CERN 11 October 2000

The LEP $B\overline{B}$ boom

All LEP Collaborations

presented by P. Roudeau (LAL, Orsay)

Flavour Physics

Part of the Standard Model dealing with CKM matrix elements and quark masses.

10 parameters! (Half S.M.)

Aim at precise measurements.

New Physics: $m_{q_i} \leftrightarrow |\mathrm{V}_{CKM}|, CP$

But....

Heavy quarks are glued inside heavy hadrons

Need to have a control of QCD in a non-perturbative regime:

- presence of symmetries: HQET, OPE, ...
- Lattice QCD: $\mathrm{B_K}$, ξ, f_B, ...
- dedicated measurements: f_{D_s}, b-hadron rates and masses, excited states, fragmentation properties, ...

Control of systematics, information relevant for higher energy colliders

Content

- Physics program overview and experimental procedures
- the LEP source of b-hadrons
- b-baryons
- the $\mathrm{B_s^0}$ meson
- b-hadron lifetimes
- tau lepton lifetime
- $\mathrm{B_d^0} - \overline{\mathrm{B_d^0}}$ oscillations
- b-hadron semileptonic decays
- $|\mathrm{V}_{cb}|$ measurement
- $|\mathrm{V}_{ub}|$ measurement
- $\mathrm{B_s^0} - \overline{\mathrm{B_s^0}}$ oscillations
- Combining everything .. and more: the CKM unitarity triangle
- Conclusions

LEP weight

$$\text{weight} = \frac{\sigma^2_{All}}{\sigma^2_{LEP}}$$

LEP b-physics program accomplishment

Main lines defined in 1989

Inclusive or semi-inclusive final states, importance of semileptonic decays.

Complex final states

A lot of tools and developments need to be in place.

LEP 4×1 M $b\bar{b}$ evts

SLD ~ 0.1 M

CLEO ~ 3 M $(9$ M$)$

$\rightarrow$ A learning phase (1990-1995)

- "new" signals: Λ_b^0, $\mathrm{B_s^0}$, Ξ_b, $\mathrm{B_d^0} - \overline{\mathrm{B_d^0}}(\mathrm{t})$, $\mathrm{B^{**}}$, ...
- "new" ideas:
  - amplitude method to study $\mathrm{B_s^0} - \overline{\mathrm{B_s^0}}$ oscillations (ALEPH),
  - inclusive π^* to select $\overline{\mathrm{B}_d^0} \rightarrow \mathrm{D}^{*+}\ell^-\overline{\nu_\ell}$ (DELPHI)

$\rightarrow$ Final results 1995-2000,...

(end of running at the Z: 1995)

- some data samples have been reprocessed: 97, 98, ..
- algorithms get more complex

  better use of information
- the unexpected: $b \rightarrow s\gamma$, $|\mathrm{V}_{ub}|$, Δm_s,..

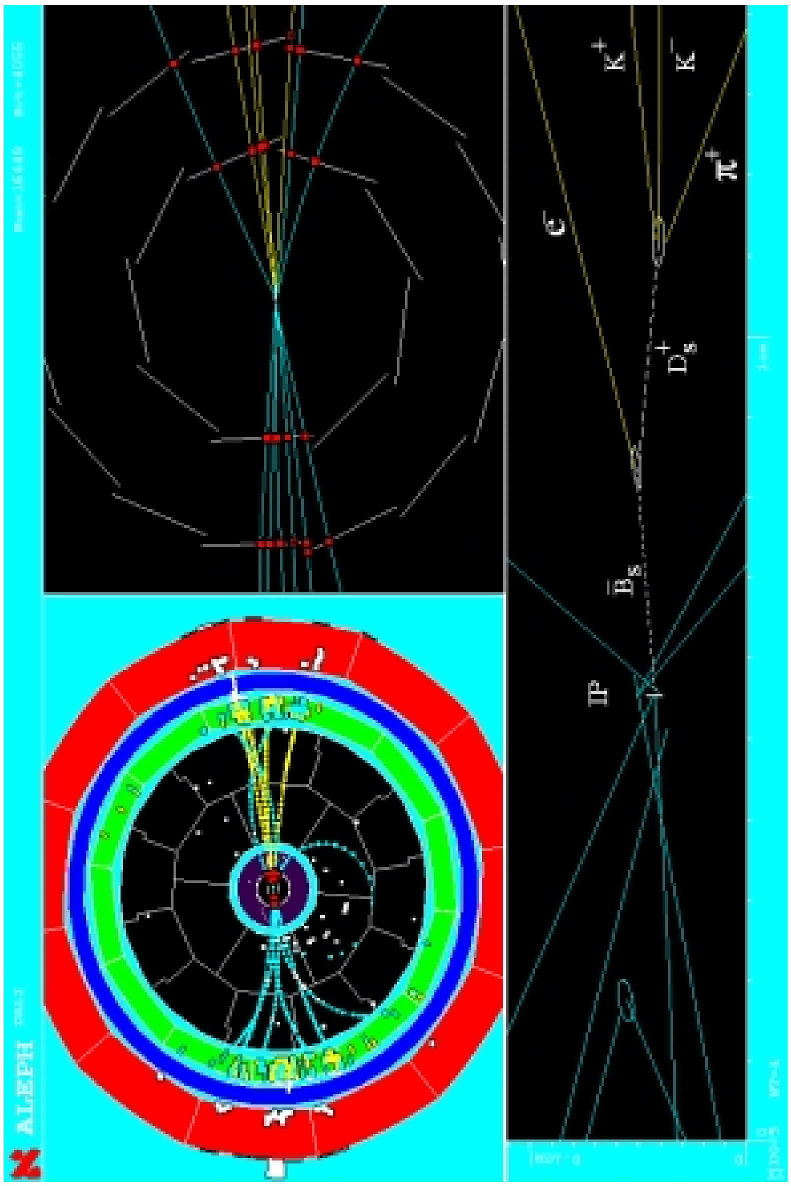
$\rightarrow$ What have we learned ?

An example: a first Tour inside the SM picture of CP violation before the start of B-factories.

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

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ \lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

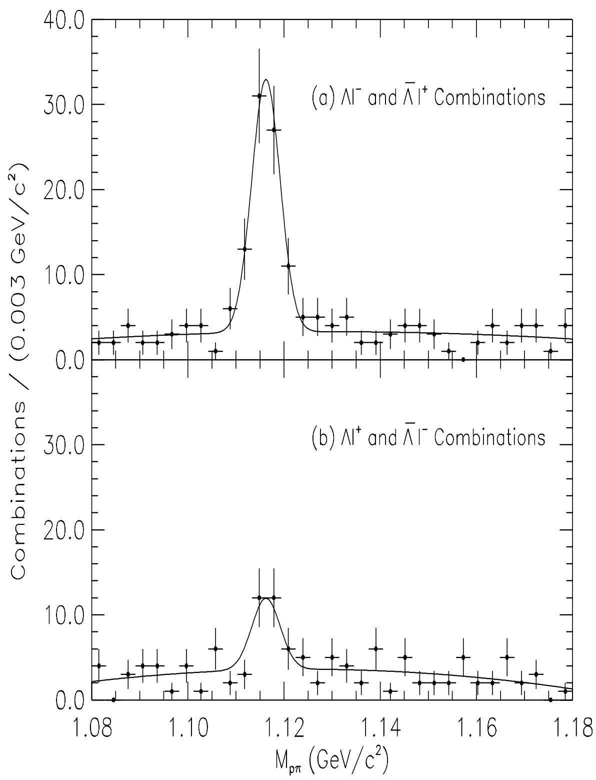
Tagging b-hadrons



- $b \leftrightarrow \mathrm{non}-b$
  - displaced vertex
  - leptons
- $b \leftrightarrow \bar{b}$
  - jet charge
  - fragmentation products
- $\mathrm{B} \leftrightarrow \overline{\mathrm{B}}$
  - lepton
  - D hadron
- $\mathrm{B_i} \leftrightarrow \mathrm{B_j}$
  - semileptonic decays
  - fragmentation products

b-baryon signals 1990: ALEPH

Excess of $\Lambda - \ell^-$ combinations as compared to $\Lambda - \ell^+$ (and charge conjugate final states).



