Final Results on Heavy Quarks at LEP and SLC

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XXX SLAC Summer Institute (August 5-16 , 2002)
Topical Conference

Selected topics :

Introduction

Example of experimental techniques

Examples of Historical evolution

Measurement of B lifetimes

*Analyses of Lifetime differences

*Semileptonic B Decays and Charm counting

Determination of $|V_{cb}|$

Determination of $|V_{ub}|$

Measurement of B oscillation frequencies

What we have learnt about the Unitarity Triangle

AVERAGES from Heavy Flavour Groups performed for Summer 2002

Flavour Physics in the *Standard Model* (SM) in the quark sector:

~ half of the *Standard Model*

10 free parameters

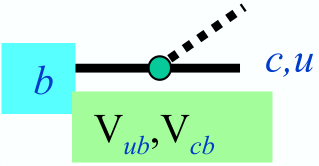
6 quarks masses

4 CKM parameters

In SM, charged weak interactions among quarks are codified in a 3 X 3 unitarity matrix : the **CKM Matrix**.

$$\begin{array}{c|ccc} & d & s & b \\ \hline u & \mathbf{1-\lambda^2/2} & \lambda & \mathbf{A\,\lambda^3(\rho-i\eta)} \\ c & -\lambda & \mathbf{1-\lambda^2/2} & \mathbf{A\lambda^2} \\ t & \mathbf{A\,\lambda^3(1-\rho-i\eta)} & \mathbf{-A\lambda^2} & \mathbf{1} \end{array}$$

V_{tb}

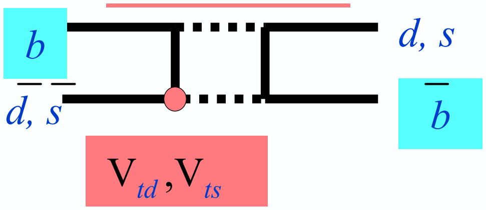


B decays

Wolfenstein parametrization

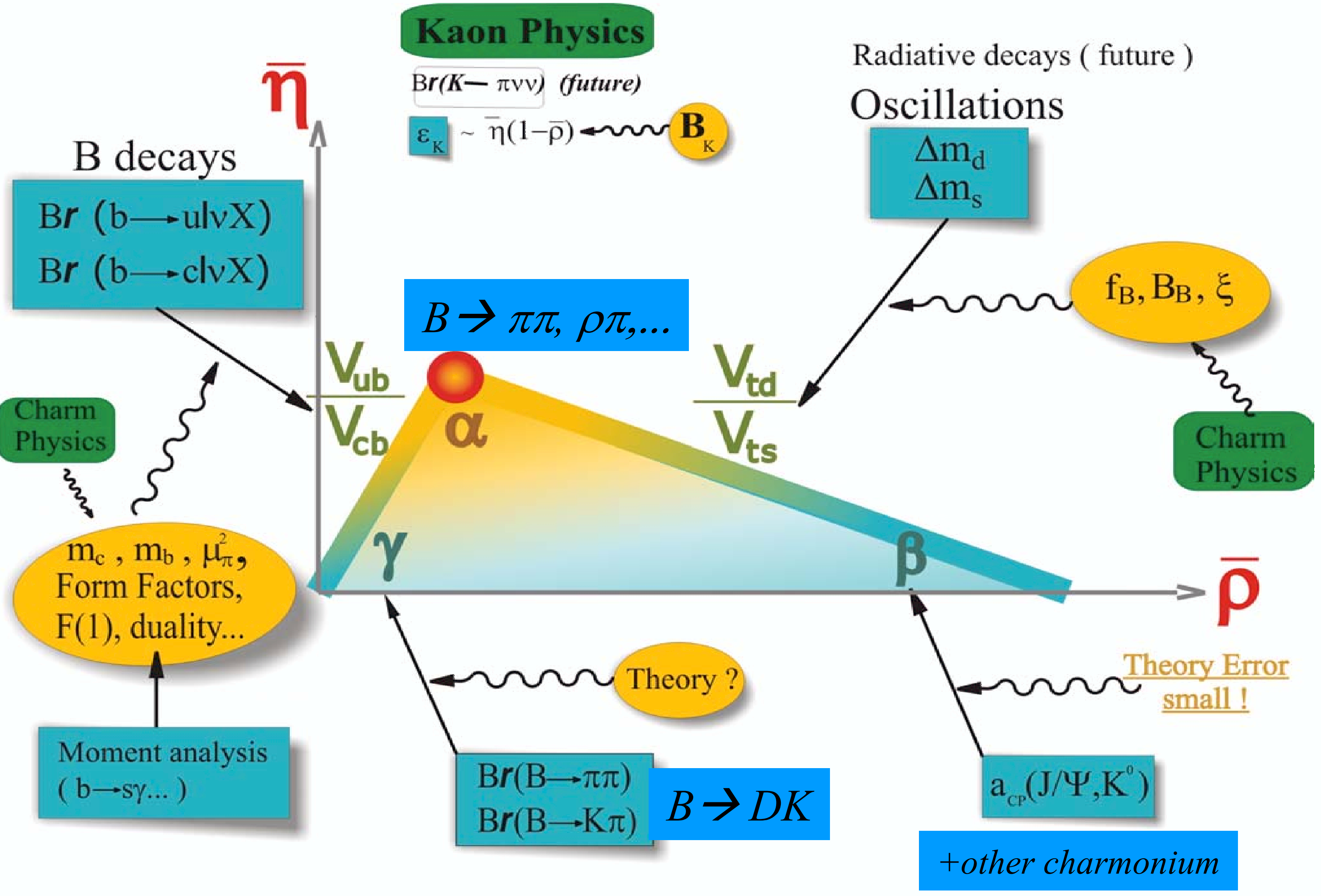
4 parameters : λ ,**A**, ρ, η

B Oscillations



Visualization of the unitarity of the CKM matrix

Unitarity **Triangle** in the **(ρ−η) plane**



B → ππ, ρπ,…

B → DK

+other charmonium

LEP, SLC
+CLEO and CDF

Played a central role in measuring the sides of the UT

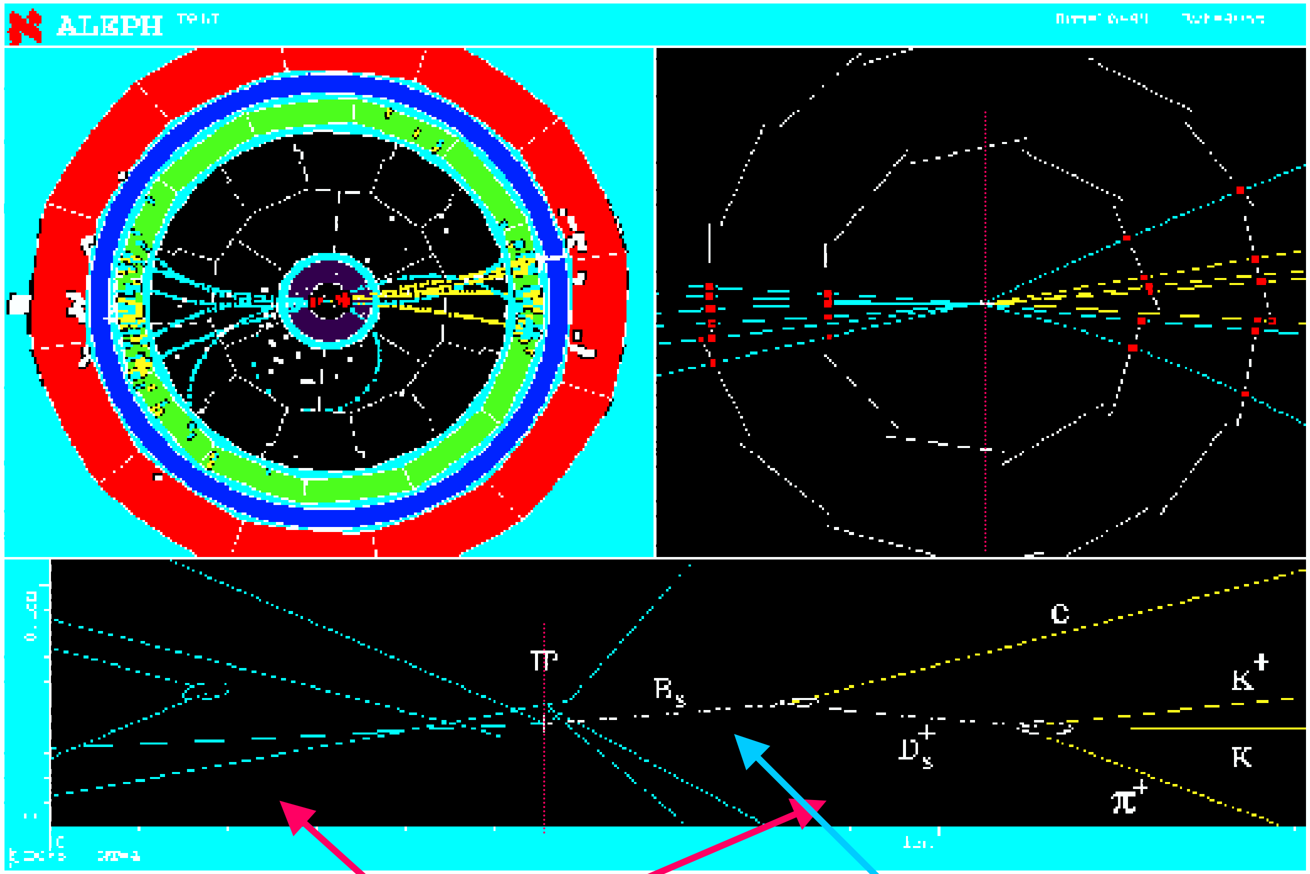
theory gives us the link from quarks to hadrons

OPE /HQET/Lattice QCD …. **Need to be tested**

Using many others important measurements as :
Lifetimes, Branching ratios, From Factors, Masses…

Example of experimental techniques

$\sigma(Z^0 \rightarrow \text{hadrons}) \sim 30\text{nb}$, $\Gamma(b\bar{b}) / \Gamma(\text{hadr}) \sim 22\%$



Jetty-like events

L~γβcτ ~ 3mm

τ(B)~1.6ps

E(B) ~ 0.7E(beam)~35GeV

TAGGING b-hadrons

b ⇔ non-b

- displaced vertices
- leptons

$b \Leftrightarrow \bar{b}$

- jet charge
- fragments products

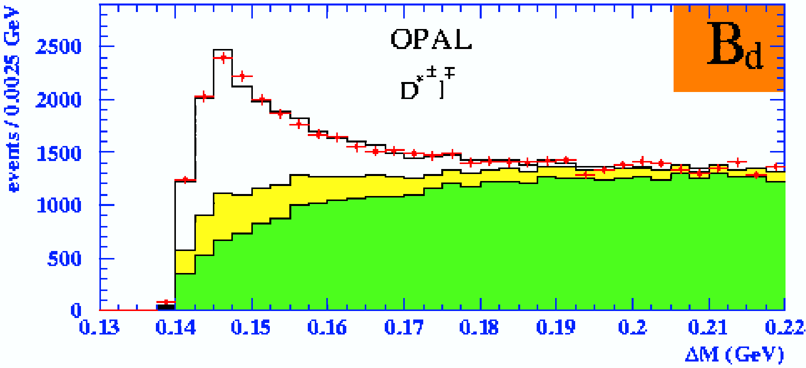
$B \Leftrightarrow \bar{B}$

- leptons
- D mesons

$B_i \Leftrightarrow B_j$

- semileptonic decays
- fragments products

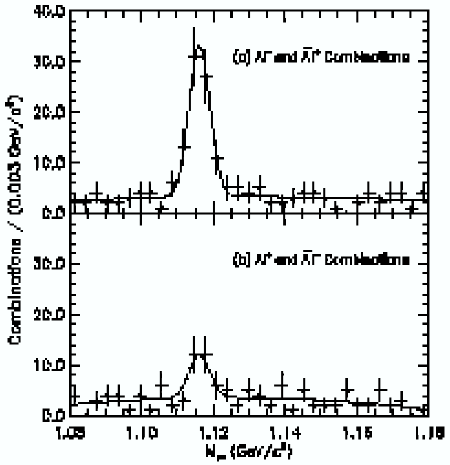
example



Examples of Historical evolution

b-baryon signals
1990 : ALEPH

Excess of Λ-l^- events
(as compared to Λ-l^+)
(and charge conjugate final states)



b-baryons in 2002

B-baryons observed using
(Λ,p, Λ_c^+,Ξ)-l events

The b-baryon rate in jets is :
f(b-baryons) = (10.5 ± 1.8)%

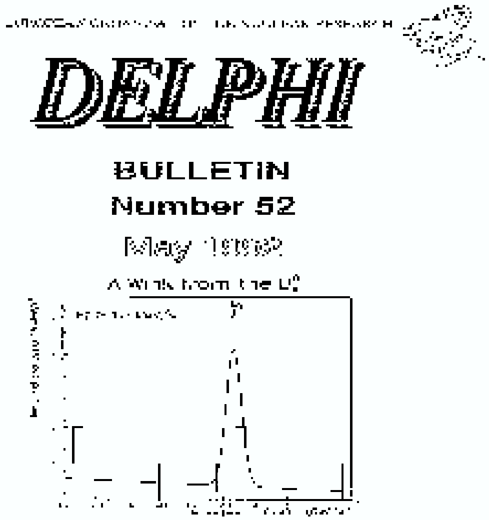
The b-quark polarization (-0.94) is diluted :
Pol(Λ_b) = –0.45 +0.19(– 0.17)

