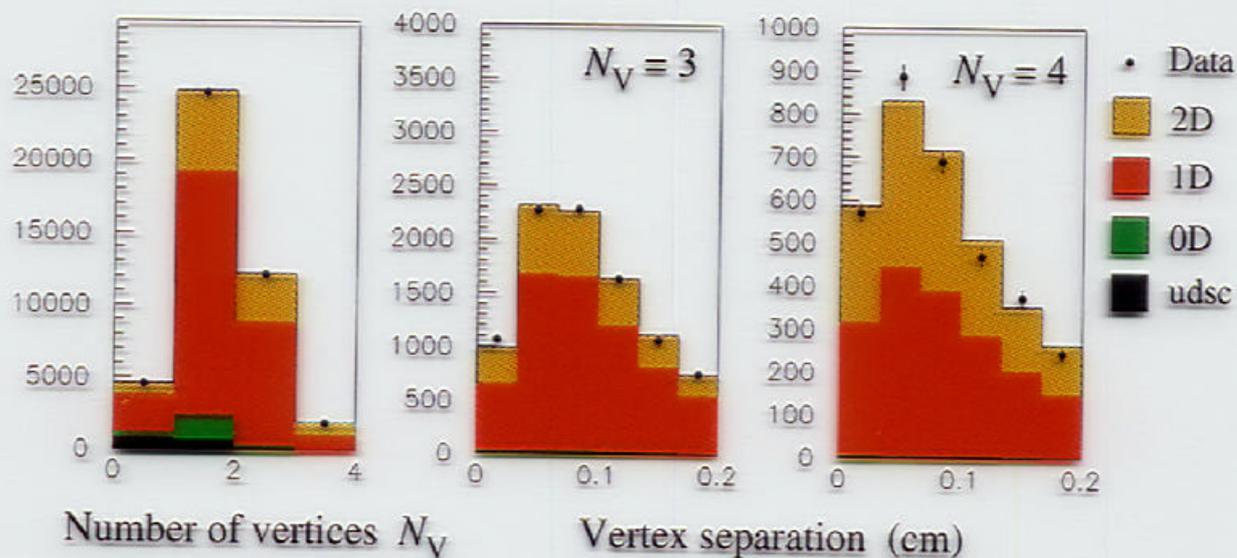
$$n_c = 1 - B_{0D} + B_{2D} + 2 \times B_\psi$$

Correcting for charmonium $B_\psi = (2.4 \pm 0.3)\%$
they extract:
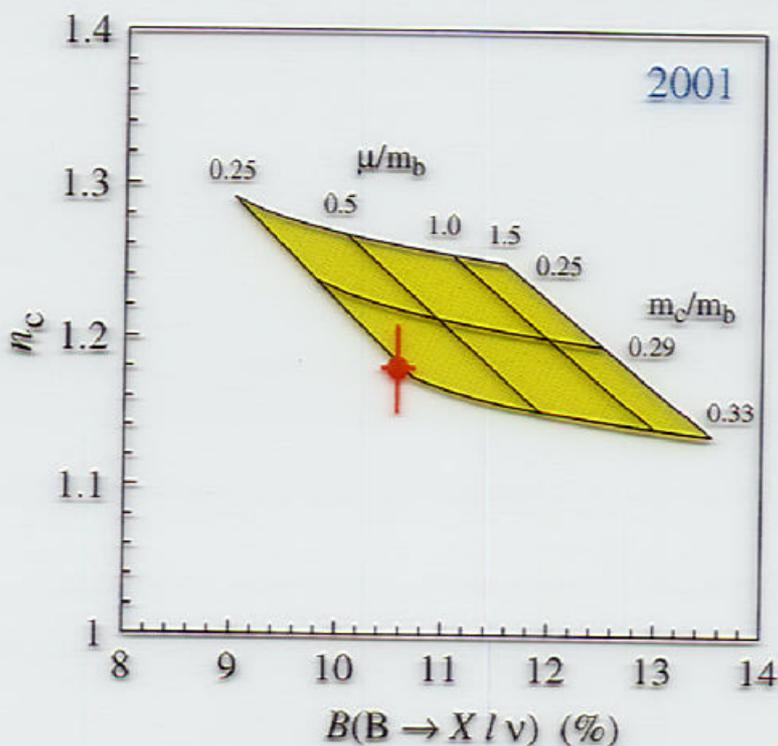Previous world average:

$$n_c = 1.238 \pm 0.027 \pm 0.048 \quad \text{[SLAC–PUB–8686]}$$
$$1.152 \pm 0.036 \quad \text{[Golutvin, ICHEP]}$$

New averages for n_c and $B(B \to X l \nu)$: no significant discrepancy

3. V_{cb} and V_{ub}

$$\Gamma(b \to c\, l^- \bar{\nu}) \equiv \frac{G_F^2\, m_b^5\, \Omega}{192\,\pi^3}\, |V_{cb}|^2 = \frac{B(b \to c\, l^- \bar{\nu})}{\tau_b}$$

assuming equal semileptonic widths

→ inclusive extraction of $|V_{cb}|$, using Heavy Quark Expansion:

$$|V_{cb}| = (0.0411 \pm 0.0018) \sqrt{\frac{B(b \to c\, l^- \bar{\nu})}{0.105}} \sqrt{\frac{1.55\ \text{ps}}{\tau_b}} \quad \text{[Bigi et al]}$$
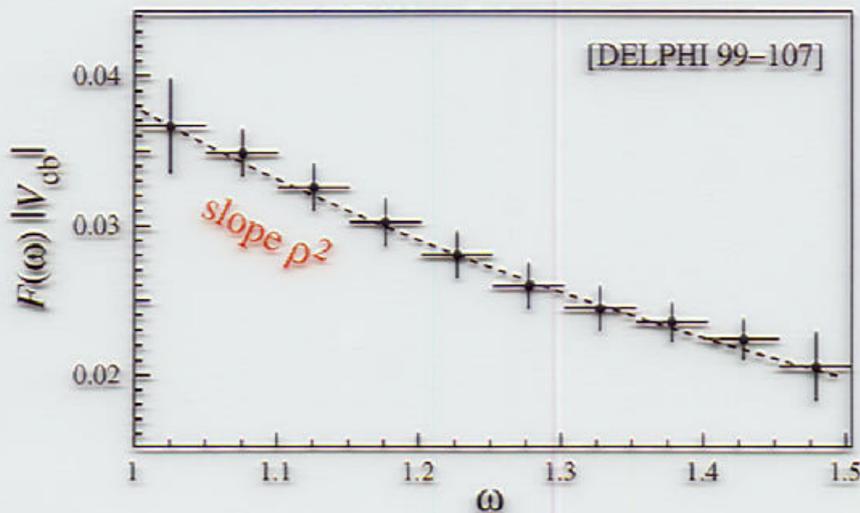
$$= (40.7 \pm 0.5 \pm 2.0) \times 10^{-3} \quad \text{[LEP } V_{cb} \text{ Working Group]}$$

$$cf \quad (40.1 \pm 0.9 \pm 0.7) \quad \text{[Thorndike (CLEO)]}$$

Alternative approach: use exclusive $\bar{B}^0 \to D^{*+}\, l^- \bar{\nu}$ decays