Ξ_b signals 1995: DELPHI

Excess of $\Xi^{\mp} - \ell^{\mp}$ combinations..

b-baryons in 2000

b-baryons have been observed using $(\Lambda, p, \Lambda_c^+, \Xi) - \ell$ correlations and also accompanying $\overline{p}$ and $\overline{\Lambda}$.

- the b-baryon rate in jets amounts to:

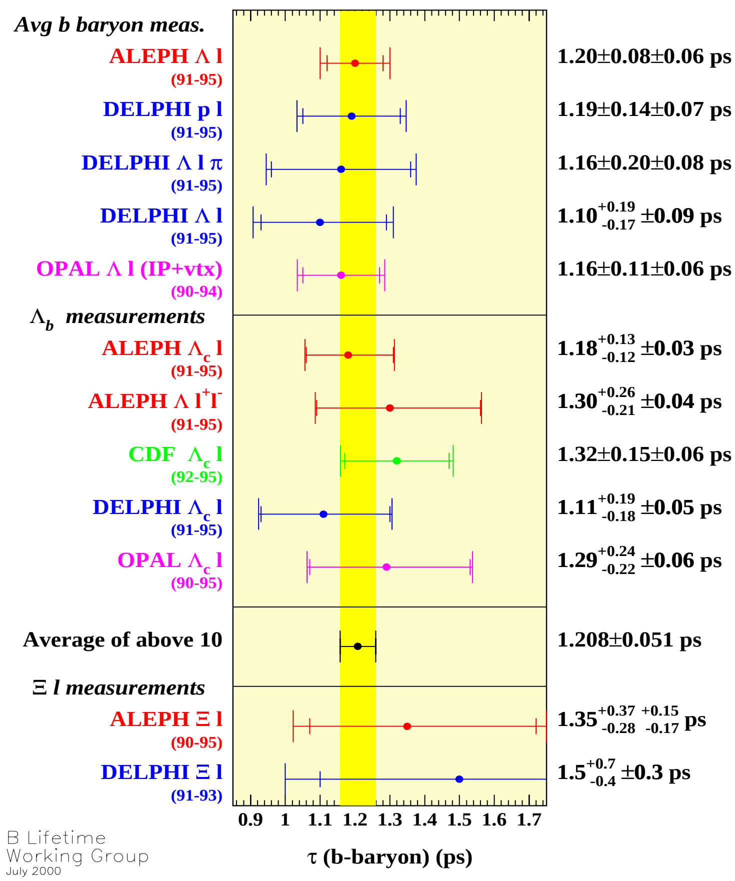
$$f_{\text{b-baryon}} = (10.4 \pm 1.7)\%$$

- the b-quark polarization (-0.94) is diluted:

$$\mathcal{P}(\Lambda_b^0) = -0.45^{+0.19}_{-0.17}$$

- the Λ_b^0 lifetime is "too short" (for theory):

$$\tau(\text{b-baryon}) = 1.208^{+0.051}_{-0.050} \text{ ps}$$



- accuracy on $f_{\text{b-baryon}}$ better than uncertainty on Λ_c^+
- polarization reflects $\Sigma_b^{(*)}$ production
- $\tau(\text{b-baryon})$??: pb. for theory

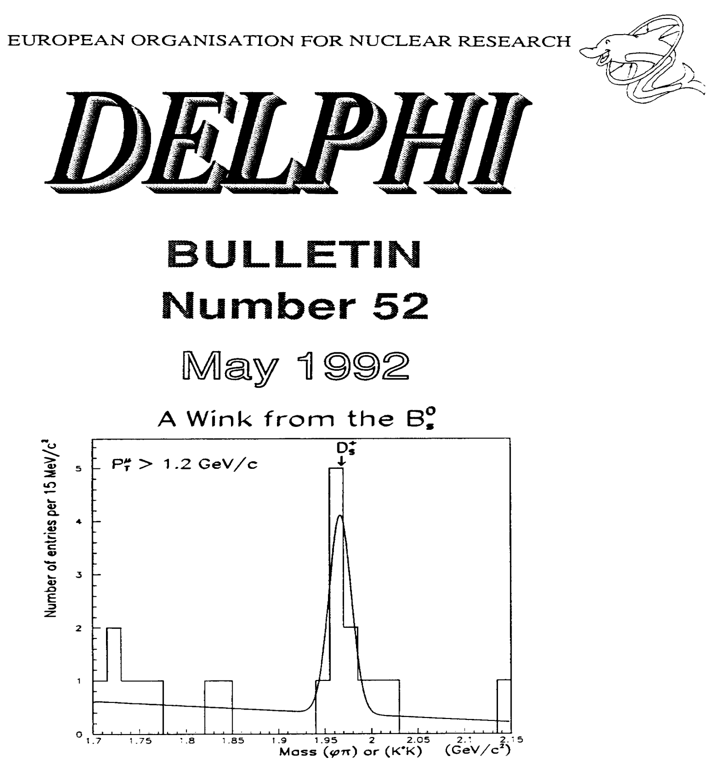
The $\overline{\mathrm{B}_s^0}$ meson (1992)

Before LEP

- UA(1) (1987): Same sign dilepton events from $\mathrm{B}^0 - \overline{\mathrm{B}^0}$ oscillations
- CUSB at $\Upsilon(5S)$ (1990):

  evidence for B_s^* using Doppler effect

First signal at LEP: DELPHI



$\overline{\mathrm{B}_s^0} \to \mathrm{D}_s^+ \ell^- \overline{\nu_\ell}$

7 events ...

The $\overline{B_s^0}$ meson in 2000

Studied mainly using using $D_s^+ - \ell^-$ events.

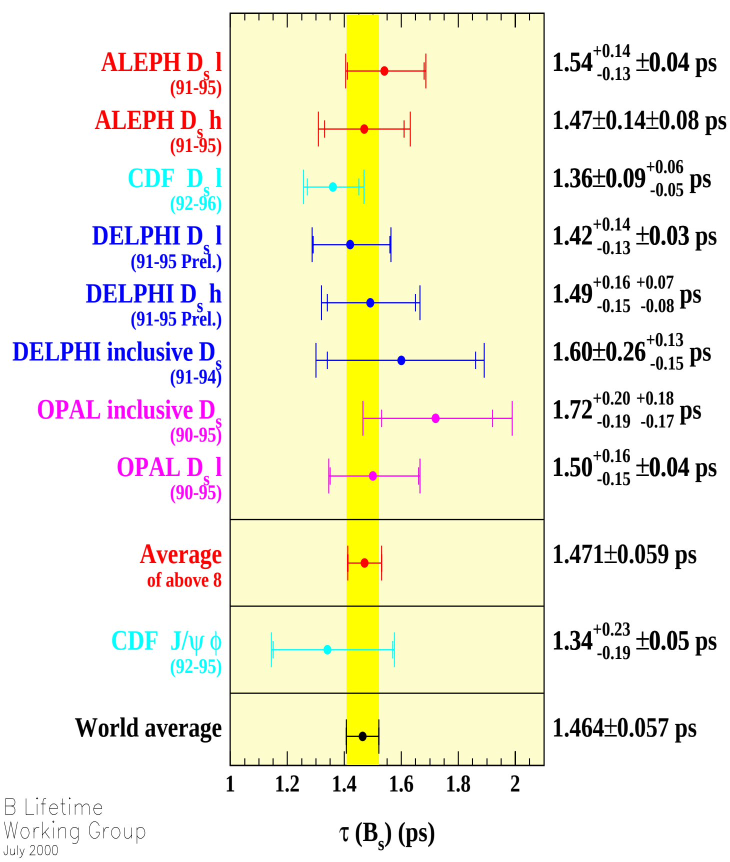
- the $\overline{B_s^0}$ rate in b-jets amounts to:

$$f_{B_s} \;=\; (9.7 \pm 1.2)\%$$

- the $\overline{B_s^0}$ lifetime is measured:

$$\tau(\overline{B_s^0}) = (1.460 \pm 0.056) \text{ ps}$$

- $B_s^0 - \overline{B_s^0}$ oscillations: see later.