Λ_b lifetime : **τ(Λ_b) = 1.208 ± 0.051 ps**

Λ_b mass : **m(Λ_b) = 5624±9 MeV**

B^0_s signals
1992 : DELPHI

Excess of D^+_s-l^- events
(as compared to D^+_s-l^+)



DELPHI

BULLETIN
Number 52
May 1992

A Wink from the B^0_s

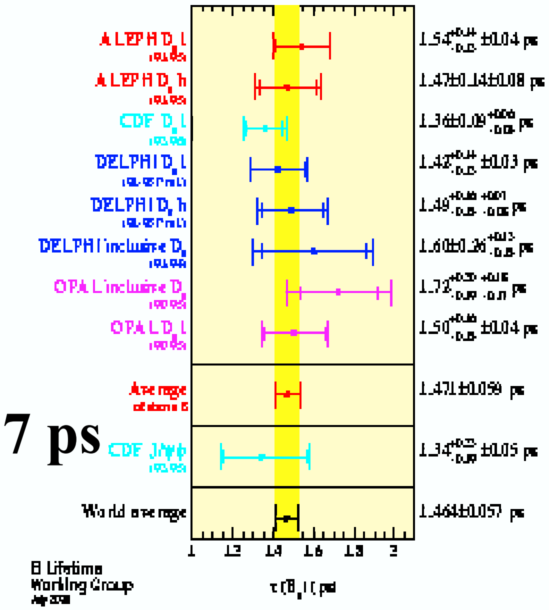
7 events : $\overline{\mathbf{B^0}}_s \rightarrow D^+_s\, l^-\ \bar{\nu}\ X$…..

Before :
UA1(1987): same sign dileptons from B oscillations
CUSB Υ(5S) (1990) : evidence of B^*_s from Doppler effect

B^0_s in 2002

B^0_s observed mainly using
D_s-l^- events

B^0_s rate in jets is :
$\mathbf{f(B^0_s) = (9.3 \pm 1.1)\%}$



B^0_s lifetime :
$\mathbf{\tau(B^0_s) = 1.461\ \pm\ 0.057\ ps}$

B^0_s mass : $\mathbf{m(B^0_s) = 5369.6 \pm 2.4\ MeV}$

B^0_s oscillations : $\mathbf{\Delta m_s > 14.4\ ps^{-1}}$

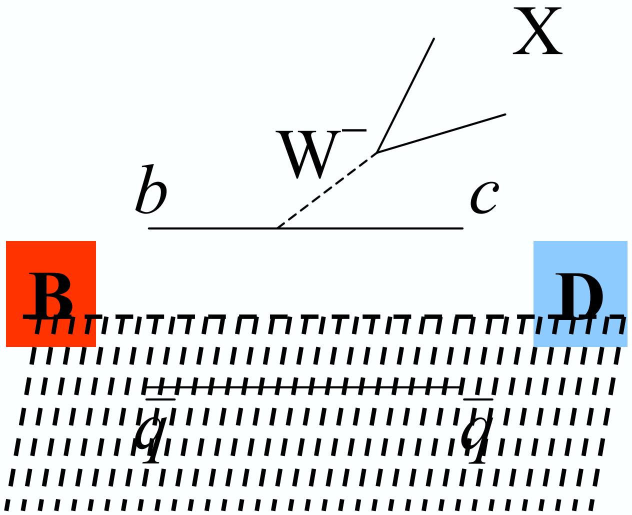
Lifetime difference:
$\mathbf{\Delta\Gamma/\Gamma < 0.31}$ **@ 95% C.L.**

Interest of measuring the Lifetimes

$$\Gamma(H) = \Gamma_{spect} + O(1/m_b^2) + \Gamma(P.I., W.A, W.S) + O(1/m_b^4)$$

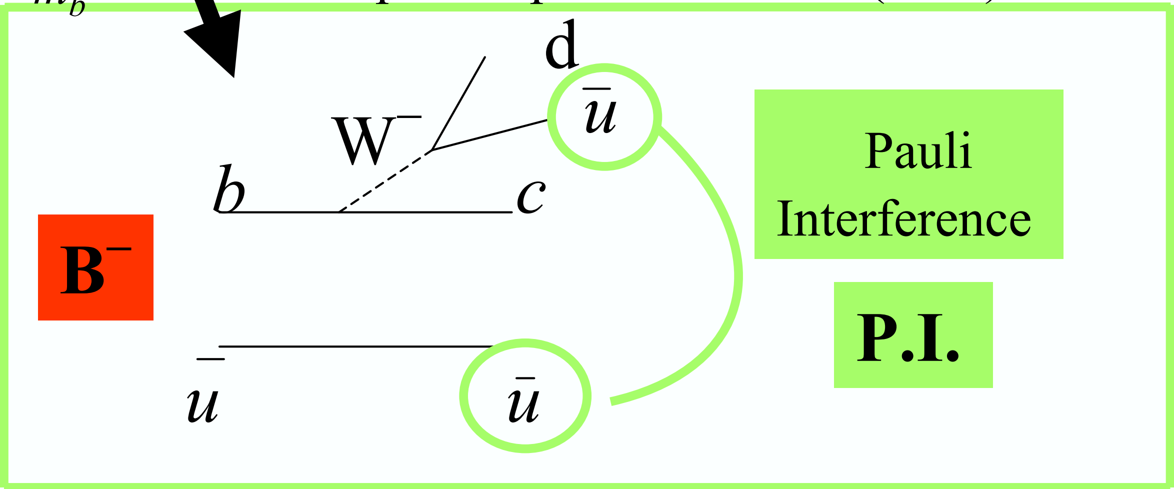
$$\frac{\tau(\text{P.I.}, \text{W.A}, \text{W.S})}{\tau(spect)} \approx \frac{f_B^2}{m_b^2}$$

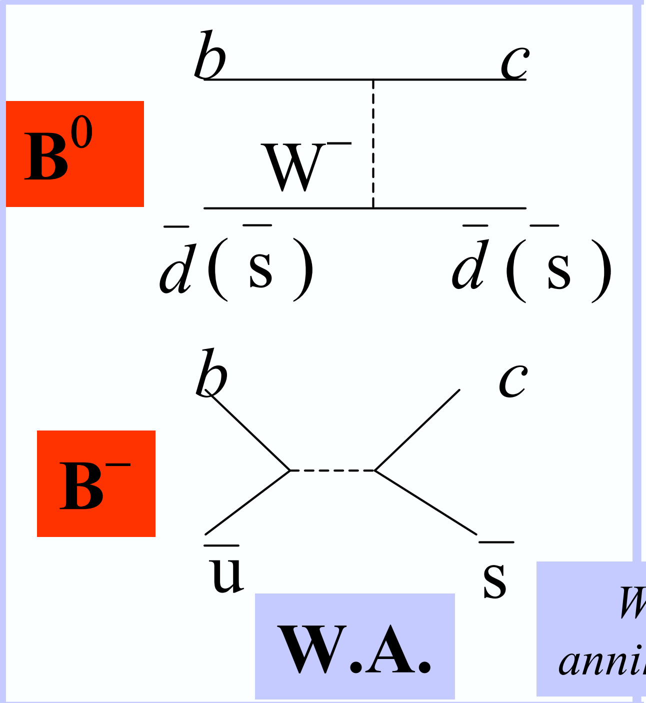
Spectator effects are at order $O(1/m_b^3)$
but phase space enhanced $(16\pi^2)$



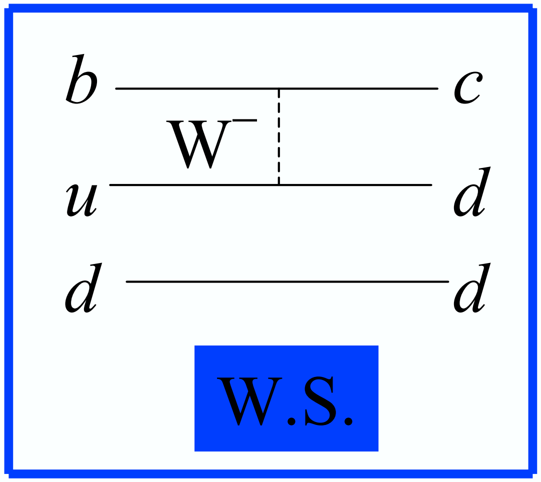
If this were the only diagram all the B/D hadron lifetimes would be the same.

Important test of B decay dynamics (OPE)





Weak annihilation



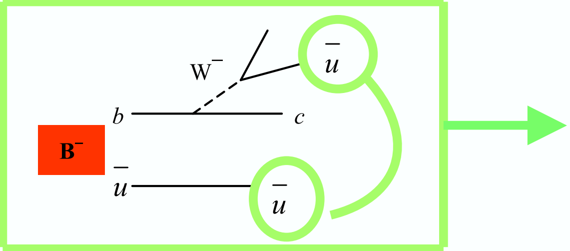
Results on B Lifetimes

Averages from LEP/SLD/Tevatron

$\tau(B^0_d)$ = 1.540 ± 0.014 ps (0.9%)
$\tau(B^+)$ = 1.656 ± 0.014 ps (0.8%)
$\tau(B^0_s)$ = 1.461 ± 0.057 ps (3.9%)
$\tau(\Lambda_B)$ = 1.208 ± 0.051 ps (4.2%)

+ B-Factories

$\tau(b)$ = 1.573 ± 0.007 ps (0.4%)

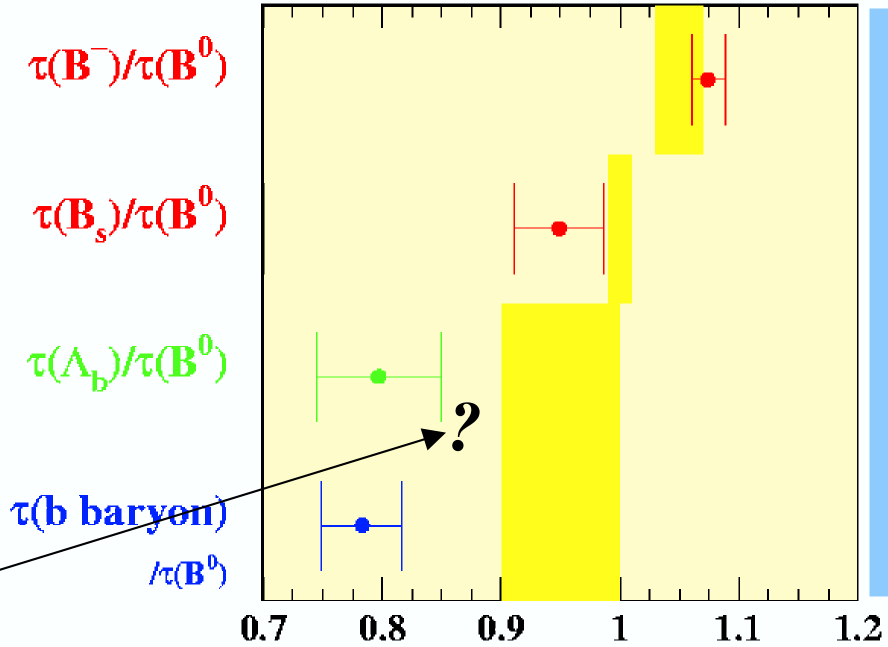


$\tau(B^+)/\tau(B^0)$ about 5σ effect
in agreement with theory

Λ_B Lifetime shorter
Because of W.A.

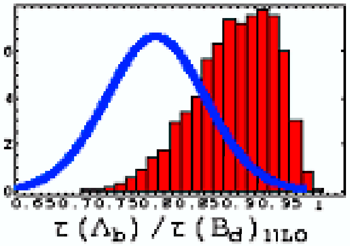
But the experimental result says the effect is more important

Is there a problem for Λ_B ?