Differential decay rate: $d\Gamma/d\omega \propto F^2(\omega)\, |V_{cb}|^2$

where $\omega = \dfrac{m_B^2 + m_{D^*}^2 - q^2}{2\, m_B\, m_{D^*}}$ is the D^* boost in the B rest frame
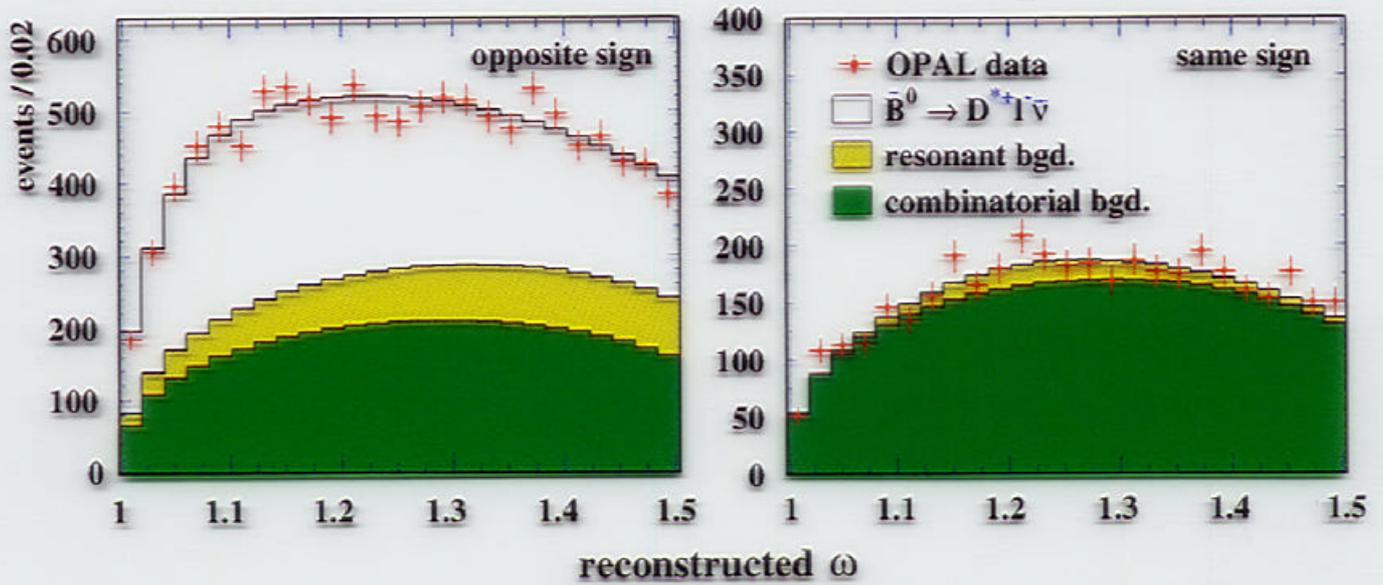

[DELPHI 99–107]

From HQET (for $m_Q \to \infty$) $F(\omega) = 1$ at $\omega = 1$ (zero recoil)

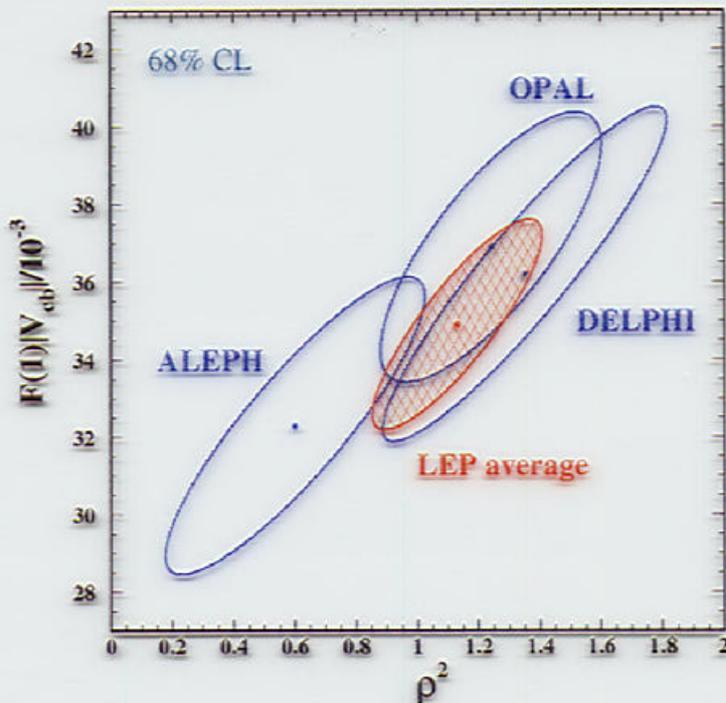Finite mass and QCD corrections → $F(1) = 0.88 \pm 0.05$ [Uraltsev et al]

phase-space

New result from OPAL (before efficiency correction):

$$\rightarrow F(1)\,|V_{cb}| = (37.1 \pm 1.0 \pm 2.0) \times 10^{-3} \quad \text{[CERN–EP–2000–032]}$$

LEP results averaged accounting for correlation with slope:

$$F(1)\,|V_{cb}| = (34.5 \pm 0.7 \pm 1.5) \times 10^{-3}$$

$$\rightarrow |V_{cb}| = (39.8 \pm 1.8 \pm 2.2) \times 10^{-3}$$

Consistent with inclusive result, averaged to give:

$$|V_{cb}| = (40.4 \pm 1.8) \times 10^{-3} \quad \text{[LEP } V_{cb} \text{ Working Group]}$$

Charmless semileptonic BR also measured at LEP

New result from DELPHI: select sample enriched in $b \to u$ decays

Recent   using K/p veto, requiring small offset of lepton from B vertex,
mass of hadronic system $m_{X_u} < 1.6$ GeV (below the D mass)