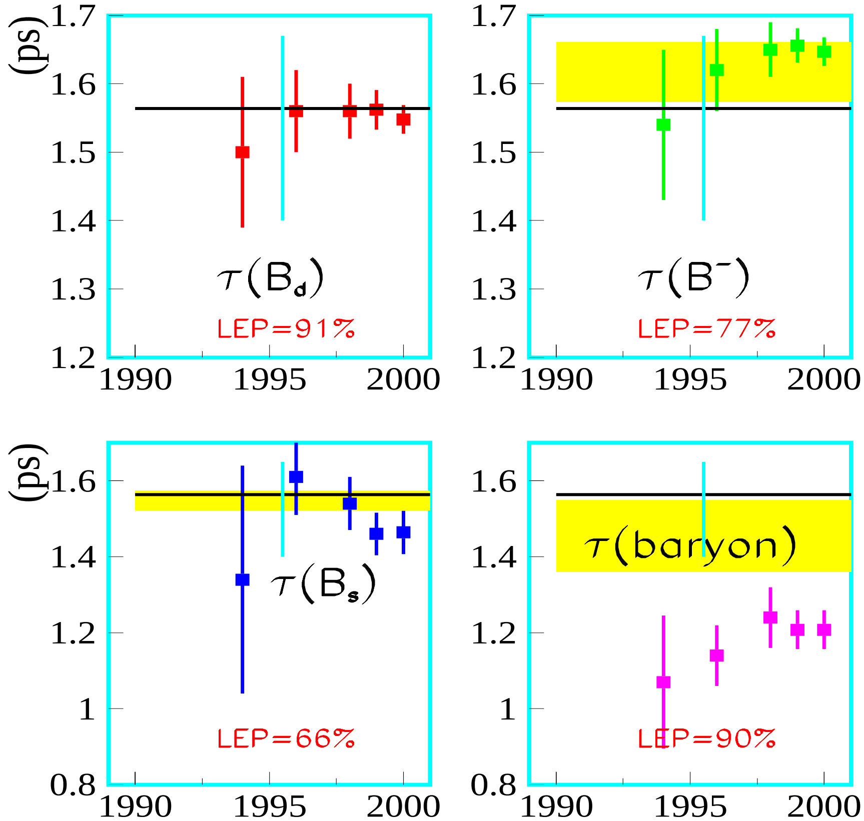


And also:

$$\Delta\Gamma_{B_s^0}/\Gamma_{B_s^0} < 0.31$$

(95% C.L.)

b-hadron lifetimes

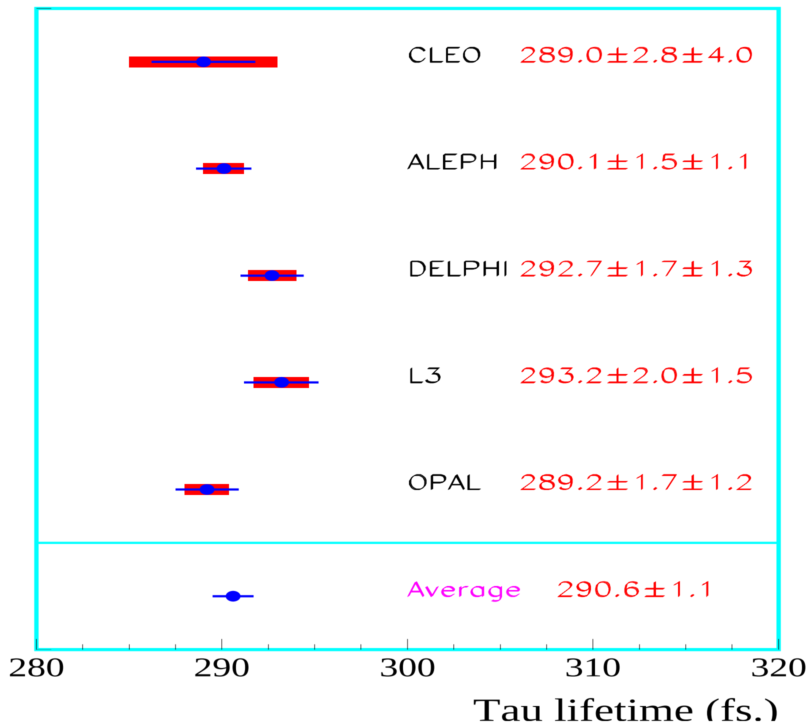


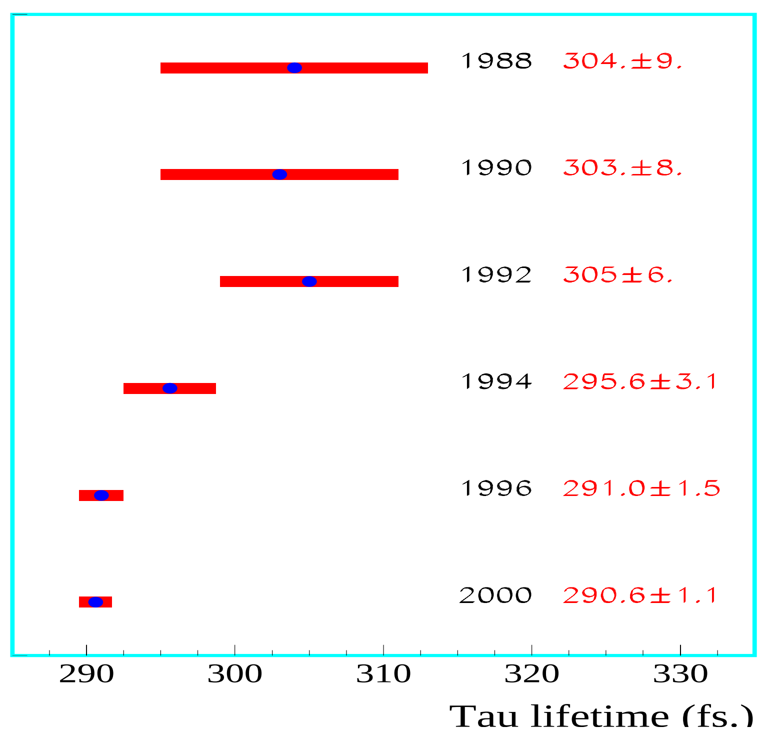
What have we learned?

- measured values are MANDATORY inputs to get partial widths: allow comparison with theory
- high accuracy: not the limiting source of uncertainty
- QCD artillery has not reached enough precision in this game: reasonable agreement for mesons, what about b-baryons?