1.073 ± 0.014
0.949 ± 0.038
0.797 ± 0.052
0.784 ± 0.034

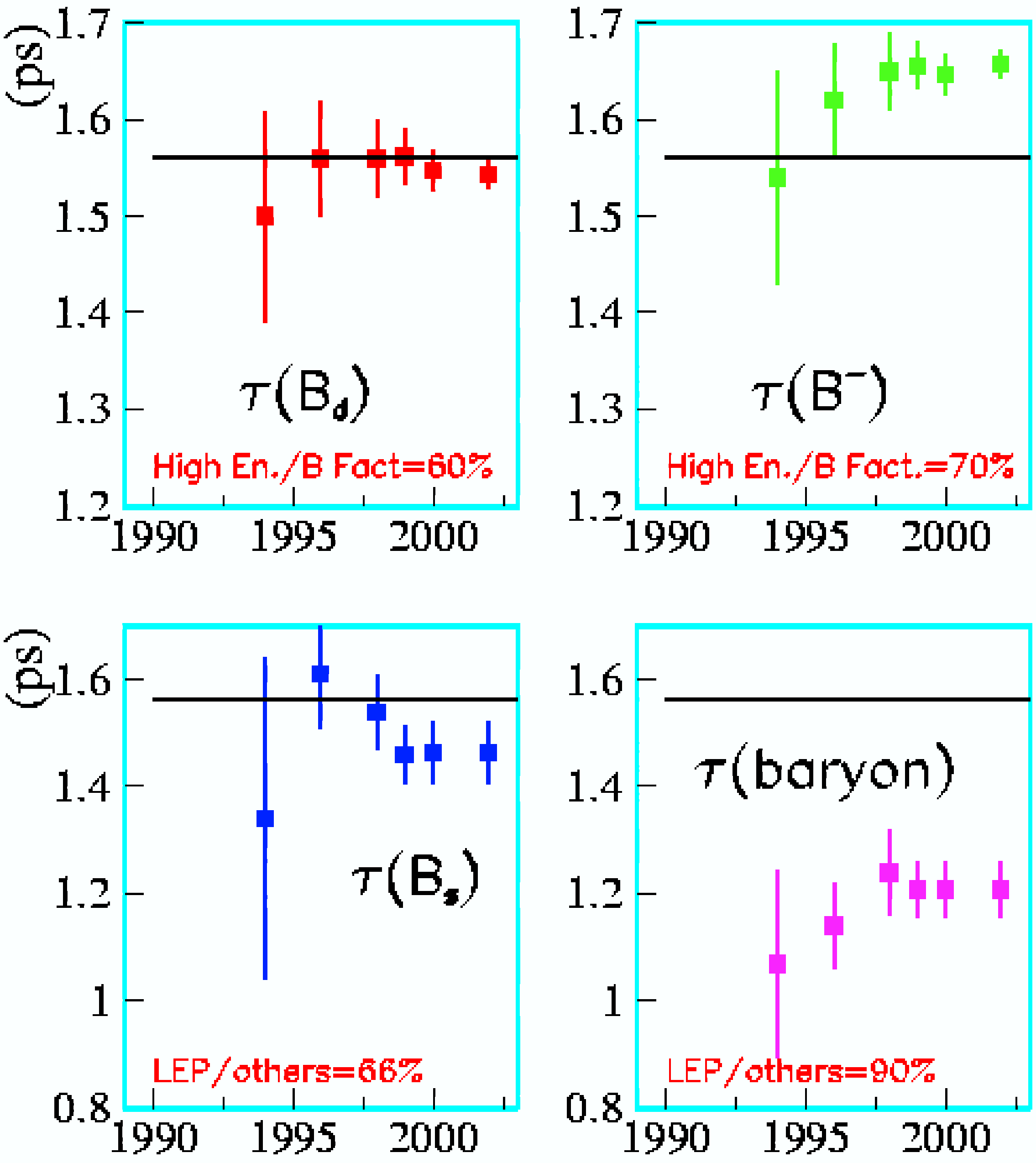
LIFETIME Working Group



RECENT calculations are able to explain lower values

Franco,Lubicz,Mescia,Tarantino

B Hadron Lifetimes History



Expected Improvements

$\tau(B^+)/\ \tau(B^0)$

Already very precise !

improvements from B-factories

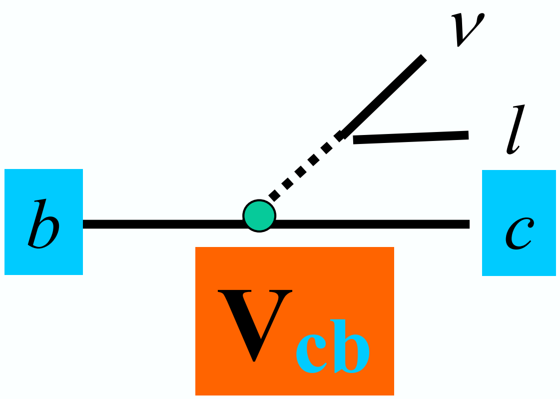
But more important

$\tau(B^0_s)$ and $\tau(\ \Lambda_B\ )$ …. and Ξ_B B_c, Ω_c

from Tevatron

Determination of V_{cb}

Inclusive Method



$$\Gamma_{sl}(b \to c l^- \nu) \overset{theo.}{=} \boxed{|V_{cb}|^2}\ F \overset{exp.}{=} \frac{Br_{sl}}{\tau_b}$$

$$\boxed{f(\mu^2_\pi, m_b, \alpha_s, \rho_D(\text{or } 1/m_b^3))}$$

$\boxed{m_b}$ $\boxed{(\text{ also named } \overline{\Lambda})}$ $\boxed{\mu^2_\pi}$ $\boxed{(\lambda_1 \text{ Fermi movement})}$

*Based on **OPE***

$$\Gamma_{sl} = (0.431 \pm 0.008 \pm 0.007)\ 10^{-10}\ MeV \quad Y(4S)$$

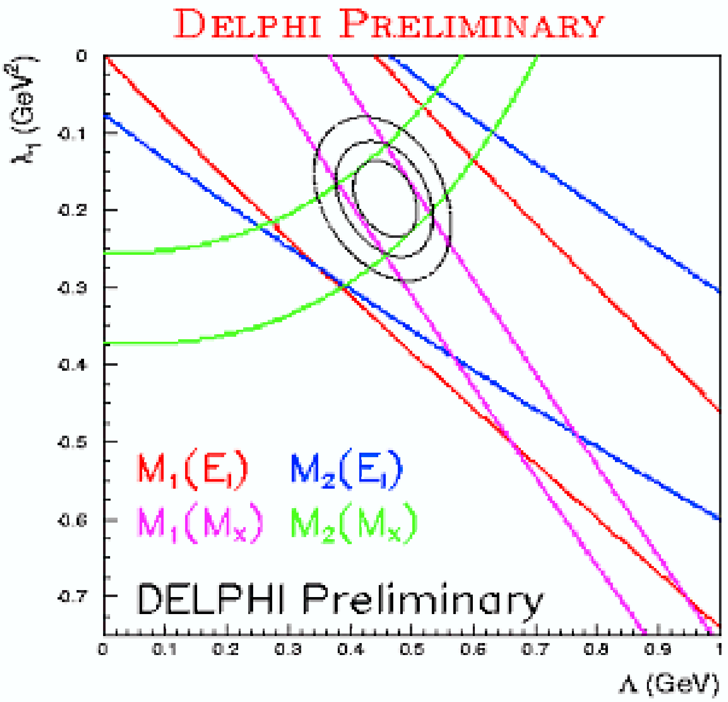
$$\Gamma_{sl} = (0.439 \pm 0.010 \pm 0.007)\ 10^{-10}\ MeV \quad LEP$$

$$\Gamma_{sl} = (0.434 \times (1 \pm 0.018))\ 10^{-10}\ MeV$$

at 2% precision

→Determination of V_{cb} limited by theoretical uncertainties …..

Measurement of the moments of the distributions of the HADRONIC MASS and LEPTON MOMENTUM



$\bar{\Lambda}$=(0.44±.04±.05±.07) GeV
λ_1=(-0.23±.04±.05±.08) GeV^2

Compatible with CLEO result :

$\bar{\Lambda}$=(0.39±.03±.06±.12) GeV
λ_1=(-0.25±.02±.05±.14) GeV^2

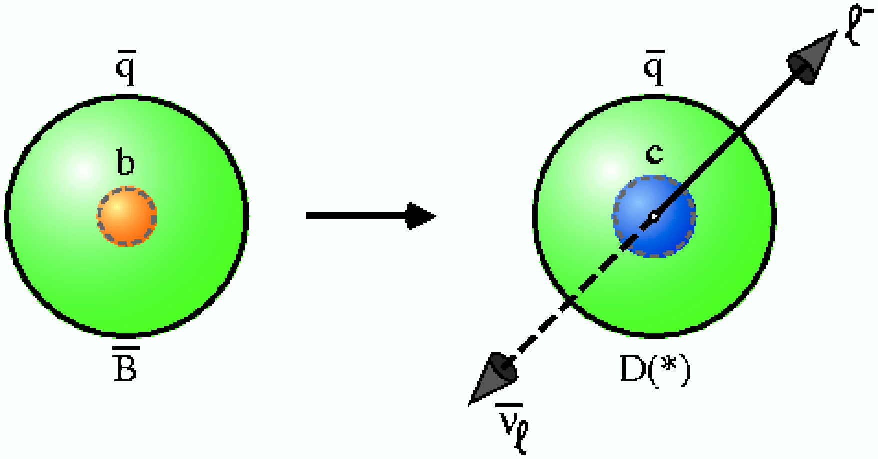
V_{cb}(inclusive)= (40.7 ± 0.6 ± 0.8(theo.)) 10^{-3}

V_{cb} Working Group

Caveat : control of power corrections $1/m_b^3$

Exclusive method

Based on ***HQET***



$$\frac{d\Gamma}{dw} = \frac{G_F^2}{48\pi^2} \; |V_{cb}|^2 \; |F(w)|^2 \; G(w)$$

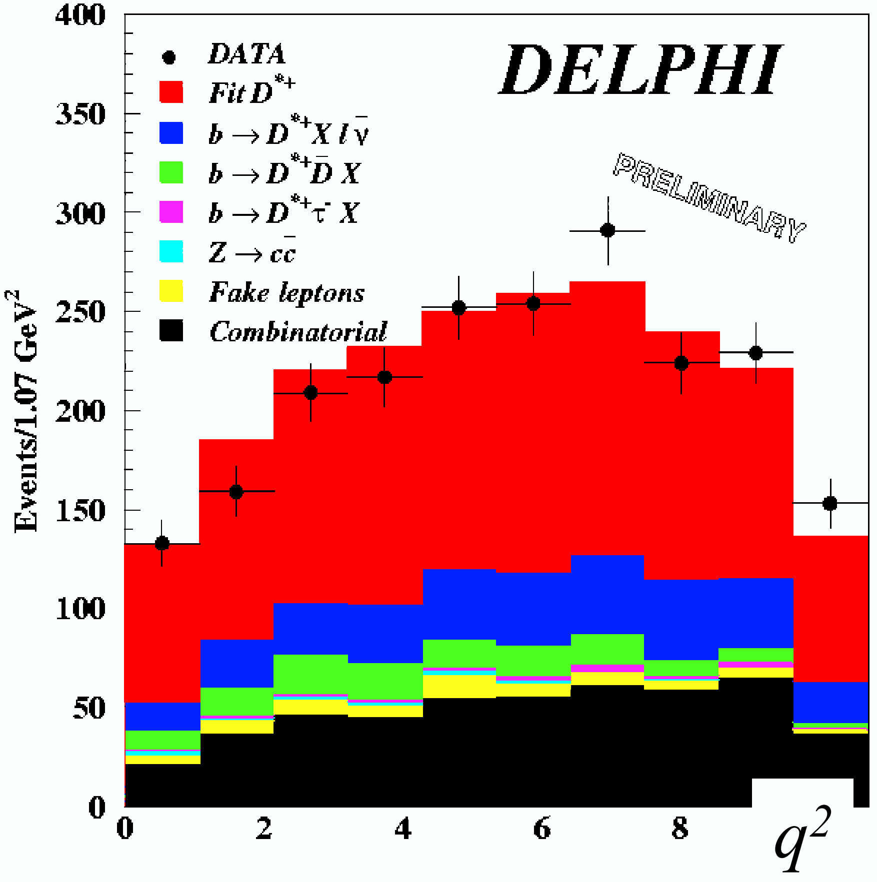
$$w = v_B . v_{D^{(*)}}$$

$$w = \frac{m_{D*}^2 + m_B^2 - q^2}{2 m_{D*} m_B}$$

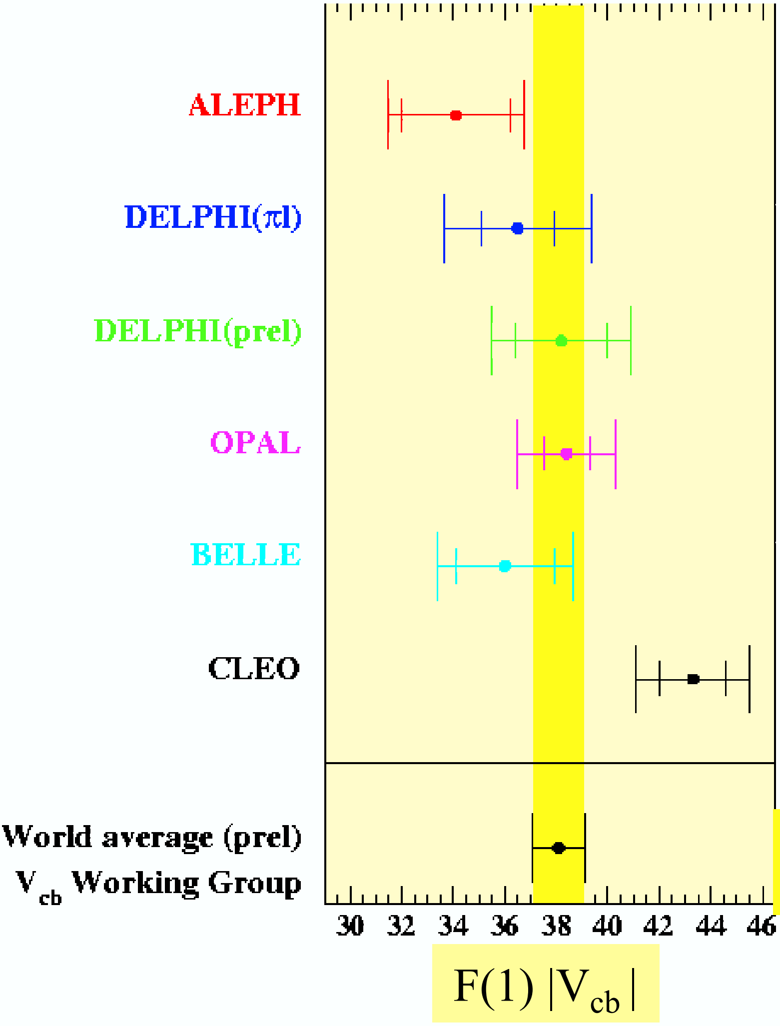
F(w) is the form factor describing the B→ D* transition