Energy of lepton in B rest frame
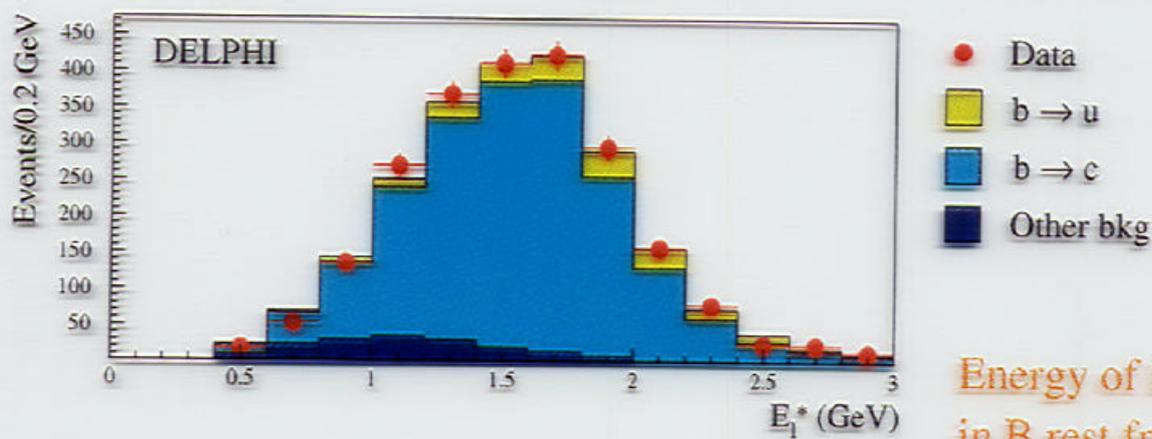
Substantial background from $b \to c$ decays, requires careful subtraction
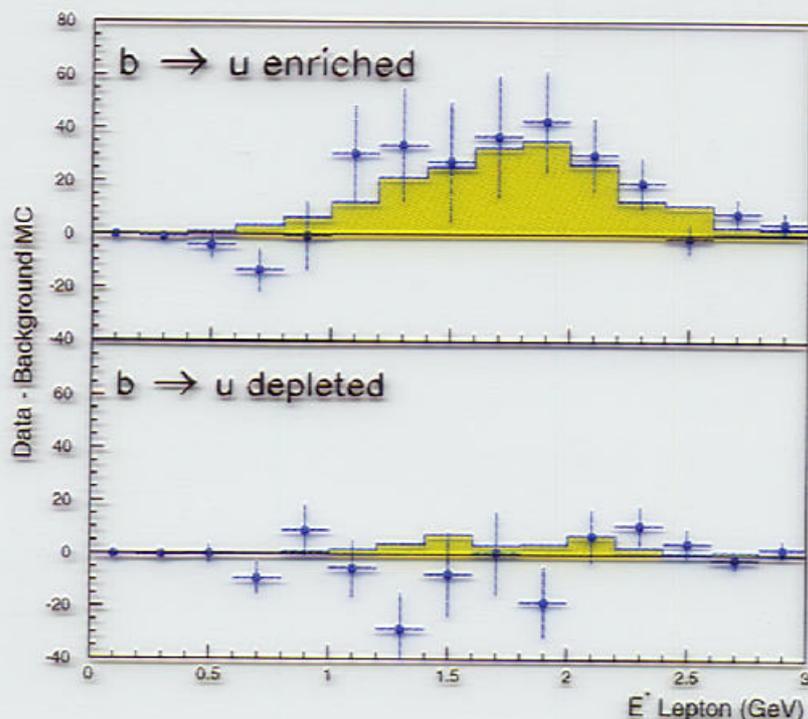
[CERN–EP–2000–030]

$\to B(b \to u\, l^- \bar{\nu}) = (1.57 \pm 0.35 \pm 0.55) \times 10^{-3}$
LEP average: $(1.74 \pm 0.57) \times 10^{-3}$

$$|V_{ub}| = (0.00445 \pm 0.00018) \sqrt{\frac{B(b \to u\, l^- \bar{\nu})}{0.002}} \sqrt{\frac{1.55 \text{ ps}}{\tau_b}}$$ [Uraltsev *et al*]
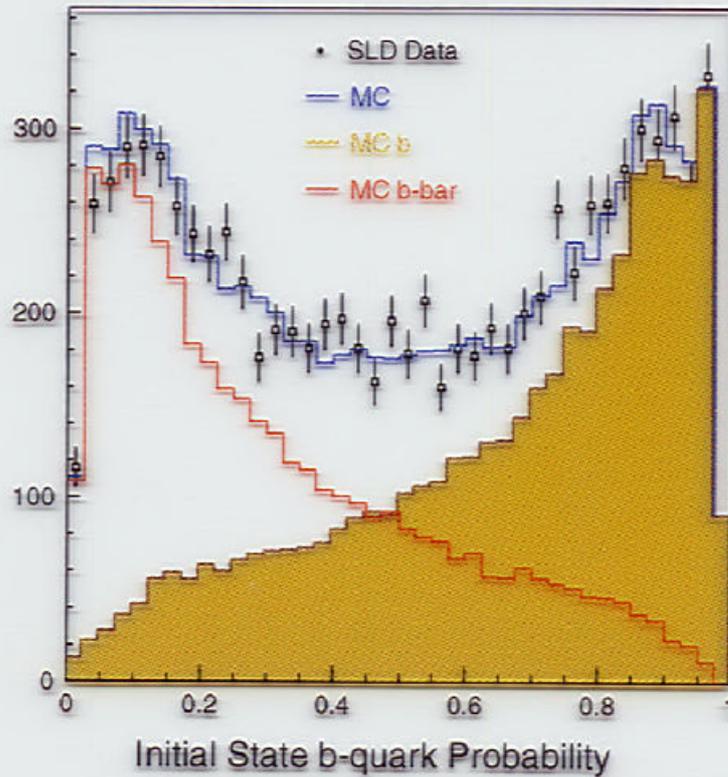
$= (4.1 \pm 0.7) \times 10^{-3}$ [LEP V_{ub} Working Group]