The tau lifetime

Governed by LEP measurements





$B_d^0 - \overline{B_d^0}$ oscillations

Before LEP

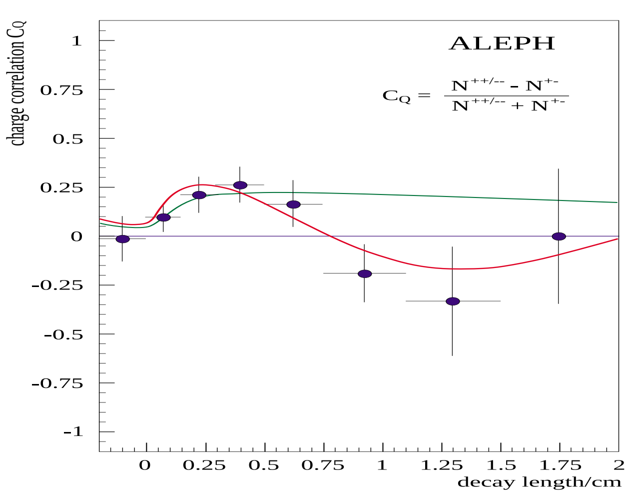
Same-sign dilepton events; $\chi_d = \frac{(\Delta m_d \ \tau(B_d^0))^2}{2+(\Delta m_d \ \tau(B_d^0))^2}$

- ARGUS, 1987, same-sign dilepton events:

$$\Delta m_d = (0.47 \pm 0.11)\ \mathrm{ps}^{-1}$$

- UA1, 1987, signal from same-sign dileptons due to B_d^0 and B_s^0 oscillations

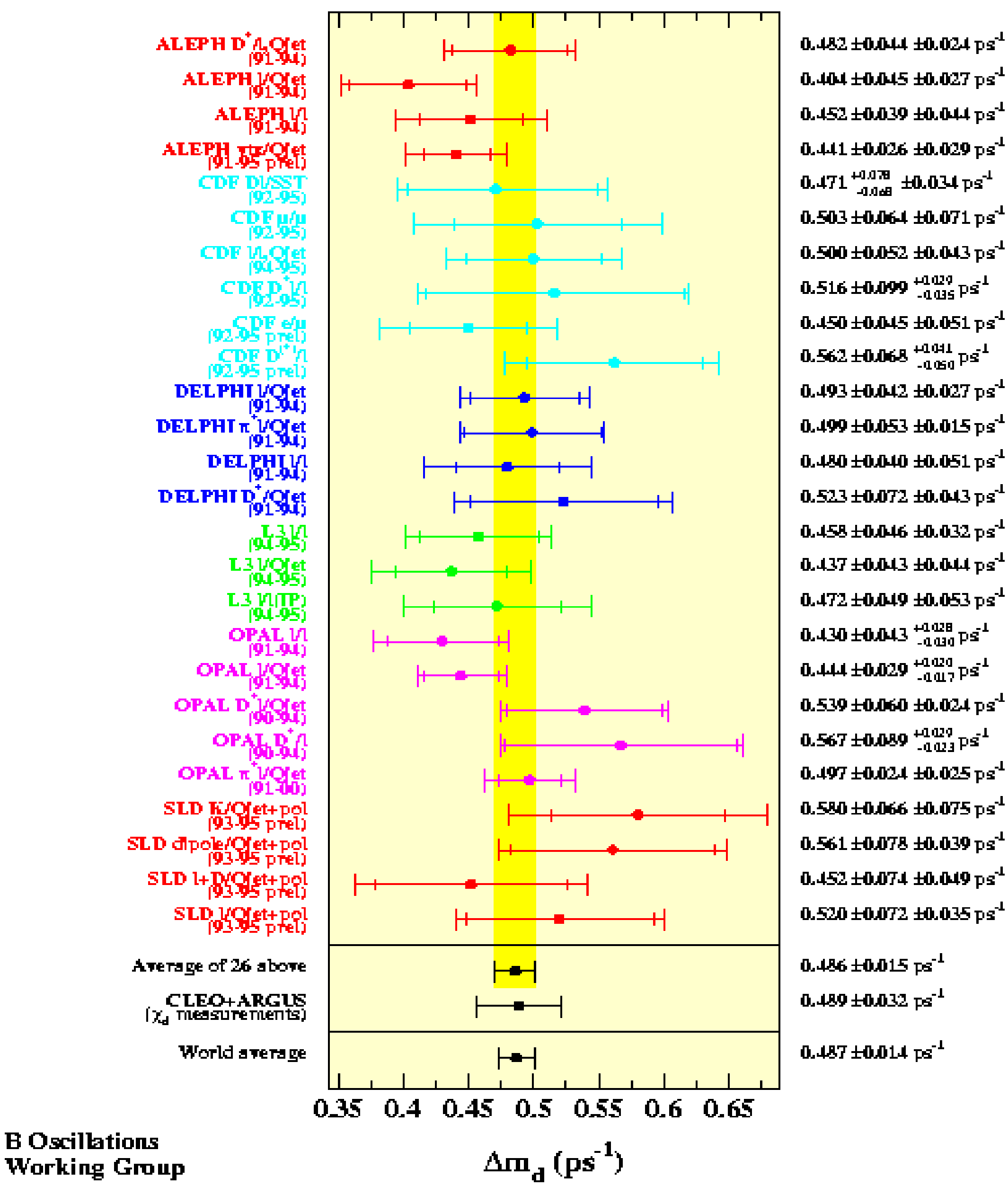
First $B_d^0(t) - \overline{B_d^0}(t)$: ALEPH (1993)



$$\mathcal{P}(B_d^0 \to \overline{B_d^0})(t) = \frac{1}{2}[1 - \cos(\Delta m_d \ t)] \exp\left(-\frac{t}{\tau(B_d^0)}\right)$$

Direct meast. of Δm_d

Δm_d in 2000



- LEP weight=70 %
- Δm_d and χ_d results agree

$$\Delta m_d = (0.487 \pm 0.014)\ \mathrm{ps}^{-1} \qquad \sigma(\Delta m_d) < 3\%$$

Interest?

- constraints on CKM parameters

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 A^2 \lambda^6 [(1-\bar{\rho})^2 + \bar{\eta}^2] m_{B_d} f_{B_d}^2 \hat{B}_{B_d} \eta_B S(m_t^2/m_W^2)$$

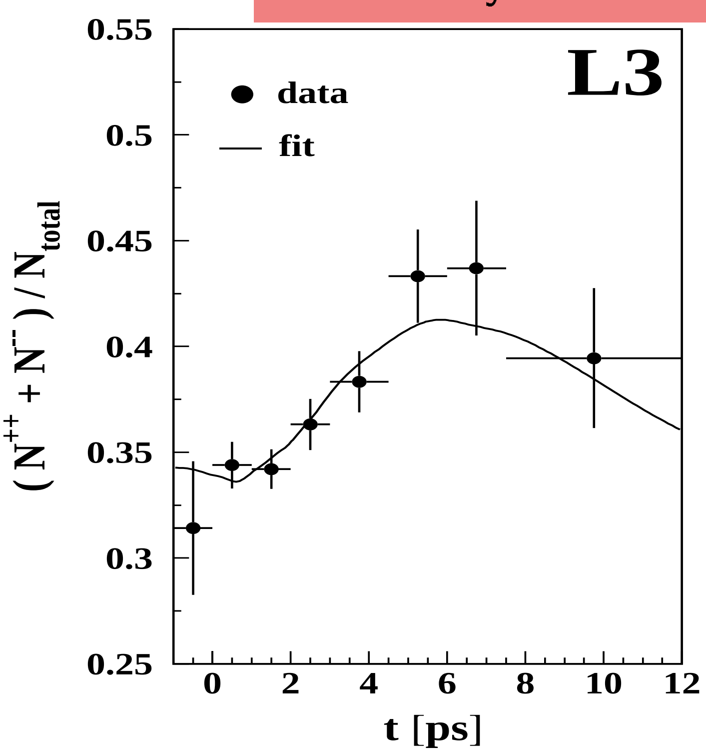
- high accuracy on Δm_d is important.