At zero recoil (w=1), as M_Q → ∞ F(1) → 1

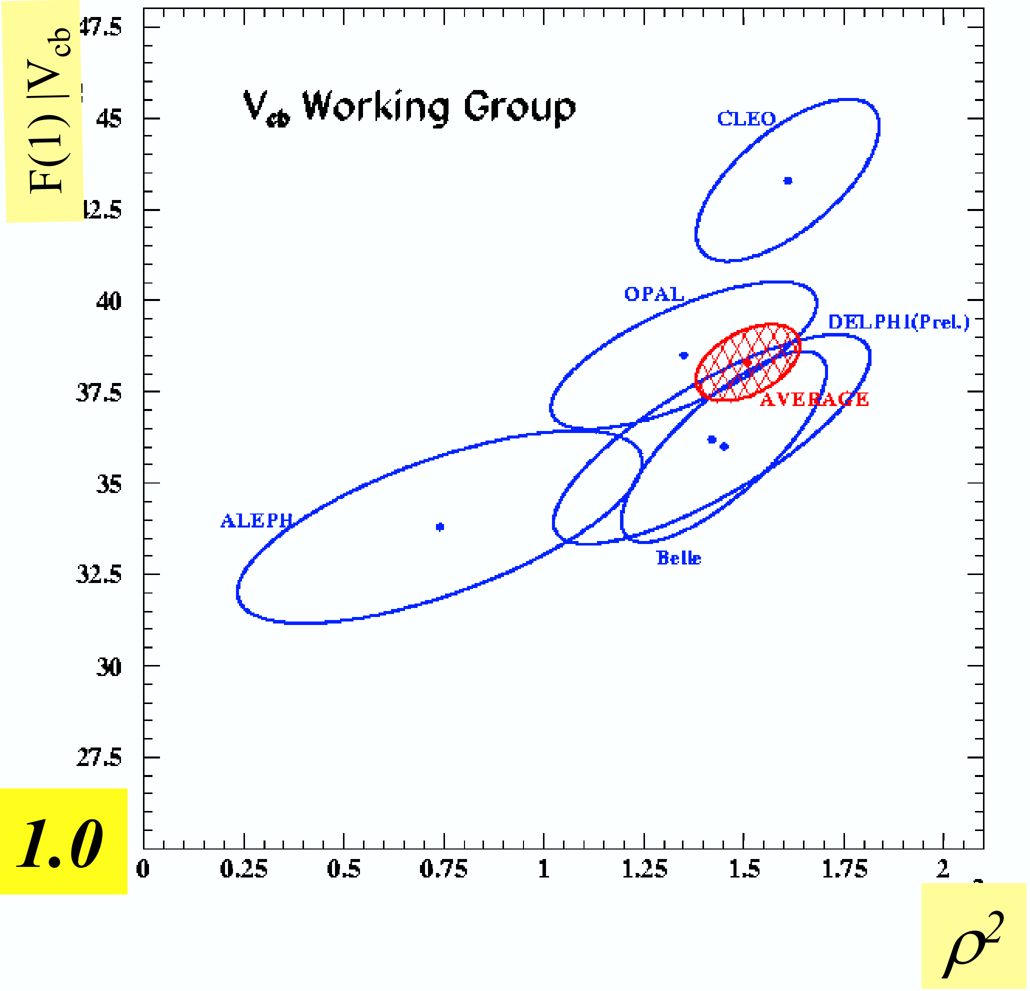
Strategy : Measure dΓ/dw extrapolate to w=1 to extract F(1) |V_{cb}|



($1 \leftarrow w \; 0 \leftarrow q^2$)



38.1 ± 1.0



F(1) = 0.91 ± **0.04**

V_{cb}(exclusive)= (41.9 ± 1.1 ± 1.9) 10^{-3}

V_{cb}(inclusive)= (40.7 ± 0.6 ± 0.8) 10^{-3}

V_{cb} = (40.9 ± 0.8) 10^{-3}

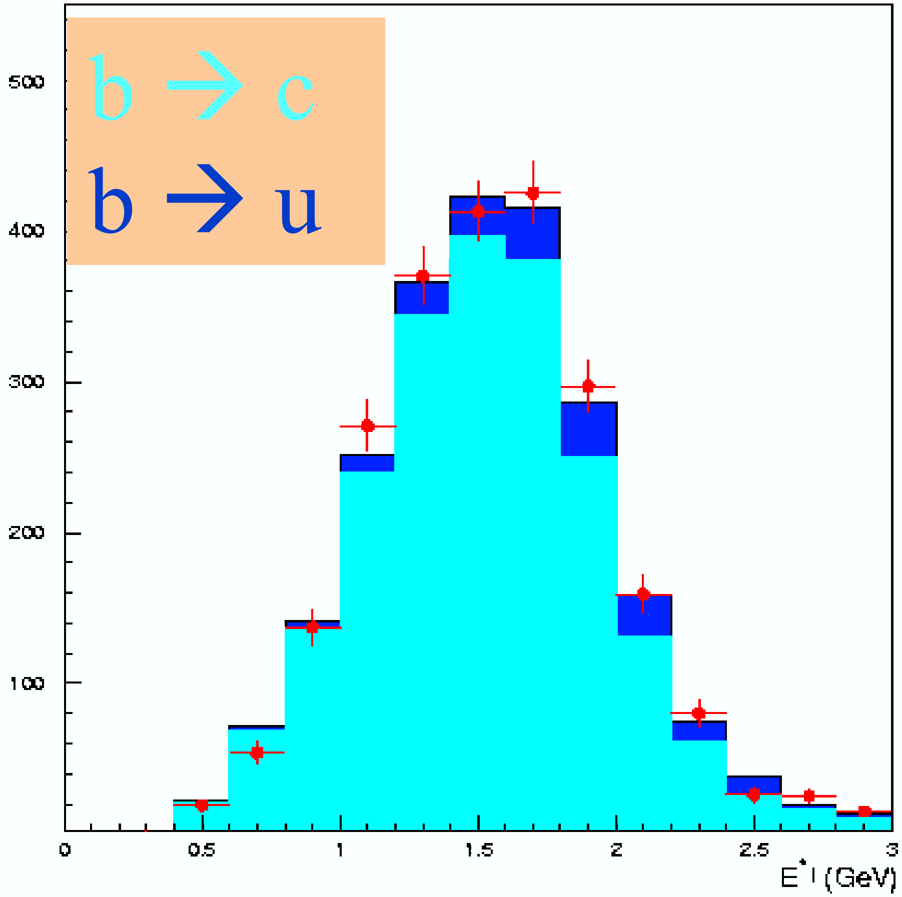
A.S. average

V_{ub}

Inclusive determination of Vub

Challenge measurement
from LEP

Using several discriminant variables to distinguish between the transitions :



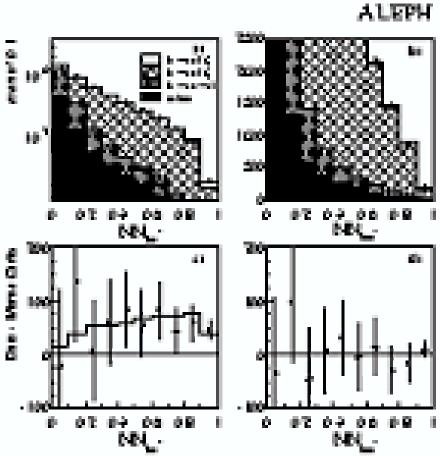
$B \rightarrow X_u \, l \, \nu$

Inclusive $b \to X_u \ell \bar{\nu}$ at LEP

Results from all the LEP experiments

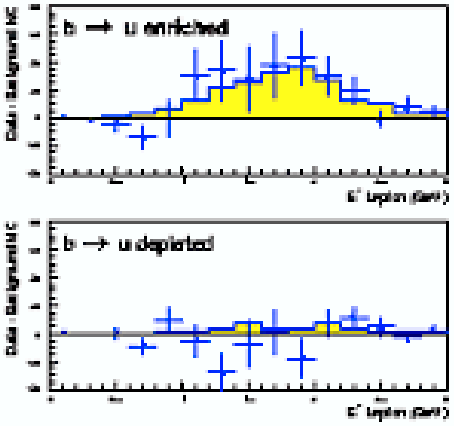
ALEPH
EPJ C6 (1999)

NN Selection
Fit NN Output
Eff = 11%, S/B = 0.07



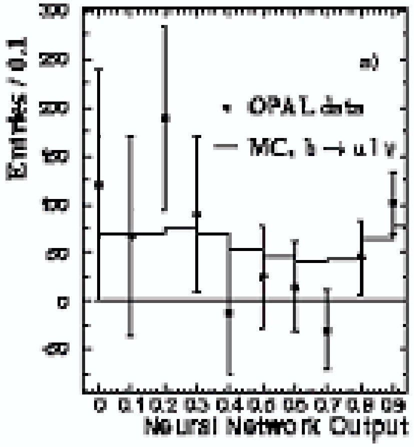
DELPHI
PLB B478 (2000)

M_X Incl.
Fit E_ℓ^* for $M \lesssim 1.6$
Eff = 6.5%, S/B = 0.10



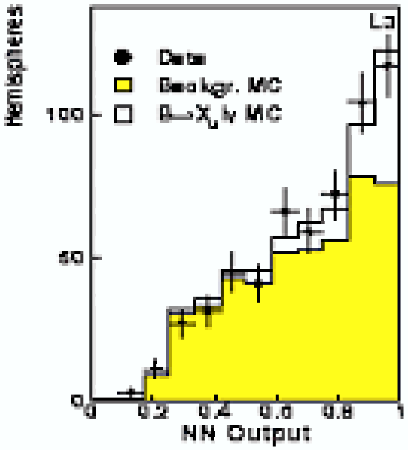
OPAL
EPJ C21 (2001)

NN Selection
Fit NN Output
Eff = 4.2, S/B = 0.05

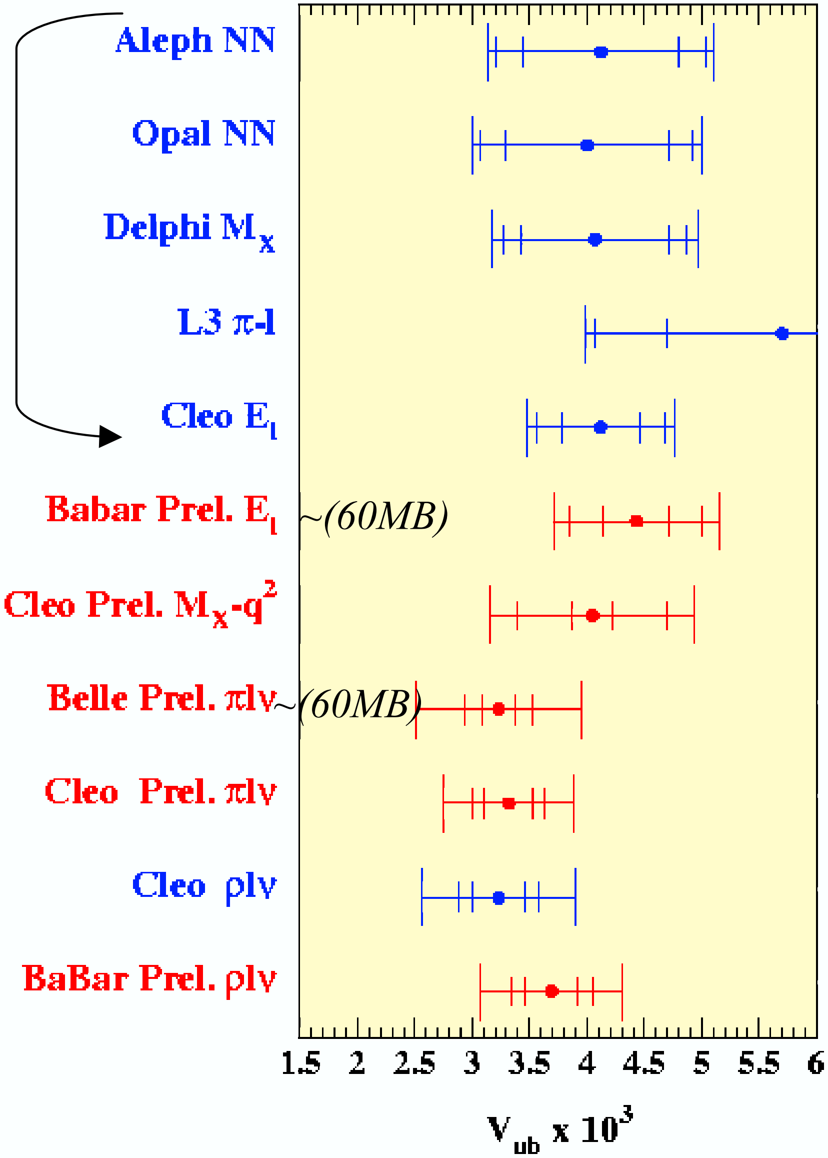


L3
PLB B436 (1998)