$\pm 13\%$ systematic from modelling · enough? [Falk]
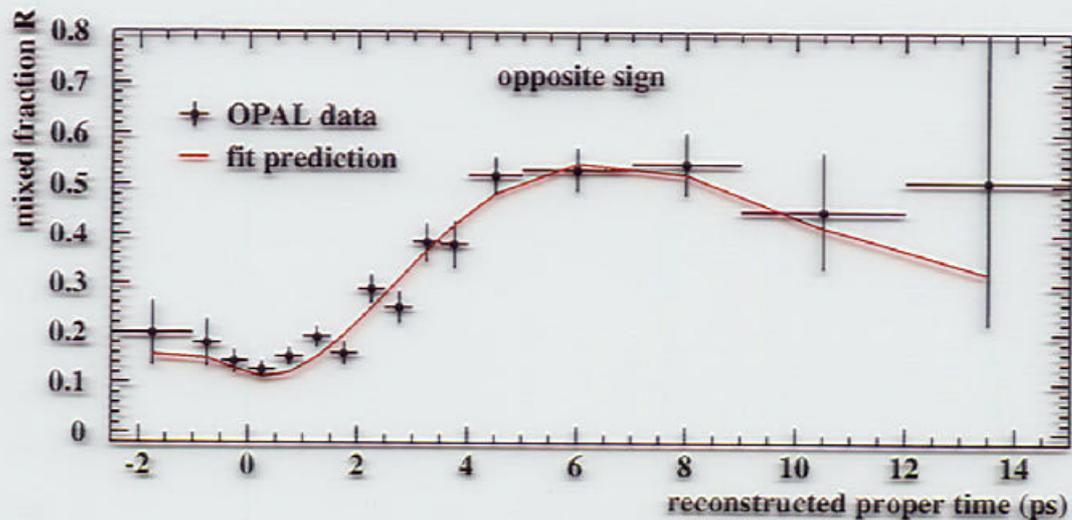
4. Oscillation

Study of B^0–$\overline{B}^0$ oscillations requires tagging of production state

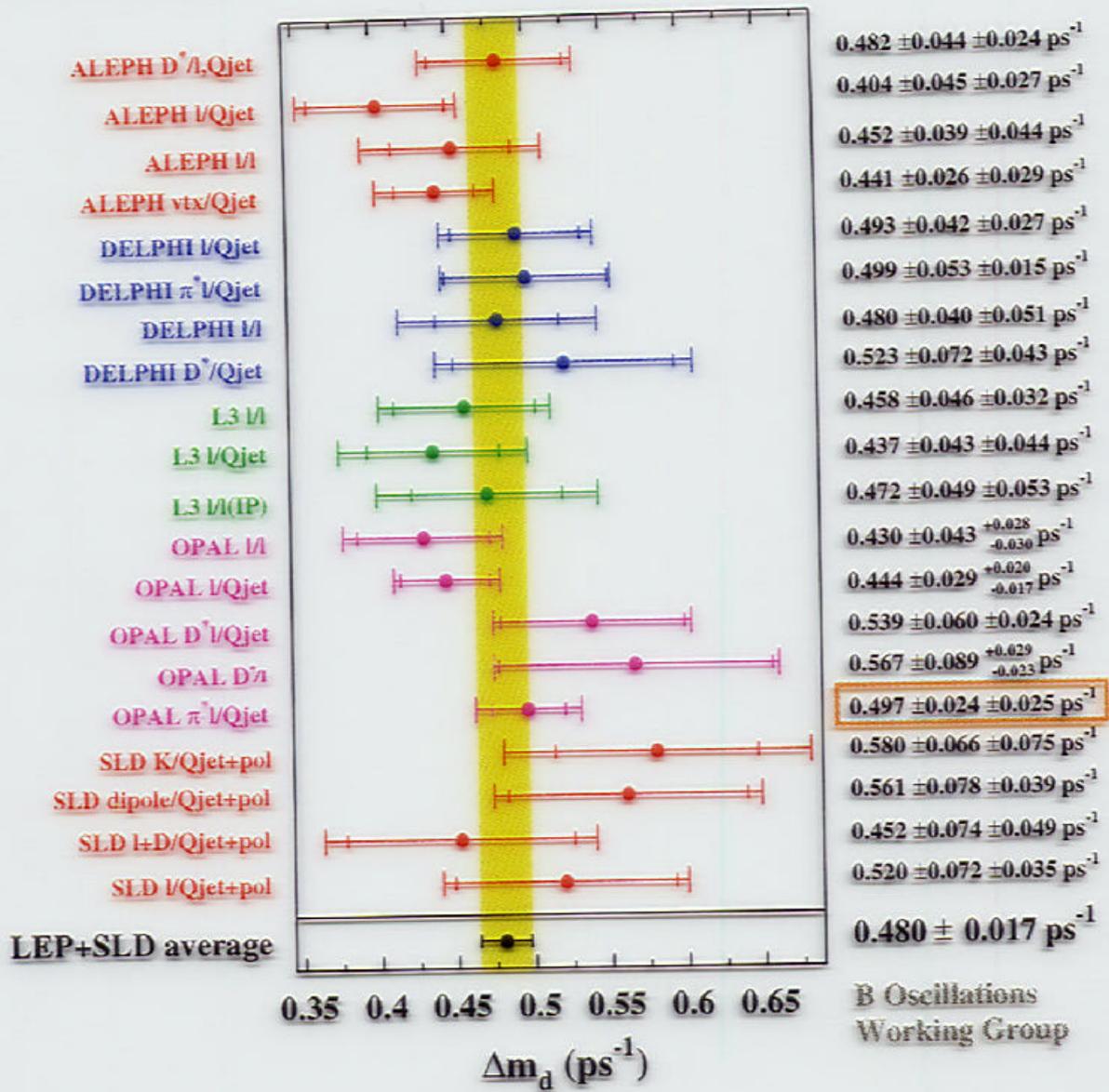SLD profit from polarized e^- beam (combined with other tags):

Overall mistag rate ~ 23% (for 100% tagging efficiency)

Example of fit for the B^0–$\overline{B}^0$ oscillation frequency Δm_d
(from the same OPAL analysis as measured τ_{B0}):

Measuring Δm_d has become an industry:

	Δm_d value
ALEPH D*/l,Qjet	$0.482 \pm 0.044 \pm 0.024$ ps^{-1}
ALEPH l/Qjet	$0.404 \pm 0.045 \pm 0.027$ ps^{-1}
ALEPH l/l	$0.452 \pm 0.039 \pm 0.044$ ps^{-1}
ALEPH vtx/Qjet	$0.441 \pm 0.026 \pm 0.029$ ps^{-1}
DELPHI l/Qjet	$0.493 \pm 0.042 \pm 0.027$ ps^{-1}
DELPHI π^*l/Qjet	$0.499 \pm 0.053 \pm 0.015$ ps^{-1}
DELPHI l/l	$0.480 \pm 0.040 \pm 0.051$ ps^{-1}
DELPHI D*/Qjet	$0.523 \pm 0.072 \pm 0.043$ ps^{-1}
L3 l/l	$0.458 \pm 0.046 \pm 0.032$ ps^{-1}
L3 l/Qjet	$0.437 \pm 0.043 \pm 0.044$ ps^{-1}
L3 l/l(IP)	$0.472 \pm 0.049 \pm 0.053$ ps^{-1}
OPAL l/l	$0.430 \pm 0.043 \,^{+0.028}_{-0.030}$ ps^{-1}
OPAL l/Qjet	$0.444 \pm 0.029 \,^{+0.020}_{-0.017}$ ps^{-1}
OPAL D*l/Qjet	$0.539 \pm 0.060 \pm 0.024$ ps^{-1}
OPAL D*l	$0.567 \pm 0.089 \,^{+0.029}_{-0.023}$ ps^{-1}
OPAL π^*l/Qjet	$0.497 \pm 0.024 \pm 0.025$ ps^{-1}
SLD K/Qjet+pol	$0.580 \pm 0.066 \pm 0.075$ ps^{-1}
SLD dipole/Qjet+pol	$0.561 \pm 0.078 \pm 0.039$ ps^{-1}
SLD l+D/Qjet+pol	$0.452 \pm 0.074 \pm 0.049$ ps^{-1}
SLD l/Qjet+pol	$0.520 \pm 0.072 \pm 0.035$ ps^{-1}
LEP+SLD average	$\mathbf{0.480 \pm 0.017}$ **ps^{-1}**