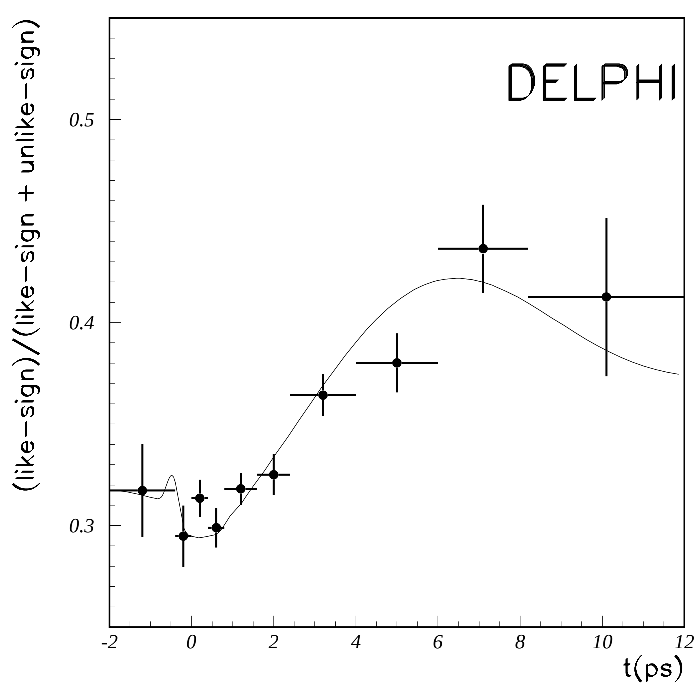
$$\frac{\Delta m_d}{\Delta m_s} = \frac{f_{B_d}^2 \hat{B}_{B_d}}{f_{B_s}^2 \hat{B}_{B_s}} \frac{m_{B_d}}{m_{B_s}} \lambda^2 [(1-\bar{\rho})^2 + \bar{\eta}^2]$$

- improve accuracy on b-rates

$$P(b \to \overline{B_d^0}) = (40.1 \pm 1.0)\%$$

LEP Heavy Flavour Steering group activity

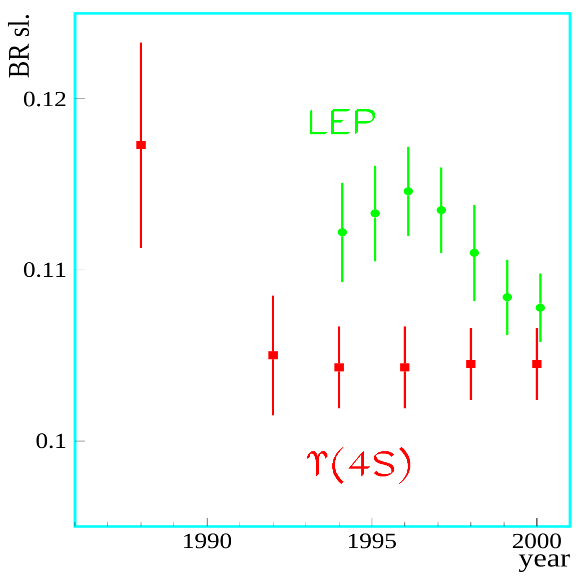


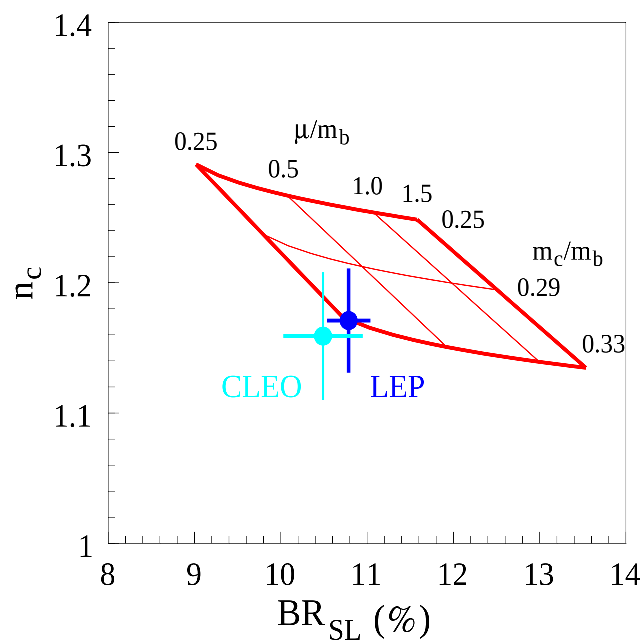


b-hadron semileptonic decays

Inclusive $\mathrm{BR}(b \to \ell \mathrm{X})$

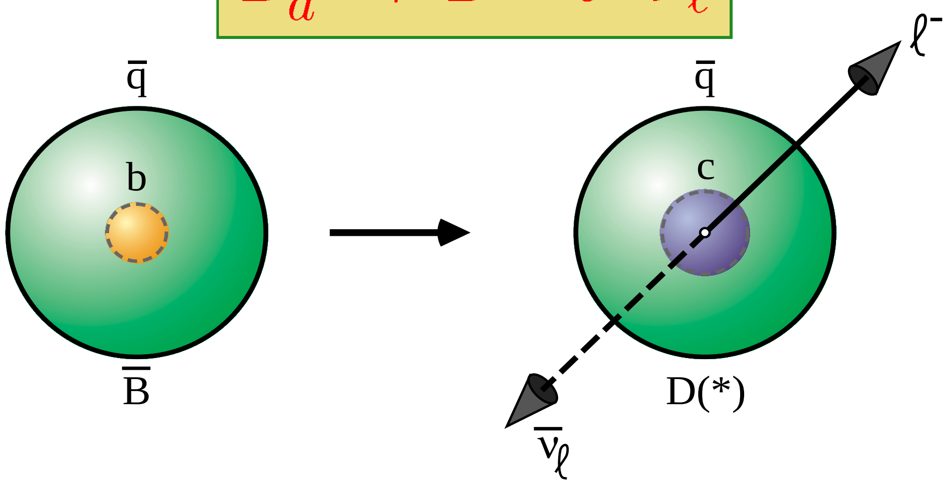
Need to separate $b \to \ell^- \mathrm{X}$ from $b \to \overset{(-)}{c} \to \overset{(-)}{\ell^+} \mathrm{X}$ and $c\overline{c}$ backgrounds.





- Measured $\mathrm{BR}(b \to \ell \mathrm{X})$ explained by Theory with a standard value for m_c and large QCD corrections.
- Uncertainty on $n_c + n_{\overline{c}}$ in b-hadron dominated by poor control of c-hadron decays.
- In 2000, $\mathrm{D_s}$, Λ_c^+, Ξ_c and Ω_c decays are still Terra Incognita .. Charm factory is needed .