Kinematic Selection
Counting Expt
Eff = 1.5%, S/B = 0.16



V_{ub} Summary



$4.12 \pm 0.67 \pm 0.62 \pm 0.35$

$4.00 \pm 0.71 \pm 0.59 \pm 0.40$

$4.07 \pm 0.65 \pm 0.47 \pm 0.39$

$5.7 \pm 1.0 \pm 1.3 \pm 0.5$

$4.12 \pm 0.34 \pm 0.44 \pm 0.33$

$4.43 \pm 0.29 \pm 0.50 \pm 0.43$

$4.05 \pm 0.18 \pm 0.63 \pm 0.60$

$3.23 \pm 0.14 \pm 0.26 \pm 0.65$

$3.32 \pm 0.21 \pm 0.23 \pm 0.47$

$3.23 \pm 0.23 \pm 0.25 \pm 0.58$

$3.69 \pm 0.23 \pm 0.27 \pm 0.50$

INCLUSIVE

EXCLUSIVE

At the CKM Workshop (LEP+End-Point CLEO)

V_{ub}(inclusive) = $(4.09 \pm 0.46 \pm 0.36)\ 10^{-3}$

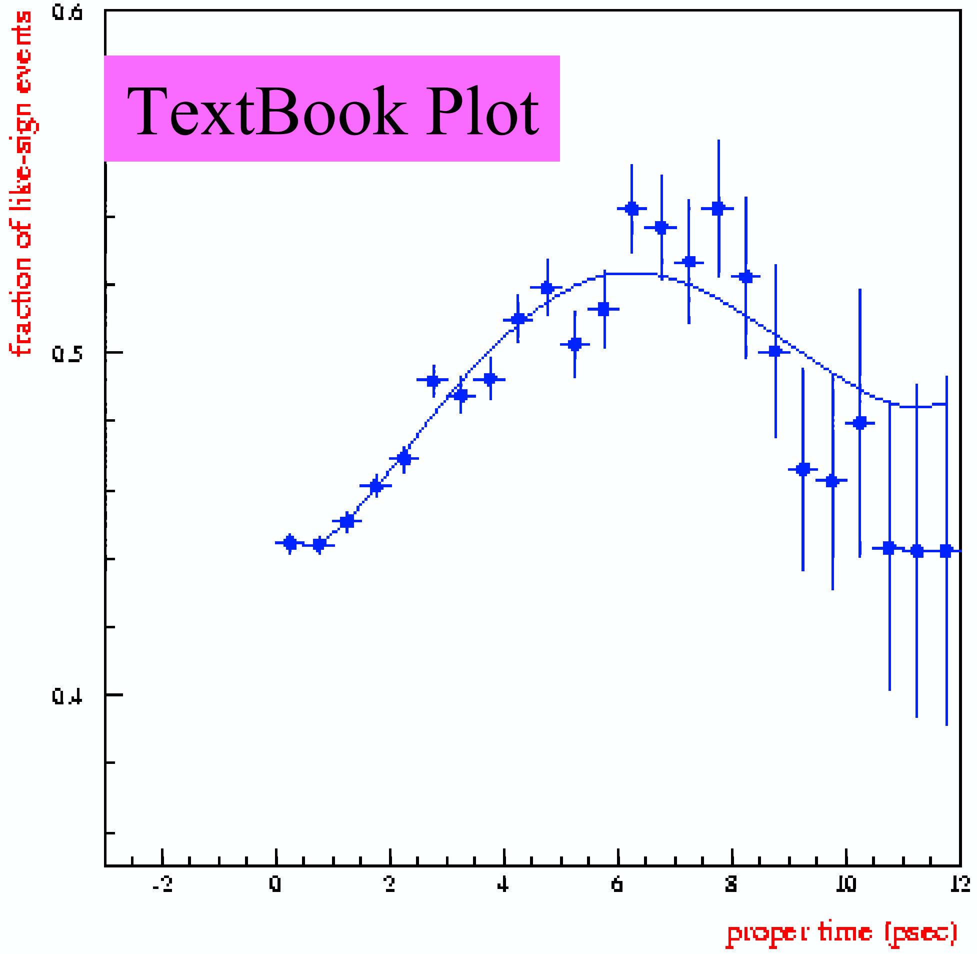
+ CLEO Exclusive results

Next V_{ub} average soon

Study of the time dependent behaviour of the Oscillation B^0-$\overline{B}^0$

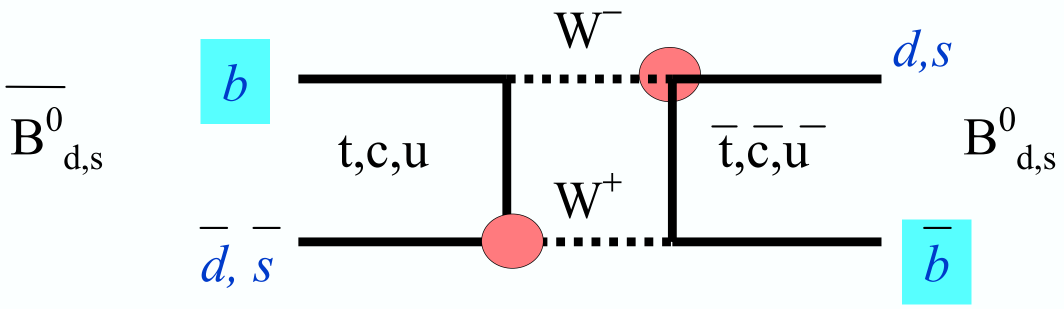
$$P_{B_q^0 \to B_q^0 (\overline{B_q^0})} = \frac{1}{2} e^{-t/\tau_q} (1 \pm \cos \Delta m_q t)$$

Δm_q can be seen as **an oscillation frequency : 1 ps^{-1} = 6.58 10^{-4} eV**


TextBook Plot

In SM :ΔF=2 process

GIM mechanism (Rate ~ $m_1^2 - m_2^2$)



*Dominated by **t** exchange*

Rate LARGE

→ V_{td} V_{ts}

$y = \Delta\Gamma/2\Gamma \ll x = \Delta m/\Gamma$

(due to the large phase phase in B decays)

Allow to access fundamental parameters of the Standard Model

$$\Delta m_d \propto f_{B_d}^2 B_{B_d} |V_{cb}|^2 \lambda^2 |V_{td}|^2 \propto f_{B_d}^2 B_{B_d} |V_{cb}|^2 \lambda^2 \boxed{((1-\overline{\rho})^2 + \overline{\eta}^2)}$$

$$\Delta m_s \propto f_{B_s}^2 B_{B_s} |V_{td}|^2 \propto f_{B_s}^2 B_{B_s} |V_{cb}|^2$$

$$\Delta m_s \approx 20\,\Delta m_d$$

Δm_s oscillations fast

Excellent time resolution required

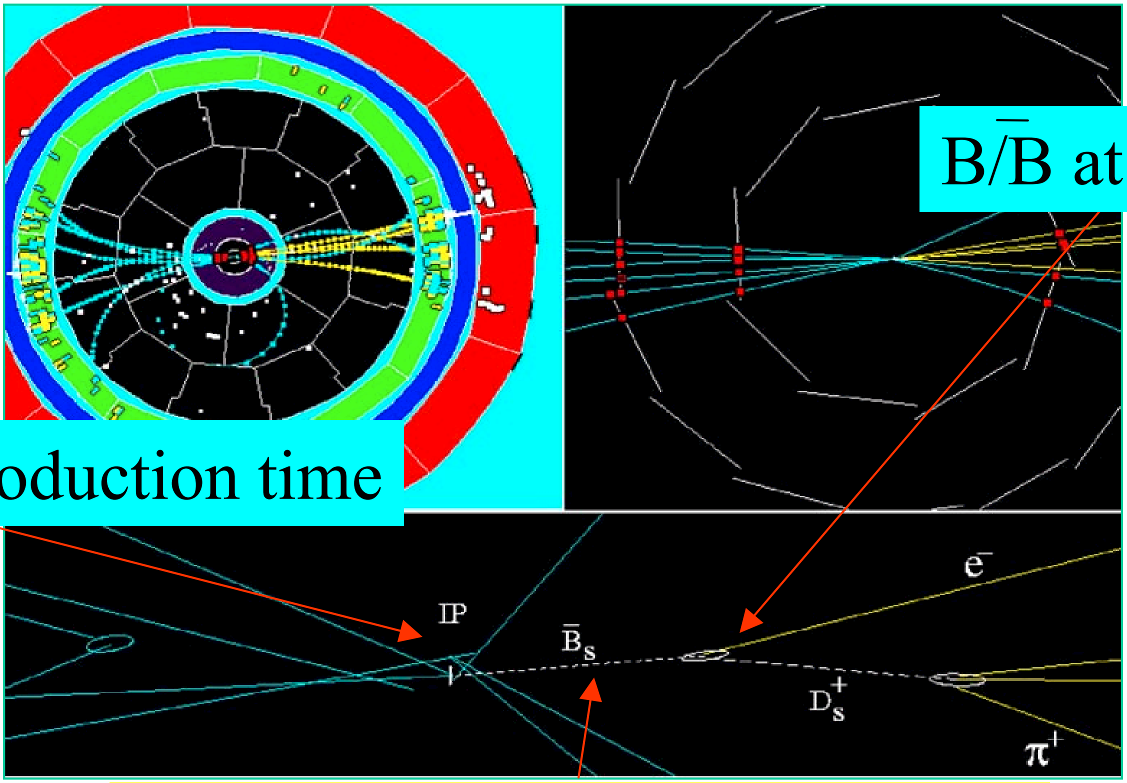
$$\frac{\Delta m_d}{\Delta m_s} \propto \frac{f_{B_d}^2 B_{B_d}}{f_{B_s}^2 B_{B_s}} \lambda^2 \boxed{((1-\overline{\rho})^2 + \overline{\eta}^2)}$$

ξ^2

ξ better know than $f_B B_B$

$\Delta m_d / \Delta m_s$ performant constraint for $\overline{\rho}$ and $\overline{\eta}$

Δm_s Analyses



$b/\bar{b}$ at the production time

Purity of tagging at production time:

ε_p

$B/\bar{B}$ at the decay time

Purity of tagging at decay time :

ε_d

Measurement of the decay time

$$\sigma(\Delta m) \quad \approx \quad \frac{1}{\sqrt{N}P_s}\frac{1}{(2\varepsilon_d-1)}\frac{1}{(2\varepsilon_p-1)}\boxed{\frac{1}{e^{-(\sigma_t\Delta m_s)^2}}}$$