Δm_d (ps^{-1})

B Oscillations Working Group

20 results from LEP+SLD, giving ~ 3% precision on Δm_d

However, extraction of V_{td} limited by uncertainty on hadronic matrix elements, taken from Lattice QCD

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 \, \eta_B \, S_0(m_t^2/m_W^2) \, m_{B_d} \, |V_{td}|^2 \, f_B^2 \, B_B$$
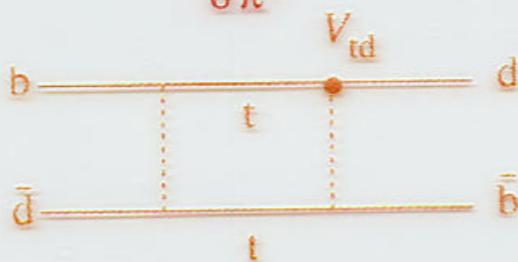
$f_B \sqrt{B_B} = (210 \pm 40)$ MeV [PDG 2000]

(230 ± 40) MeV [Aoki]

Some uncertainties cancel in the ratio with the $B_s - \bar{B}_s$ frequency:

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

$$\xi = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}} = 1.16 \pm 0.07 \quad \text{[Kenway, ICHEP 2000]}$$
$$1.16 \pm 0.05 \quad \text{[Aoki]}$$

Measurement of Δm_s is still a hot topic [see talk of Gaelle Boix]
Analyses are combined using the Amplitude technique:
Fit the time dependence with a term $(1 \pm A \cos \Delta m_s t)$

$A = 1$ at true Δm_s

0 for test frequency < true Δm_s

$$\sigma_A \sim \frac{e^{-\frac{1}{2}(\Delta m_s \sigma_t)^2}}{P(1-2w)\sqrt{N}}$$

for an analysis with N events,
B_s purity P, and mistag rate w

← σ_A needed to exclude Δm_s at 95% CL (if $A = 0$)
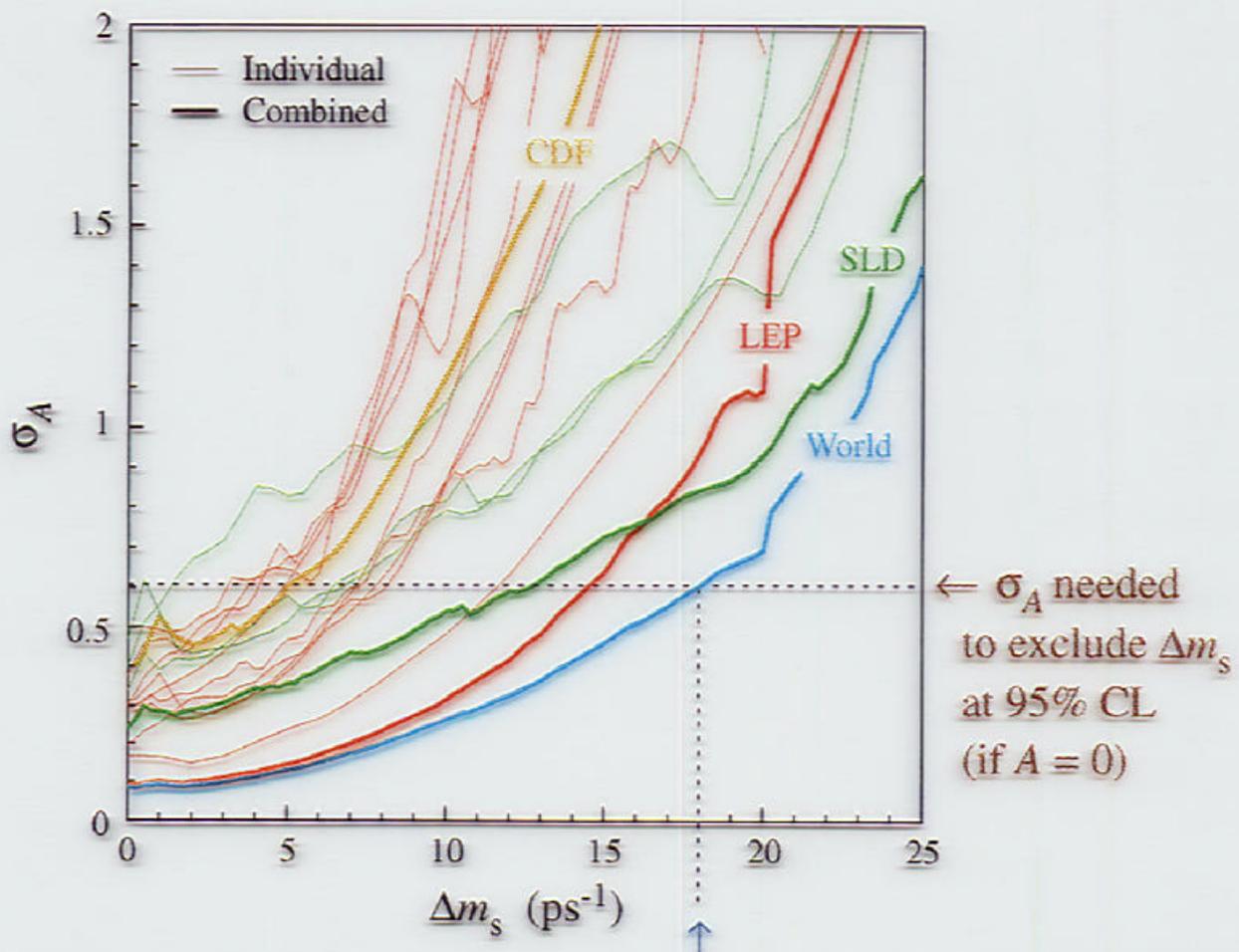
"Sensitivity" (expected limit if no signal present) = 18 ps^{-1}