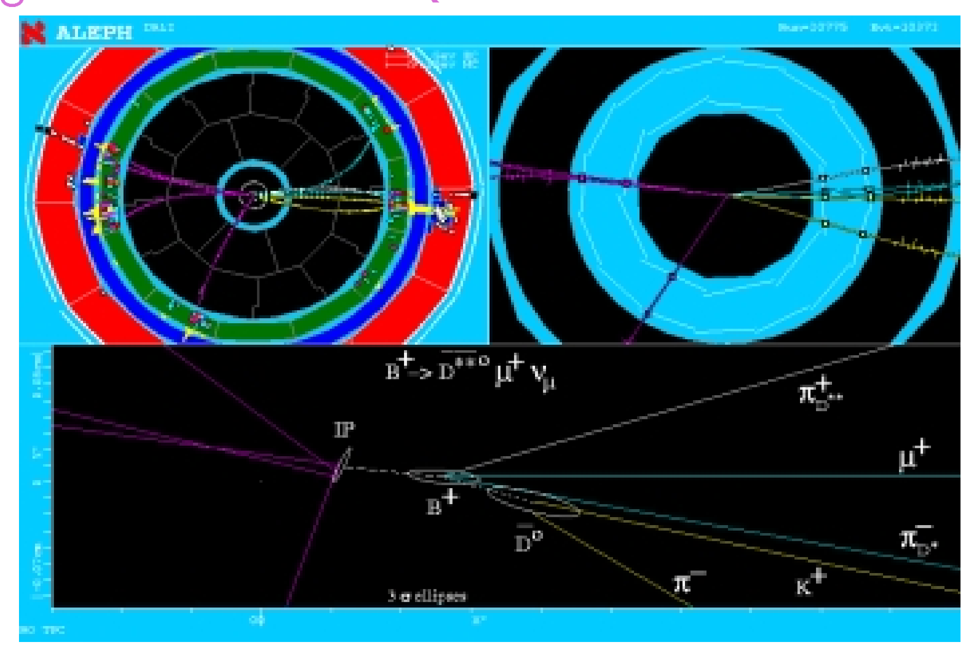
$\overline{\mathrm{B}_d^0} \rightarrow \mathrm{D}^{*+} \ell^- \overline{\nu_\ell}$



$$\frac{d(\mathrm{BR})}{dw} = \mathcal{K}(w)\mathcal{F}^2(w)\,|\mathrm{V}_{cb}|^2\,;\;\; \mathcal{F}(1) = 1 \text{ if } m_{c,b} \rightarrow \infty$$

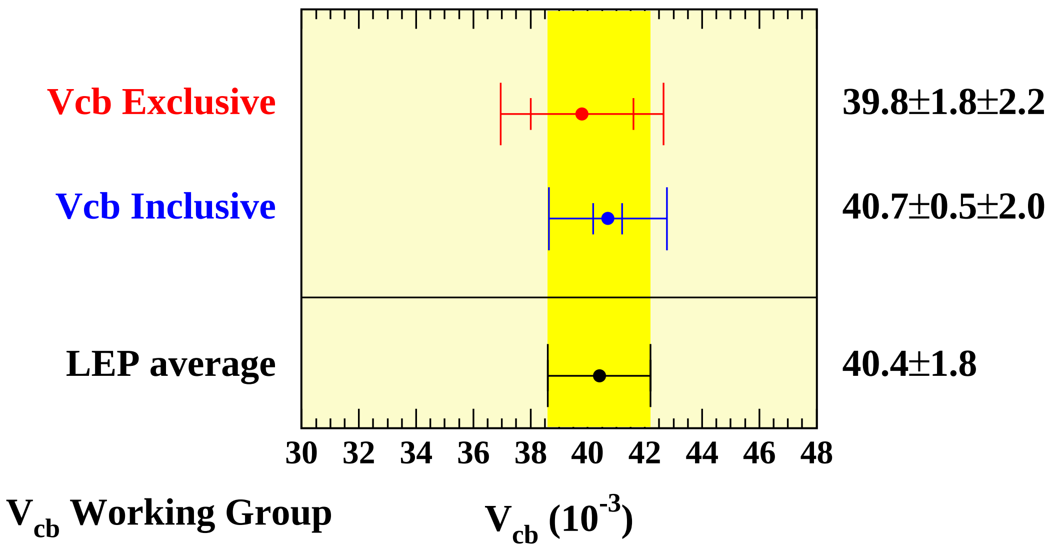
LEP results

- 4 measurements
- dedicated studies on $\mathrm{B} \rightarrow \overline{\mathrm{D}^{**}} \ell^- \overline{\nu_\ell}$, $\overline{\mathrm{D}^{**}} \rightarrow \mathrm{D}^{*+}\mathrm{X}$, large corrections to HQET.



LEP $|\mathrm{V}_{cb}|$ measurements

$$\frac{1}{\tau_{B_d}} \frac{dBR(\overline{\mathrm{B}^0_d} \rightarrow \mathrm{D}^{*+}\ell^-\overline{\nu_\ell})}{dw} = \mathcal{K}(w)\mathcal{F}^2(w)|\mathrm{V}_{cb}|^2$$



Considering only LEP measurements (uncertainties from Theory dominate):

$$|V_{cb}| = (40.4 \pm 1.8)10^{-3}$$

$$A = 0.838 \pm 0.037$$

Vub measurements

At other machines

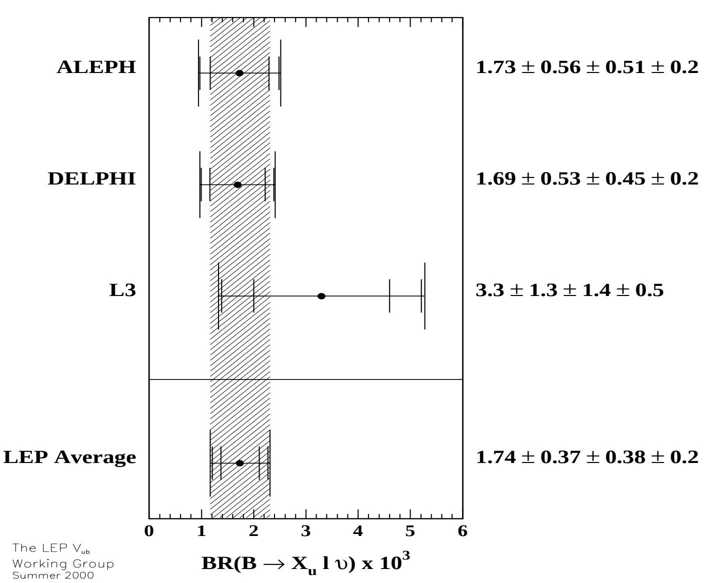
- $b \to u\ell^- \overline{\nu_\ell}$ discovery: CLEO (1990) end-point lepton energy spectrum
- exclusive $\mathrm{B} \to (\pi,\ \rho)\ell^- \overline{\nu_\ell}$ decays: CLEO (1996)

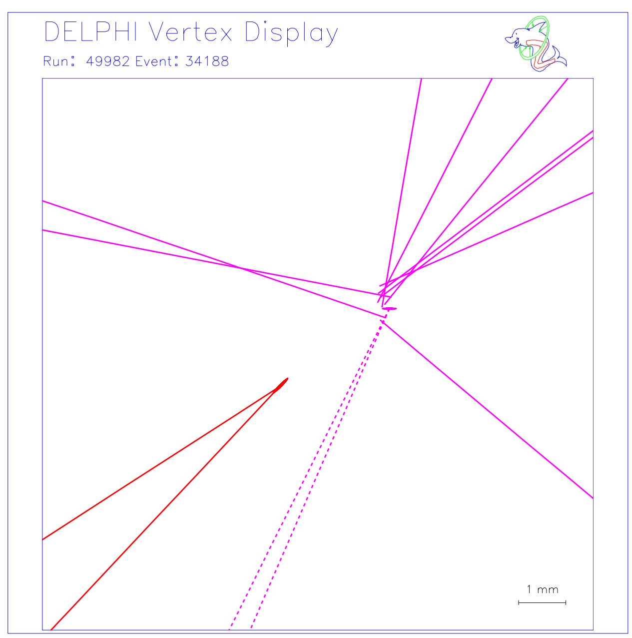
$$|\mathrm{V}_{ub}| = (3.25 \pm 0.14^{+0.21}_{-0.29} \pm 0.55) \times 10^{-3}$$

At LEP

Extremely difficult exercise at LEP because of $b \to c$ background.