N = *number of events ;* P_s = *B_s purity*

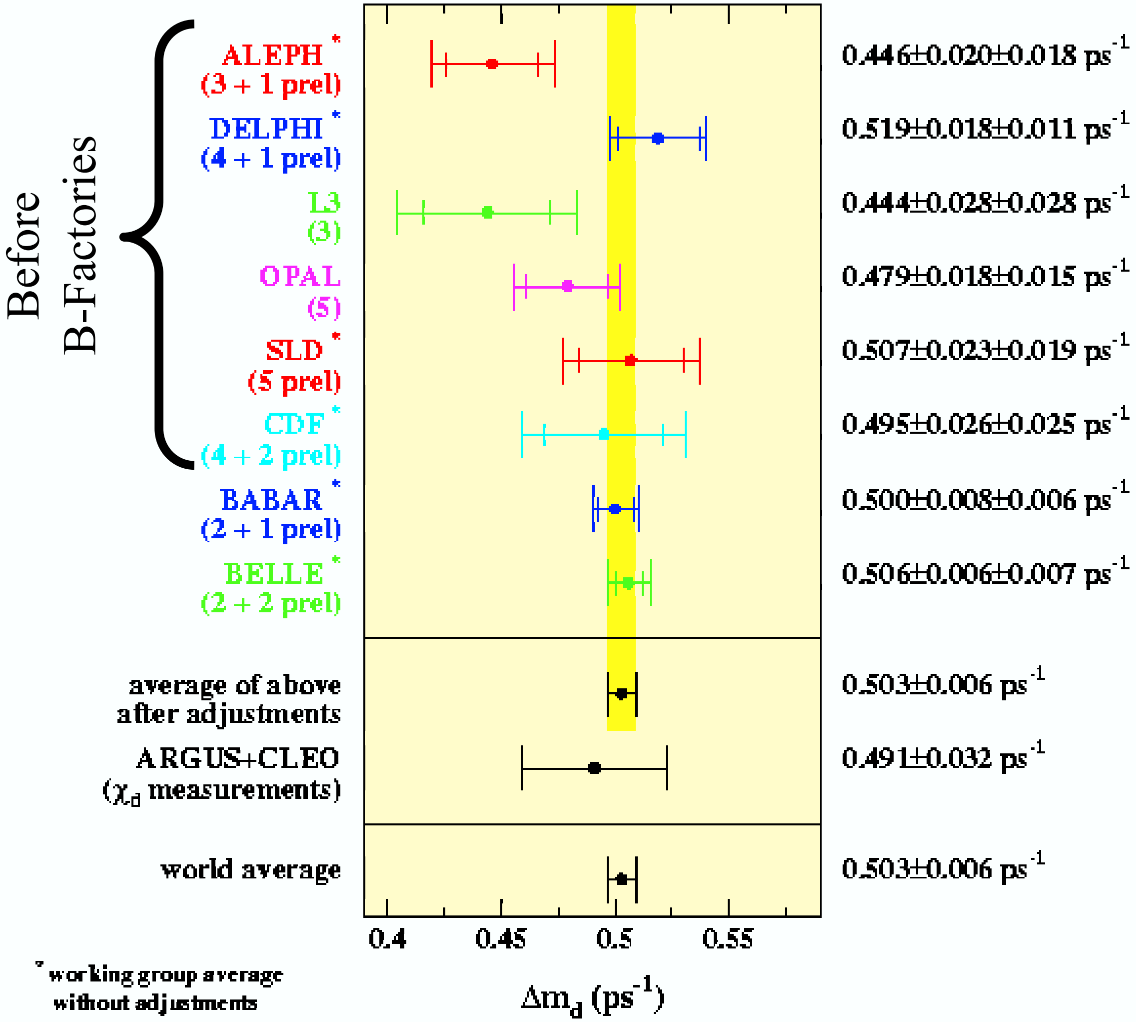
σ_t is the time resolution. As soon as Δm_s becomes larger, the precision on the time measurement becomes crucial

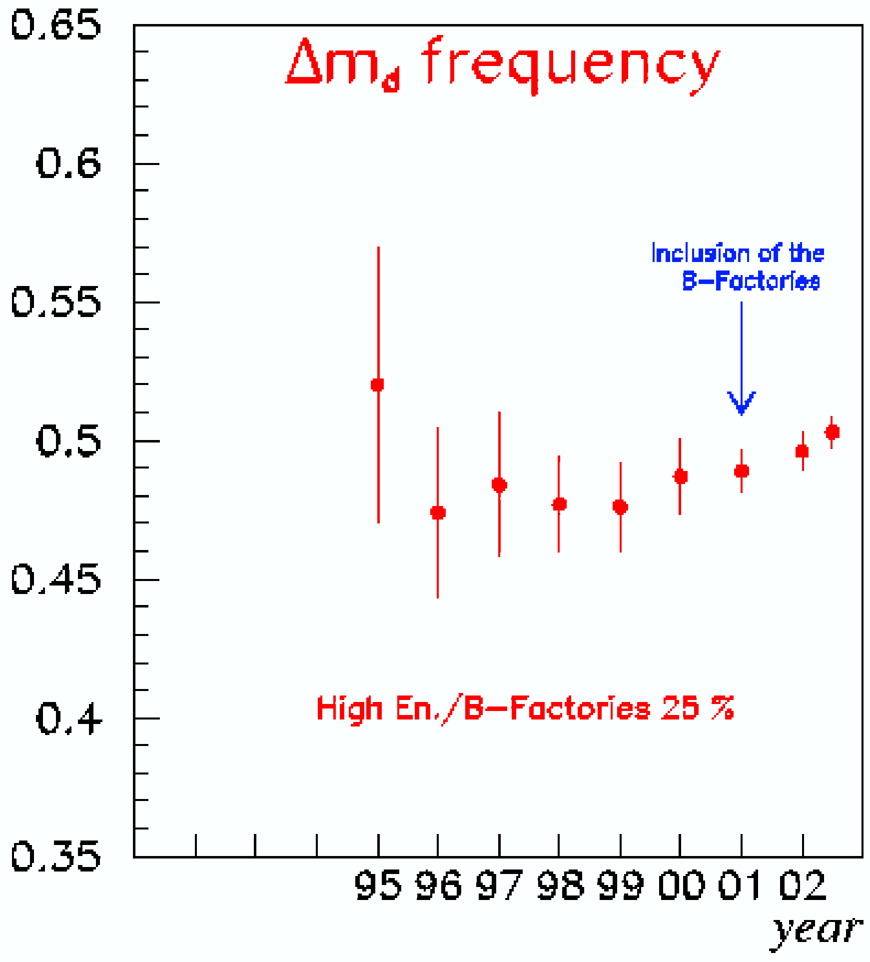
LEP/SLD/CDF measured precisely the $\Delta \mathbf{m_d}$ frequency

$$\Delta \mathbf{m_d} = 0.498 \pm 0.013 \text{ ps}^{-1} \text{ LEP/SLD/CDF } \mathbf{(2.6\ \%)}$$

B-factories confirmed the value improving the precision by a factor 2

$$\Delta \mathbf{m_d} = 0.503 \pm 0.006 \text{ ps}^{-1} \text{ LEP/SLD/CDF/B-factories } \mathbf{(1.2\%)}$$





Δm_s

Combine many different analyses which give limits

Combination using the **amplitude method**

Measurement of A at each Δm_s

$$P_{B_s^0 \rightarrow B_s^0 (\overline{B}_s^0)} = \frac{1}{2} e^{-t/\tau_s} (1 \pm \mathsf{A} \cos \Delta m_s t)$$