Most sensitive analysis from ALEPH using inclusive lepton events:
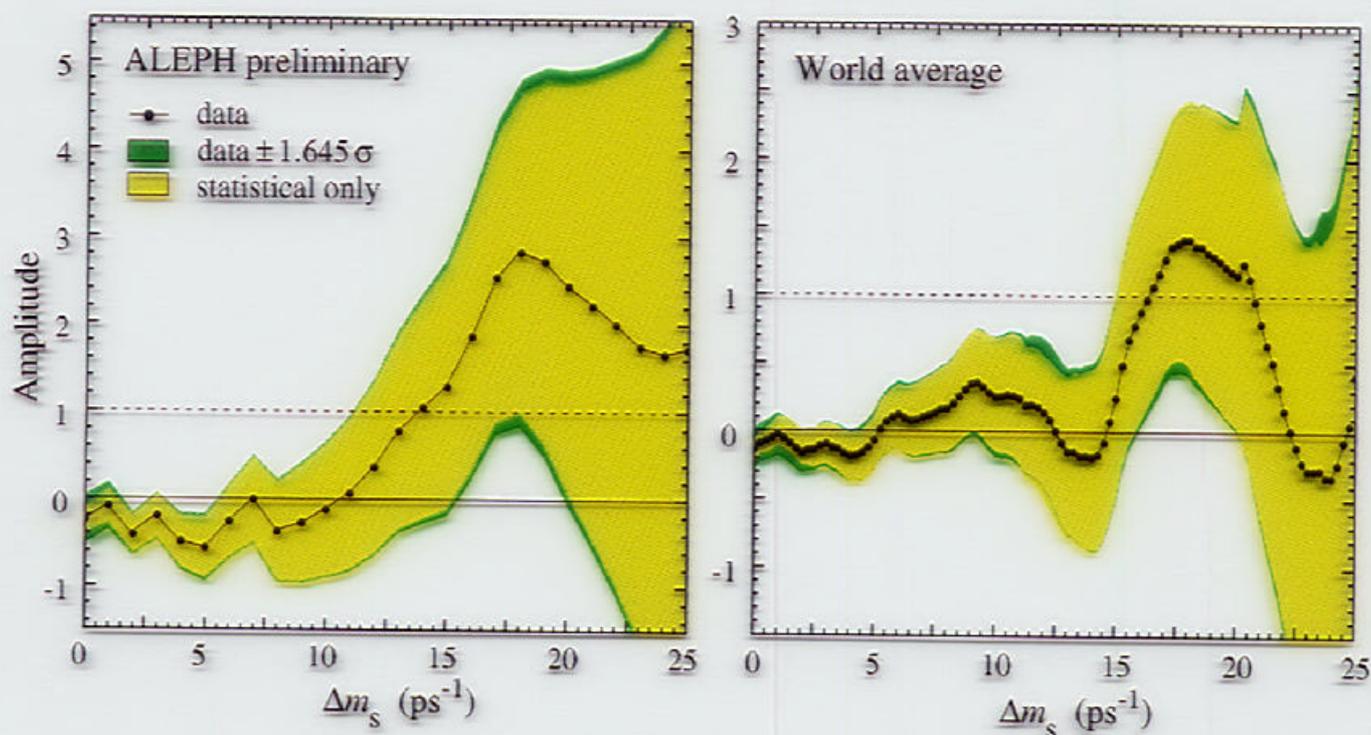
World average combination gives limit $\Delta m_s > 15 \text{ ps}^{-1}$ at 95% CL
Indication for a signal at $\Delta m_s \sim 17 \text{ ps}^{-1}$

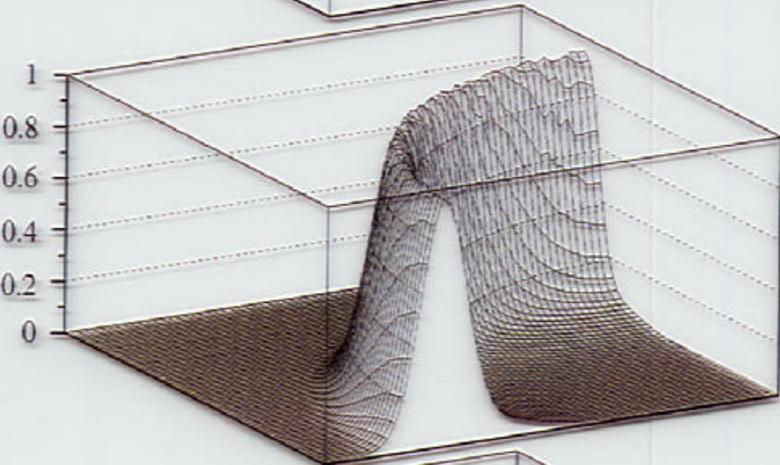Converting the world-average Amplitude into log-likelihood:
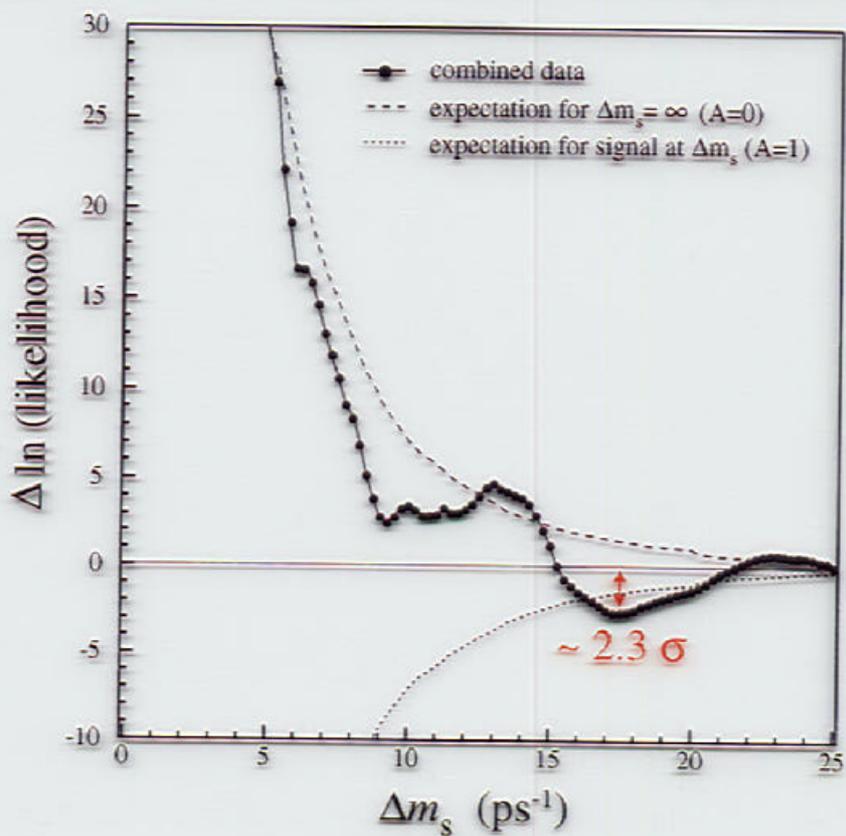
5. CKM constraints