$$|\mathrm{V}_{ub}| = (4.13 \pm 0.45^{+0.43}_{-0.48} \pm 0.32) \times 10^{-3}$$



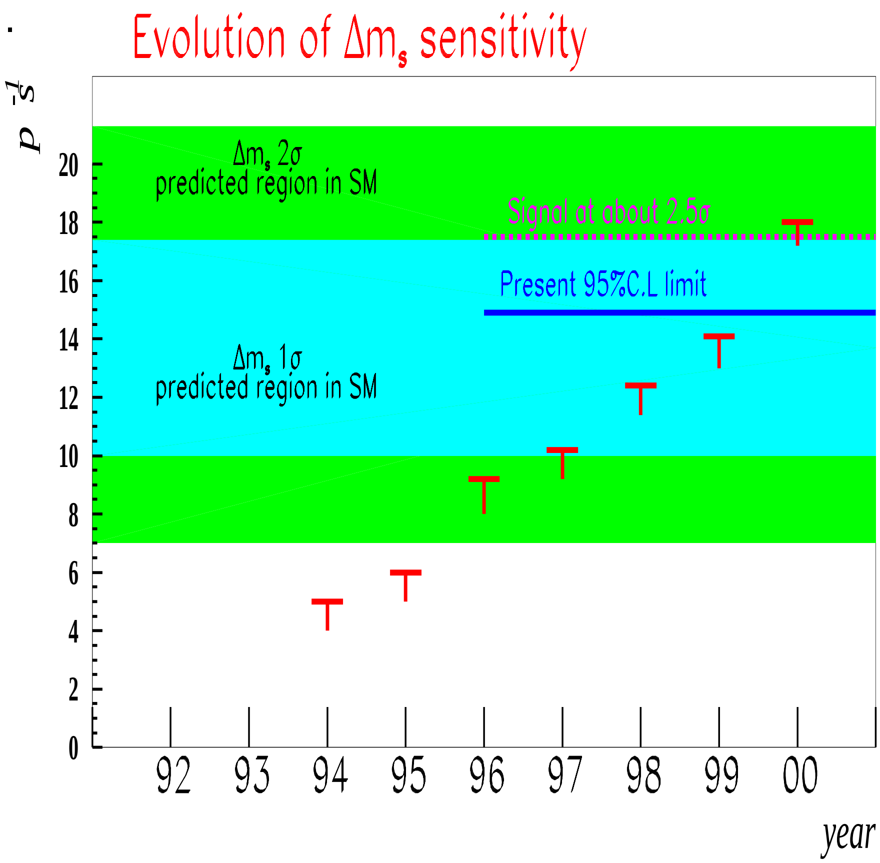


$B_s^0 - \overline{B_s^0}$ oscillations

The oscillation amplitude

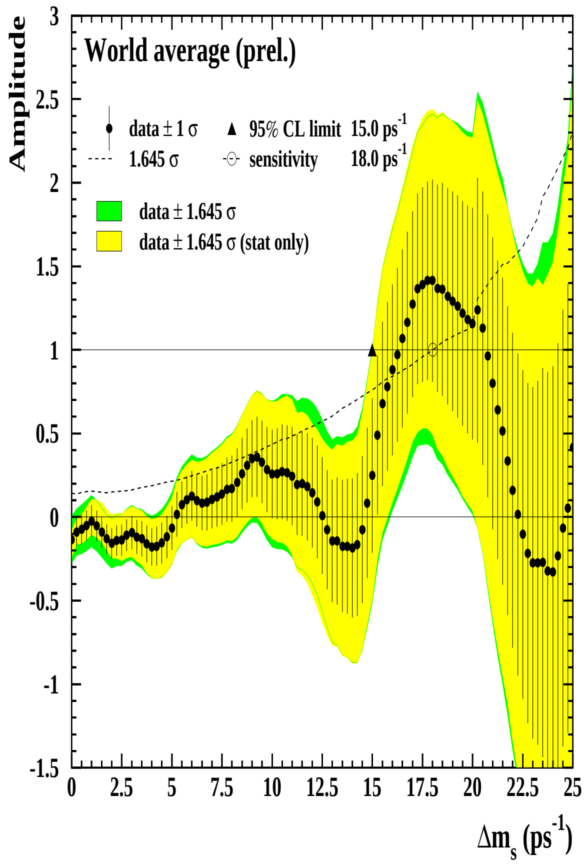
$$\mathcal{P}(B_s^0 \to \overline{B_s^0}) = \frac{1}{\tau_{B_s^0}}[1 - \mathcal{A}\cos(\Delta m_s\ t)]\exp\left(-\frac{t}{\tau_{B_s^0}}\right)$$

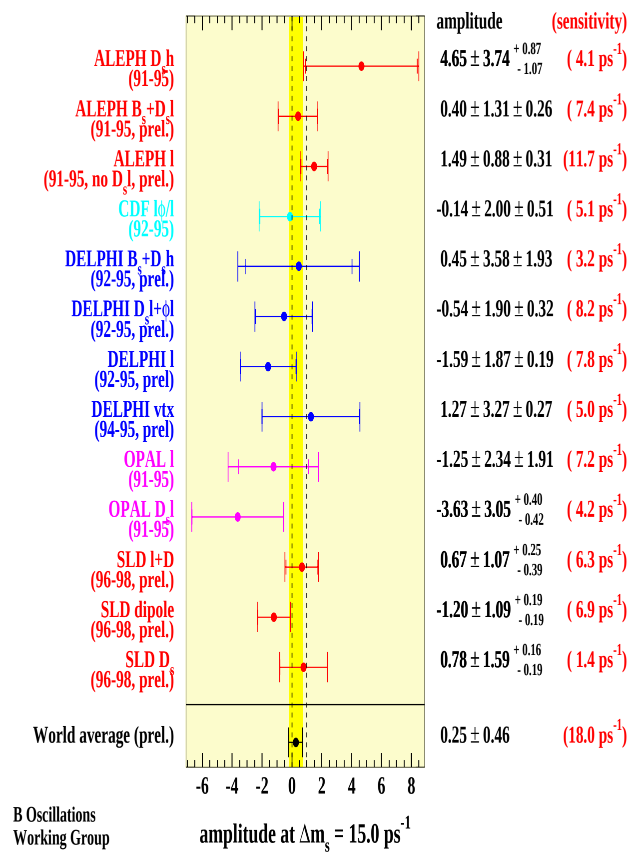
$\mathcal{A}$ is named the oscillation amplitude and its value is fitted on data.



Impressive improvements! Will they stop eventually?
Intrinsic limitation governed by VD accuracy (ultimate resolution on the B decay time)

Results in 2000





$\Delta m_s > 15.0\ \mathrm{ps}^{-1}$ at 95% C.L.

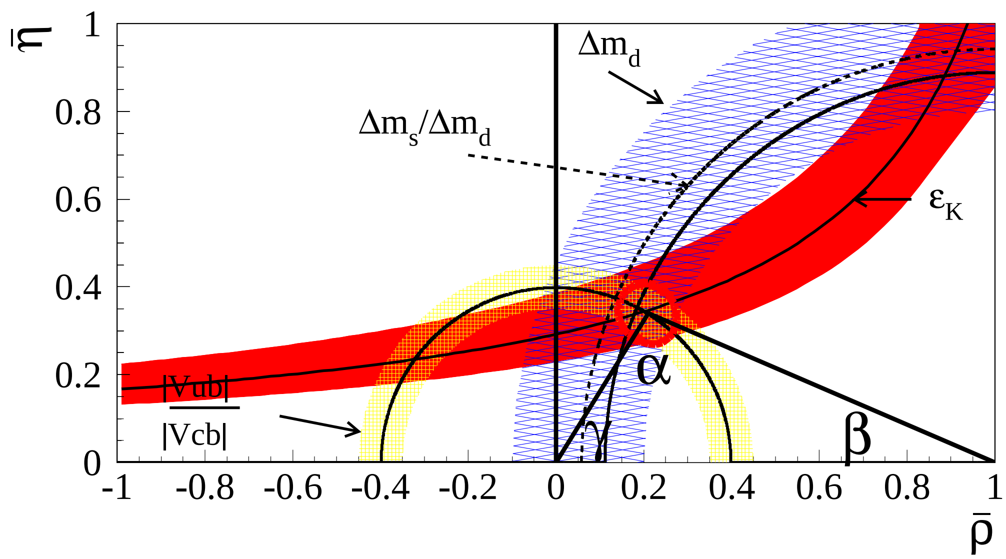
SLD has 50% weight

2.5σ effect at $17.8\ \mathrm{ps}^{-1}$

The b-CKM unitarity triangle

$$V_{ud}^* V_{ub} + V_{cd}^* V_{cb} + V_{td}^* V_{tb} = 0$$

$$\overline{AC} = \frac{1-\lambda^2/2}{\lambda} \left| \frac{V_{ub}}{V_{cb}} \right| \qquad \overline{AB} = \frac{1}{\lambda} \left| \frac{V_{td}}{V_{cb}} \right|$$