Combination using A and σ_A

At given Δm_s

A = 0 no oscillation

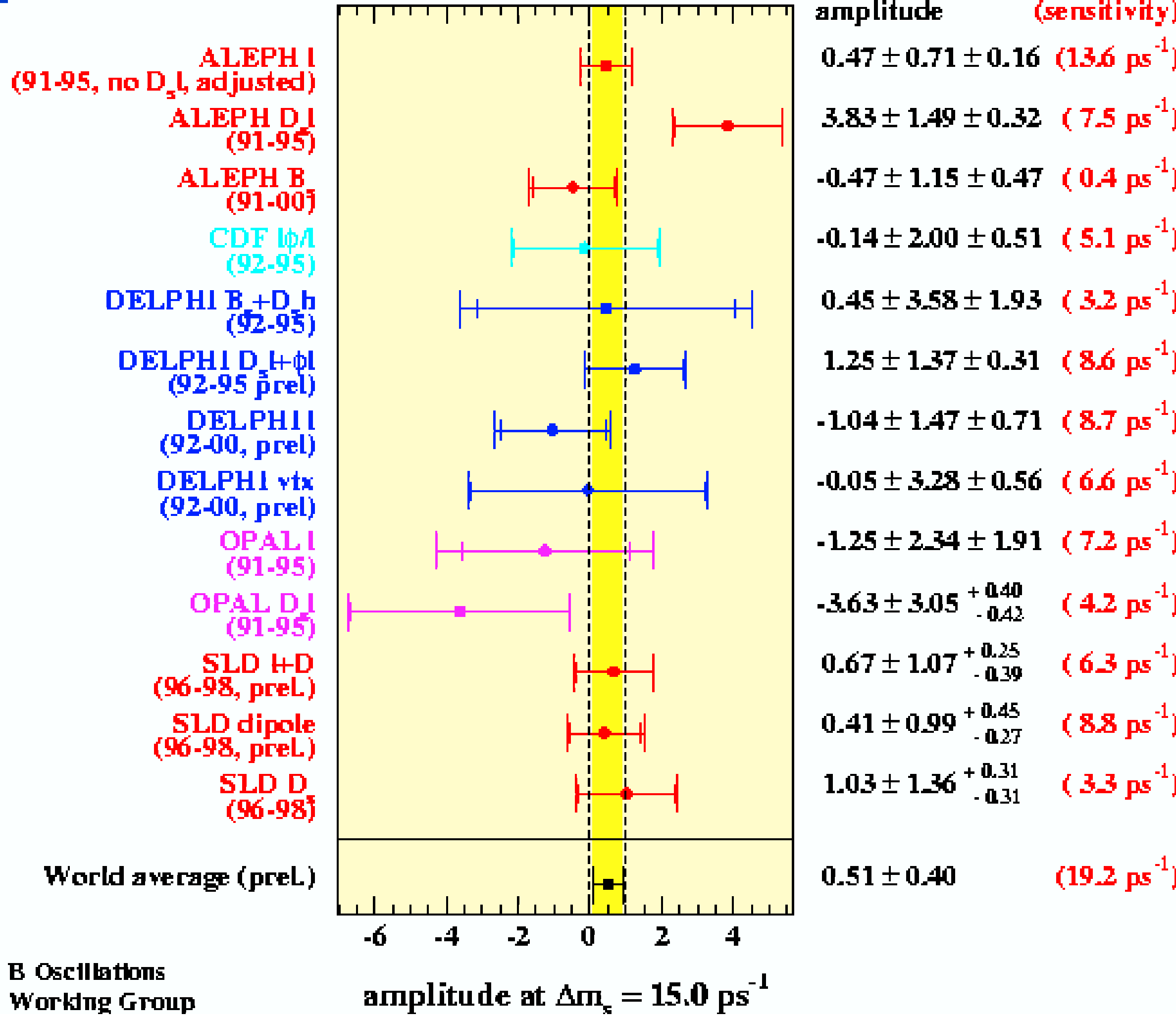
A = 1 oscillation

Δm_s excluded at 95% CL

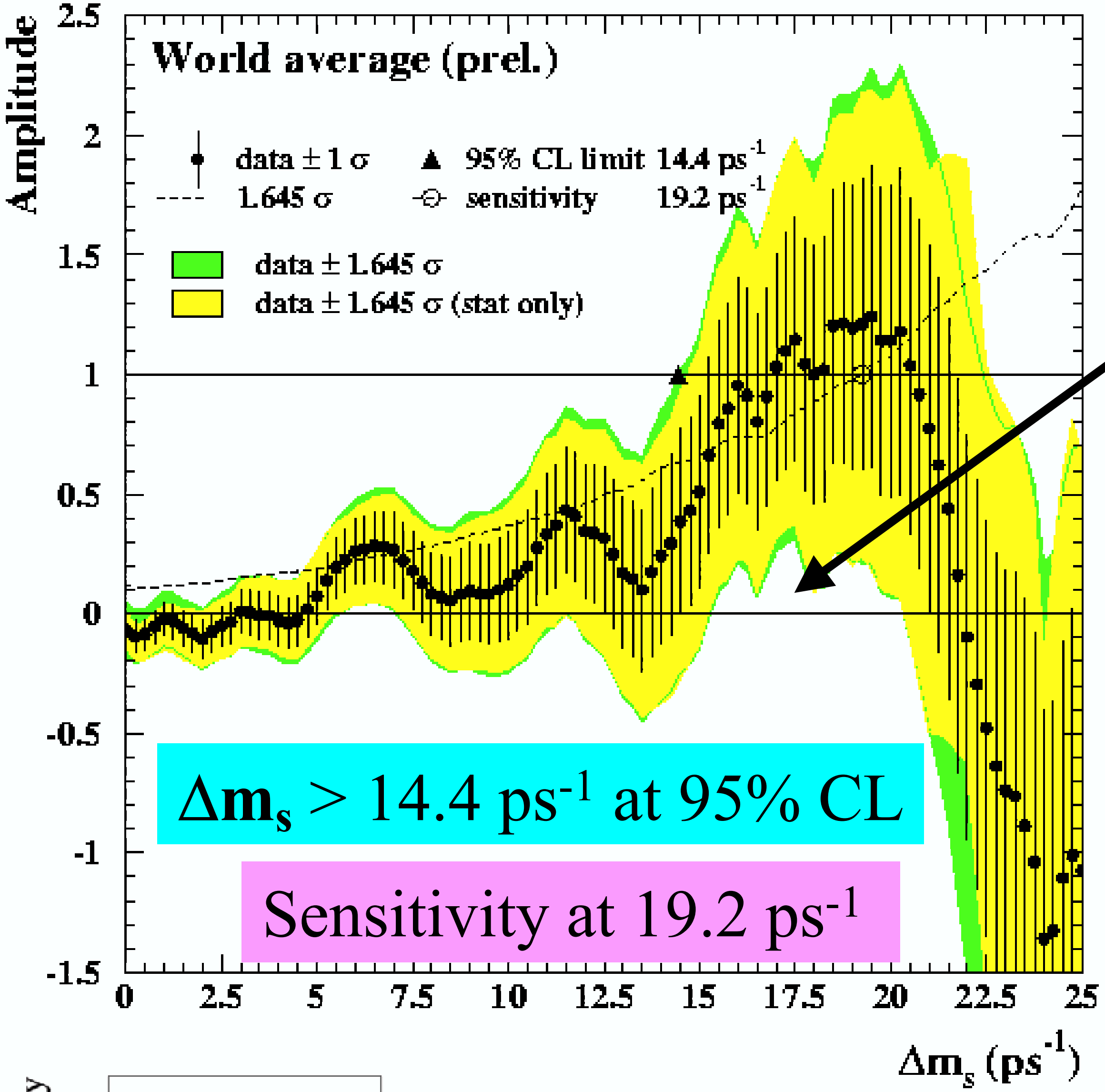
$$A + 1.645\sigma_A < 1$$

Sensitivity same relation with A = 0

$$1.645\sigma_A < 1$$

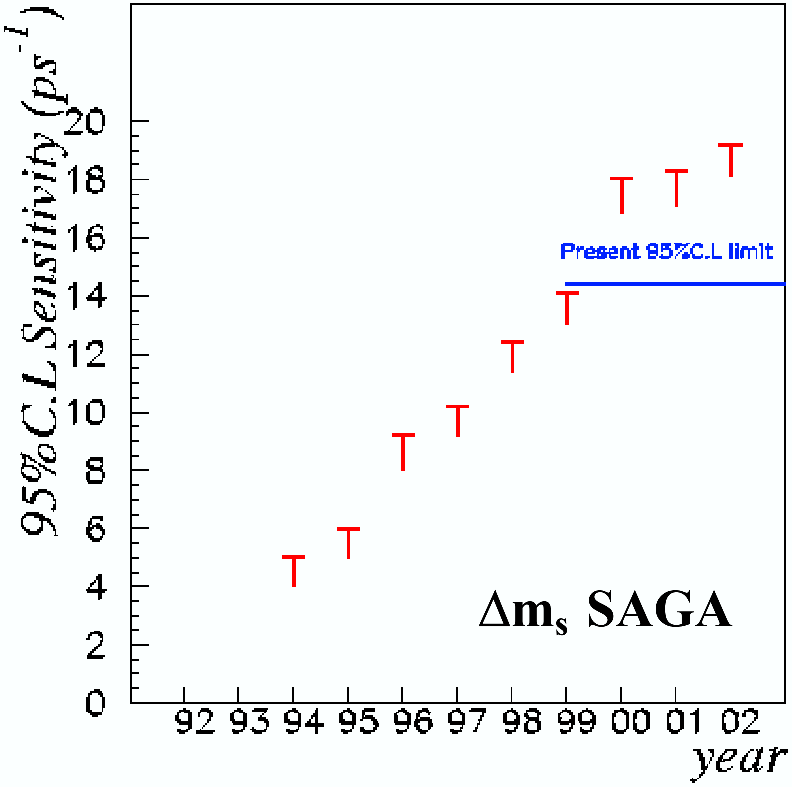


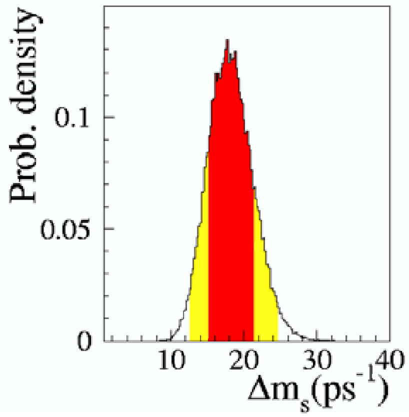
“Hint of signal”
at $\Delta \mathbf{m_s} \sim 17.5\ \mathrm{ps}^{-1}$
with significance at 2.3 σ



$\Delta \mathbf{m_s} > 14.4\ \mathrm{ps}^{-1}$ at 95% CL

Sensitivity at 19.2 ps^{-1}





Expectation in
The Standard Model

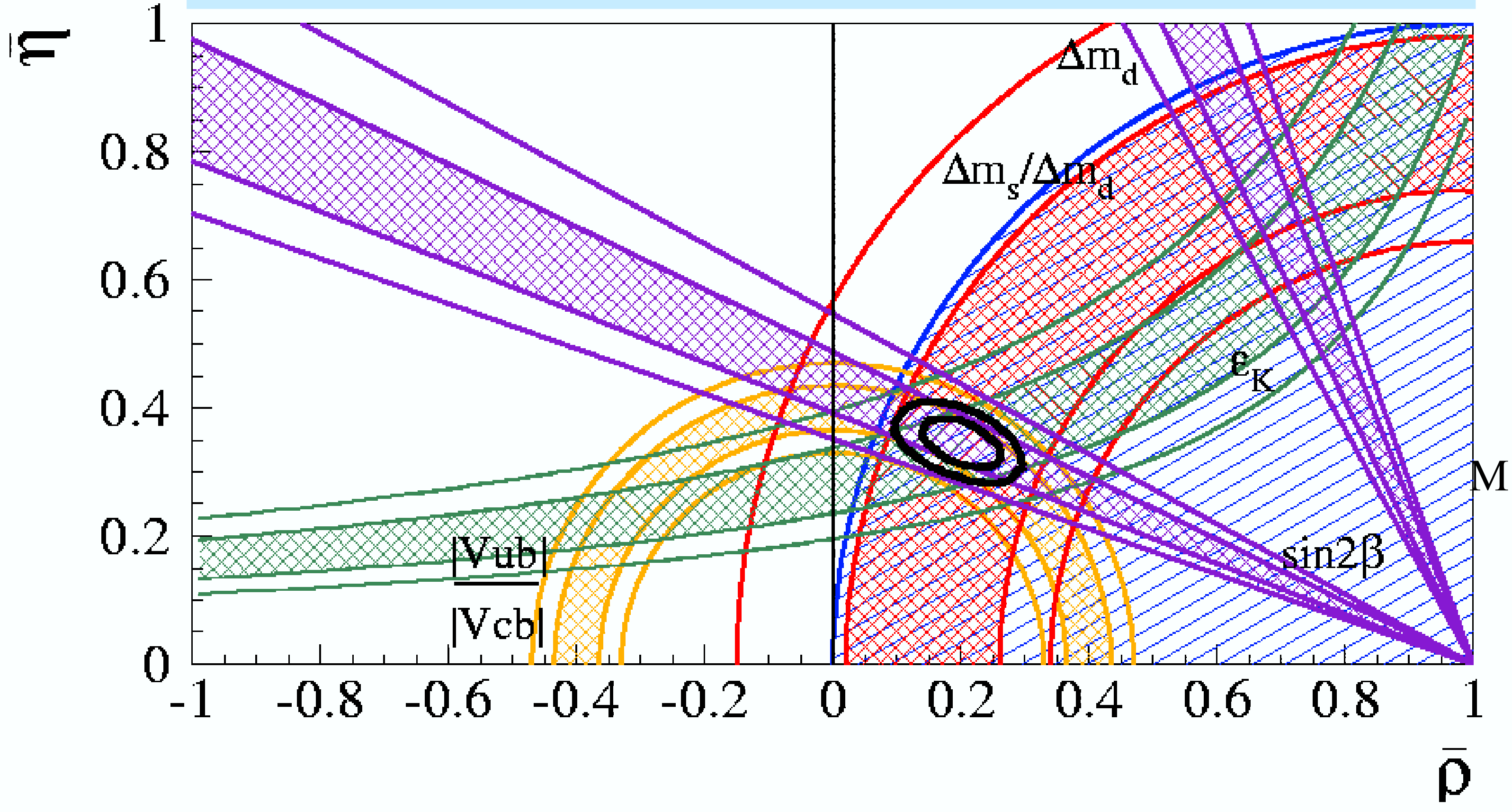
$$\Delta m_s = 18.0^{+3.4}_{-2.8}\ ps^{-1}$$
$$< 24.6 \quad @95\% \quad C.L.$$

Including $\Delta \mathbf{m_s}$ →

$$\Delta m_s = 17.6^{+1.9}_{-1.3}\ ps^{-1}$$
$$< 20.9 \quad @95\% \quad C.L.$$

What we have learnt about the Unitarity Triangle

Constraints : V_{ub} , V_{cb} , ε_K , Δm_d , Δm_s , $\sin 2\beta$



M.Ciuchini et al.