Plot likelihood as a function of $(\bar{\rho}, \bar{\eta})$ Wolfenstein parameters, as constraints from LEP+SLD are added in turn:
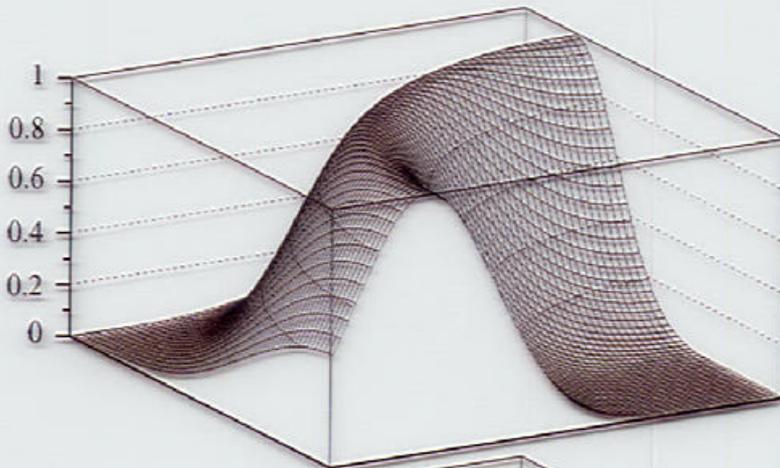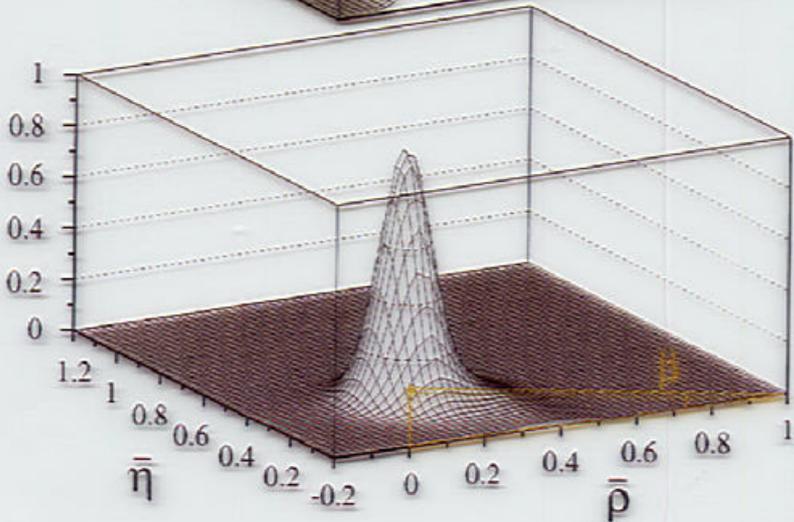

Δm_d

using $f_B \sqrt{B_B} = (210 \pm 40)$ MeV

$\dfrac{\Delta m_s}{\Delta m_d}$

using $\xi = 1.16 \pm 0.07$

$\left| \dfrac{V_{ub}}{V_{cb}} \right| = 0.10 \pm 0.02$

Interpretation as a confidence level is debatable, due to problem of ascribing a strict confidence level for theoretical errors

and Bayesian vs. Frequentist interpretation [Höcker et al.]