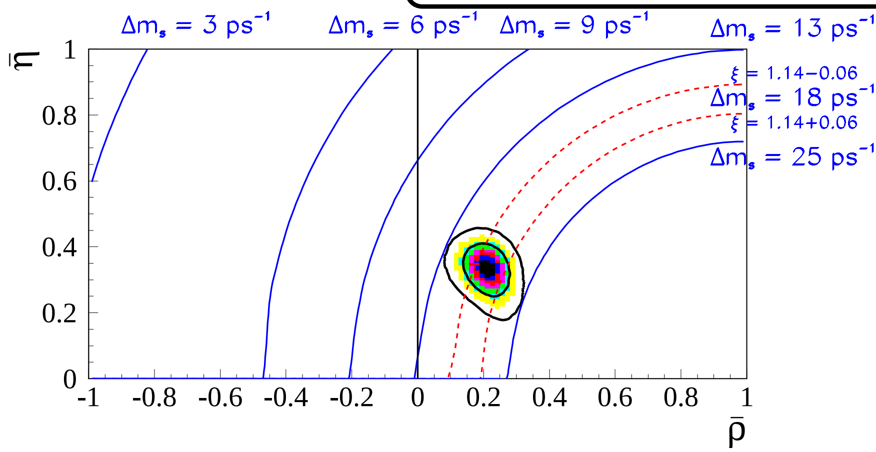


Measurement	$V_{CKM} \times$other	Constraint
$b \to u / b \to c$	$\lvert V_{ub}/V_{cb}\rvert^2$	$\bar\rho^2 + \bar\eta^2$
Δm_d	$\lvert V_{td}\rvert^2 f_{B_d}^2 \hat{B}_{B_d} f(m_t)$	$(1-\bar\rho)^2 + \bar\eta^2$
$\frac{\Delta m_d}{\Delta m_s}$	$\left\lvert \frac{V_{td}}{V_{ts}} \right\rvert^2 \frac{f_{B_d}^2 B_{B_d}}{f_{B_s}^2 \hat{B}_{B_s}}$	$(1-\bar\rho)^2 + \bar\eta^2$
ϵ_K	$f(A, \bar\eta, \bar\rho, \hat{B}_K)$	$\propto \bar\eta(1-\bar\rho)$

$\bar\rho = \rho(1-\lambda^2/2), \ \bar\eta = \eta(1-\lambda^2/2)$

SM picture of CP violation

B decays $\leftrightarrow |\epsilon_K|$



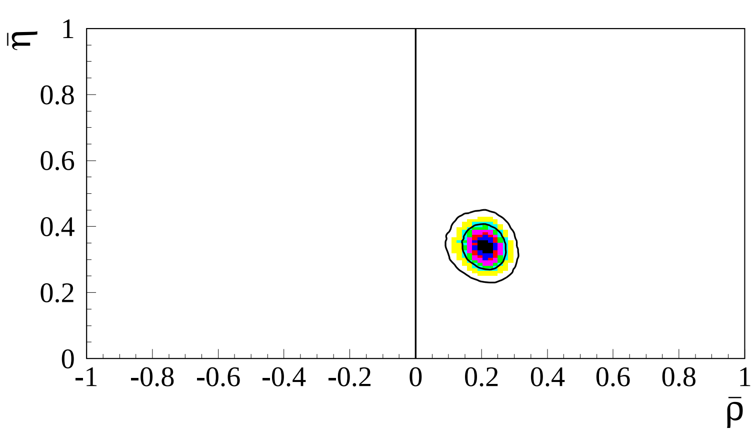
$B_K^{b-phys.} = 0.89^{+.23}_{-.19}$

$B_K(Lattice) = 0.87 \pm 0.15$

B decays + $|\epsilon_K| \leftrightarrow \sin(2\beta)$

$$\sin 2\beta = 0.72 \pm 0.07, \ \ \gamma = (59.5 \pm 6.9)^\circ$$

$$\Delta m_s = (17.3^{+1.3}_{-0.9}) \text{ ps}^{-1}, \ \ f_{B_d}\sqrt{\hat{B}_{B_d}} = (225 \pm 13) \text{ MeV}$$

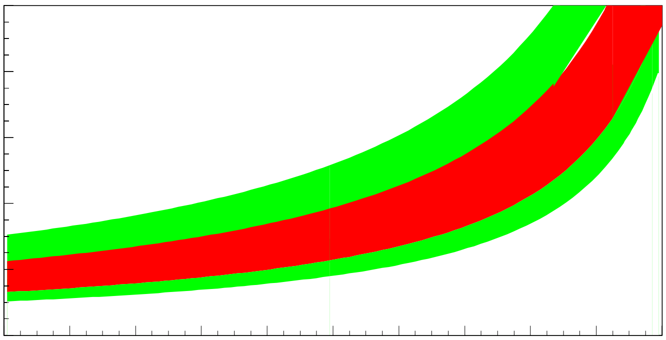


$\sin(2\ \beta)(B_d \to J/\Psi K^0_S)$

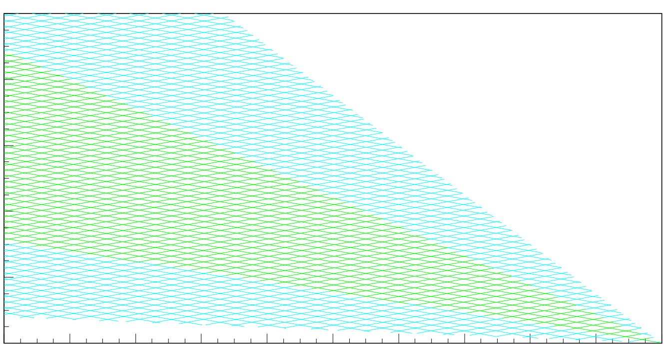
$= 0.52 \pm 0.22$

Only bands

B decays $\leftrightarrow |\epsilon_K|$



B decays + $|\epsilon_K| \leftrightarrow \sin(2\beta)$



Conclusions

Large improvements since LEP1 stops

LEP is still the main actor in:

- b-lifetimes, $\mathrm{B_d^0} - \overline{\mathrm{B_d^0}}$ oscillations, $|\mathrm{V}_{cb}|$, b-hadron rates: almost completed

1-few % accuracy on several measurements

systematics match high statistical accuracy

LEP has important contributions in:

- $|\mathrm{V}_{ub}|$: completed
- $\mathrm{B_s^0} - \overline{\mathrm{B_s^0}}$ oscillations: still in progress +SLD

exploring $\Delta m_s \sim 17\ \mathrm{ps}^{-1}$ was unexpected

Non-trivial test of SM CP violation

LEP (mainly) + m_t + Lattice QCD

B decays agree with CP violation in K physics