However, the result is rather insensitive to the functional form used
to decribe the theoretical errors
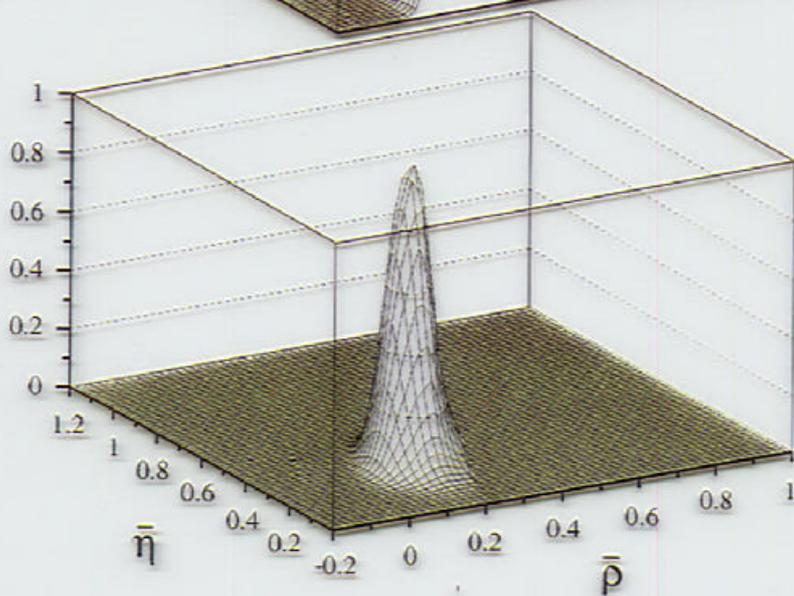For example, using a "top hat" form ⎍ instead of Gaussian:
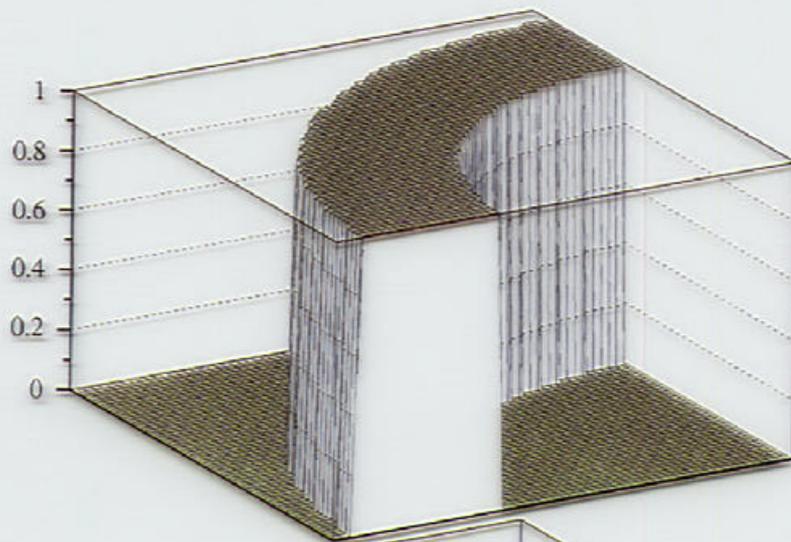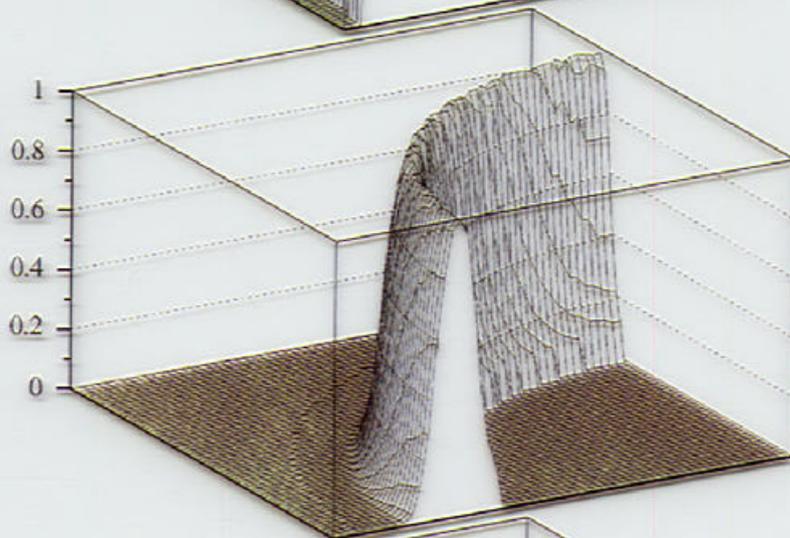
Corresponding distribution of sin 2β:
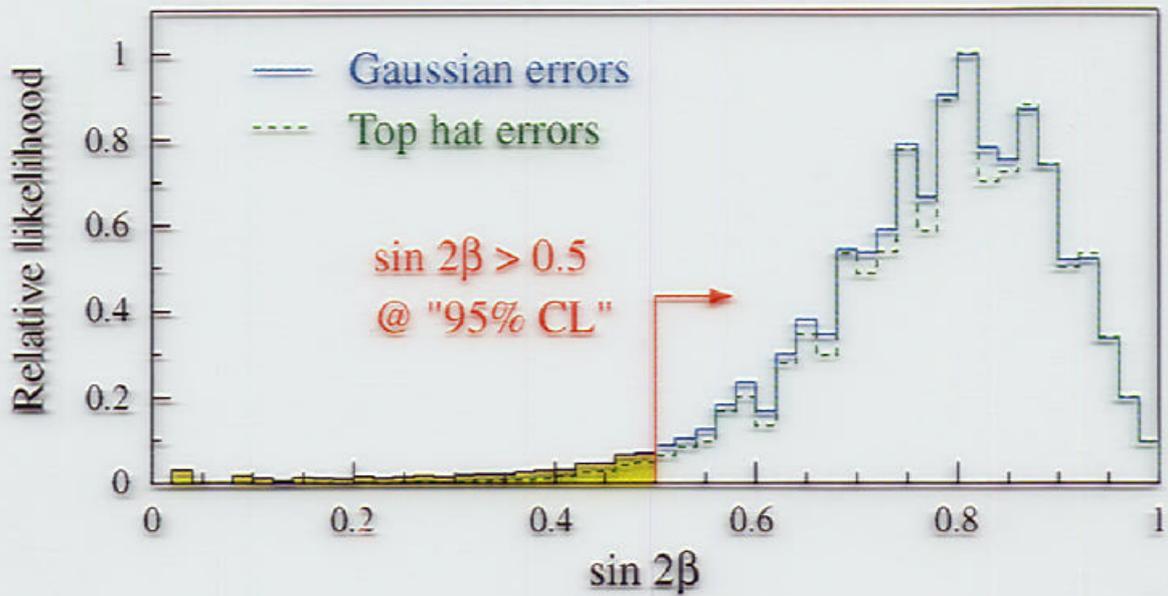
Severe statistical limitation to direct measurement at LEP:
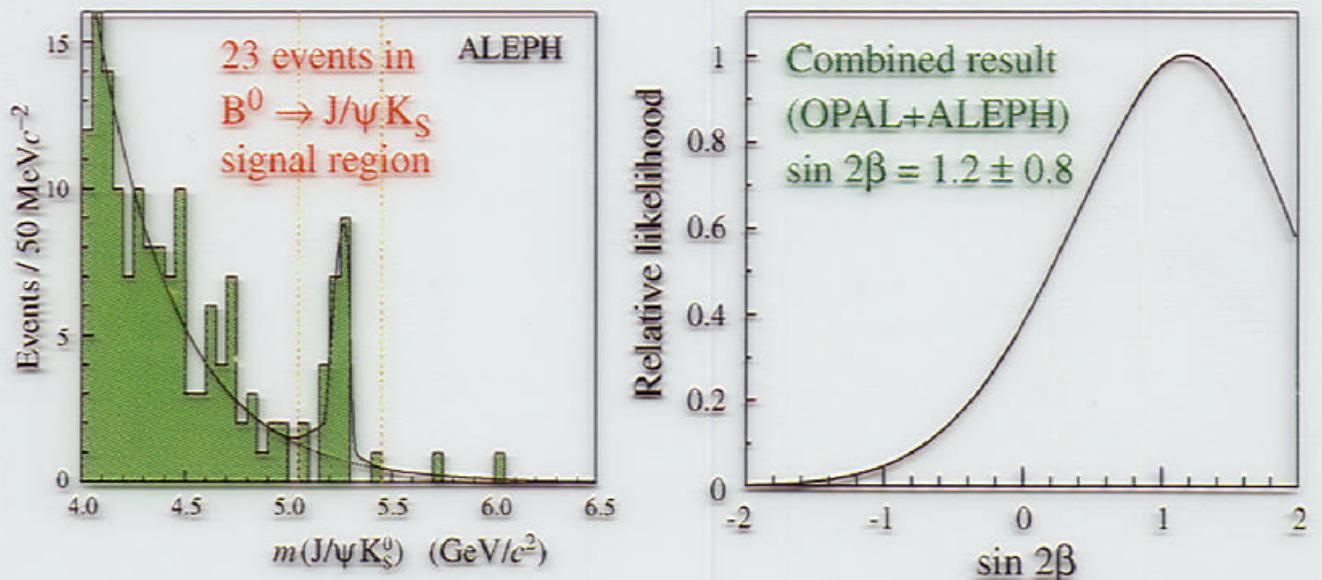
Conclusions

A wide spectrum of B physics results has come from LEP+SLD

The B decay measurements have been amongst the most precise
in the world, and give strong constraints on the CKM matrix

Most analyses complete, but final push for B_s oscillations