$$\sin 2\beta = 0.724^{+0.035}_{-0.034}$$

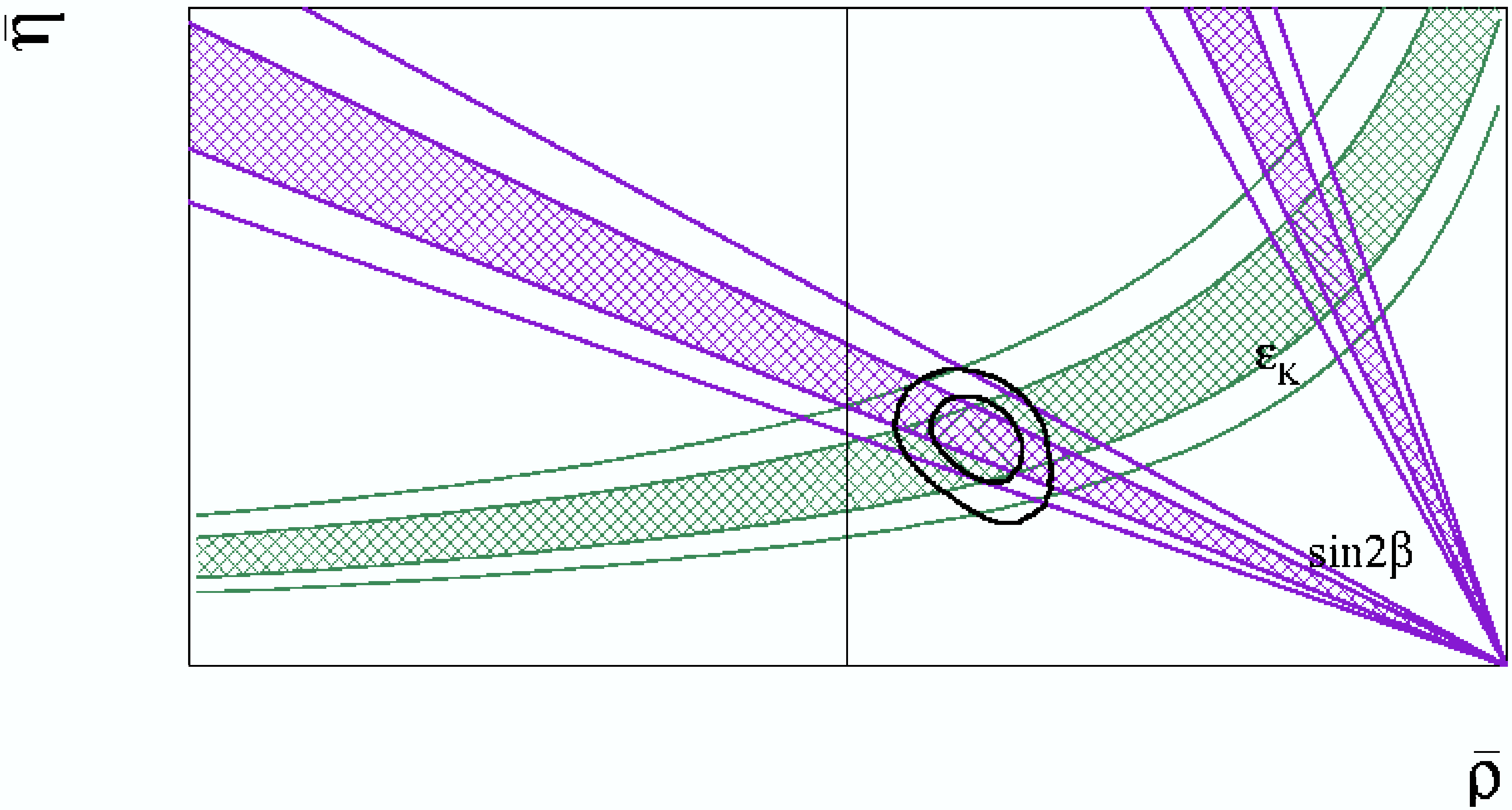
$$\bar{\rho} = 0.199 \pm 0.040$$

$$\bar{\eta} = 0.345 \pm 0.026$$

$$\gamma = (59.5^{+6.5}_{-5.5})^{\circ}$$

$$\Delta m_s = 17.6^{+1.9}_{-1.3}\ ps^{-1}$$

$$\sin 2\alpha = -0.24^{+0.24}_{-0.20}$$

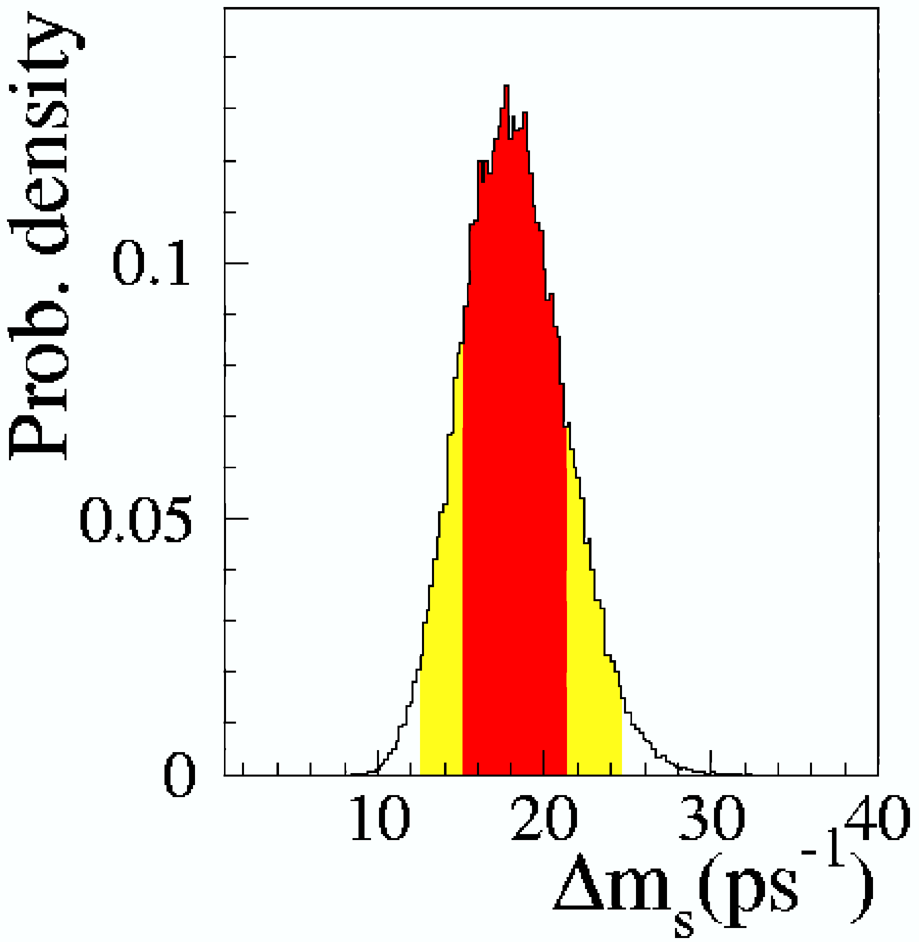


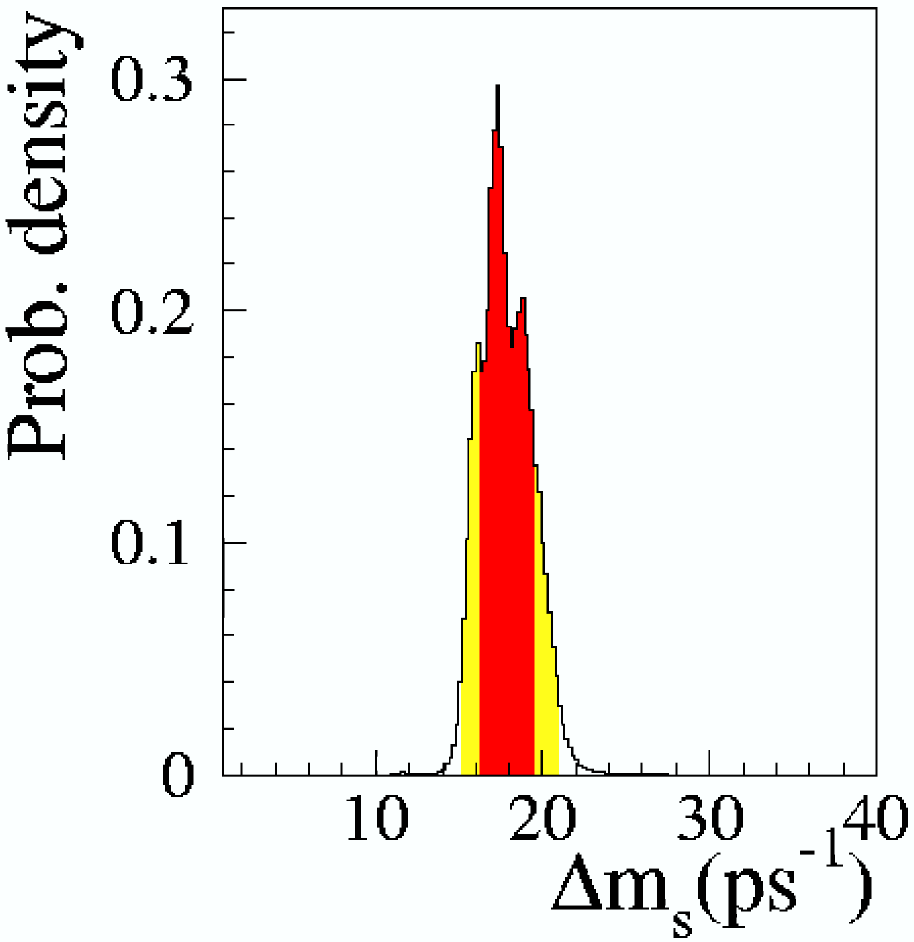
$\sin 2\beta = 0.734 \pm 0.054$ direct from B → J/ψ K^0_s

$\sin 2\beta = 0.715^{+0.055}_{-0.045}$ *"indirect" sides* + ε_K

Coherent picture of CP Violation in SM

Prediction for Δm_s





$$\Delta m_s = 18.0^{+3.4}_{-2.8}\ ps^{-1}$$

$[12.5 - 24.6]$ @95% $C.L.$

$$\Delta m_s = 17.6^{+1.9}_{-1.3}\ ps^{-1}$$

$[15.2 - 20.9]$ @95% $C.L.$

Conclusions

In 10 years our understanding of the flavour sector of the SM Model improuved.
LEP and SLC played a central role.

B hadron lifetimes have been precisely measured
(~1% B^0_d and B^+ (with B-factories) and 4% for B^0_s and Λ_B)

V_{cb} is known at the 2-3% level

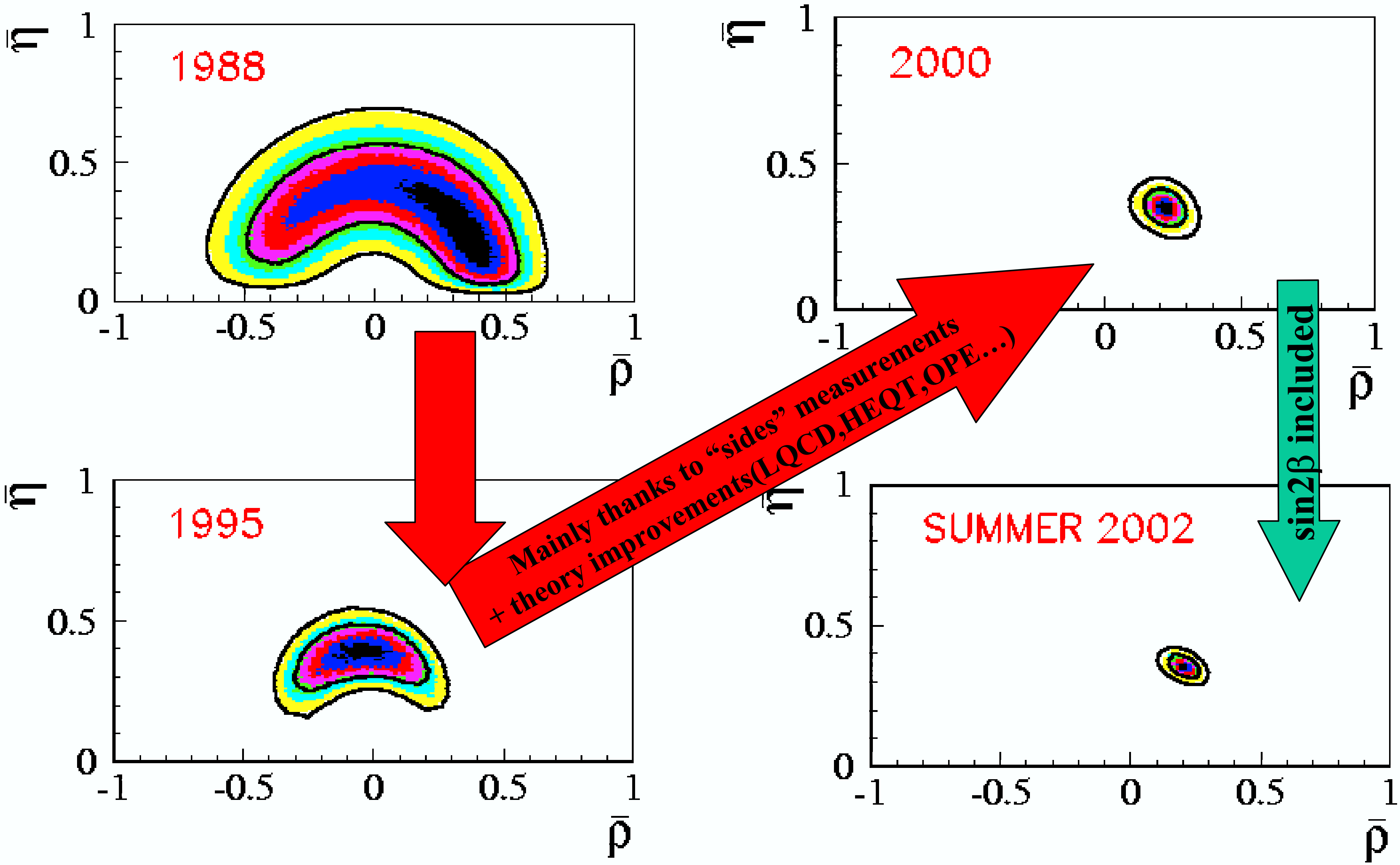
V_{ub} is known at the 10% level

CLEO measurements very important

Time behaviour of the oscillation observed
Δm_d precisely measured (2.6% → 1.2% with B-factories)

B_s oscillates at least 30 times faster than B_d ($\Delta m_s > 14.4 \mathrm{ps}^{-1}$ @95%C.L.)

UT parameters knowledge much improuved



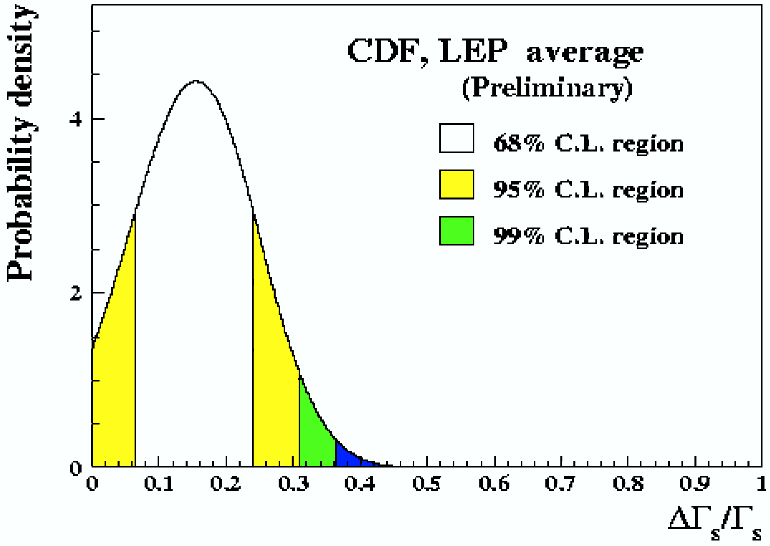
Mainly thanks to “sides” measurements
+ theory improvements(LQCD,HEQT,OPE…)

sin2β included

Additional Material

Lifetime Difference : $\Delta\Gamma_s$

- Benefit from the work done on lifetime
- Interest : $\frac{\Delta\Gamma}{\Delta m_s} \simeq \frac{3}{2}\pi(\frac{m_b^2}{m_t^2})$ (naively)
  $\rightarrow$ possible visibility for $\Delta\Gamma_s$
  Δm_s accessible via $\Delta\Gamma_s$ (important if Δm_s is too high)
- Caveat : Theory still uncertain....



Assuming $\tau(B^0) = \tau(\mathrm{B_s^0})$	No assumptions
$\Delta\Gamma_s/\Gamma_s = 0.16^{+0.08}_{-0.09}$	$\Delta\Gamma_s/\Gamma_s = 0.24^{+0.16}_{-0.12}$
$\Delta\Gamma_s/\Gamma_s < 0.31$ 95% C.L.	$\Delta\Gamma_s/\Gamma_s < 0.53$ 95% C.L.

n_c versus $Br(b \to \ell\nu)$

Br_{sl} : $b \to c\ell^- \bar{\nu}$ is on the low side of the theo. expectation

A possible explanation is that the c-quark effective mass is low $\to$ large decay rate for $b \to c\bar{c}s(d)$

$\to n_c (= n_c + n_{\bar{c}})$ is NEGATIVELY CORRELATED TO Br_{sl}

The simultaneous measurement of Br_{sl} and n_c may help to clarify the theoretical picture

Many different ways of measuring n_c :

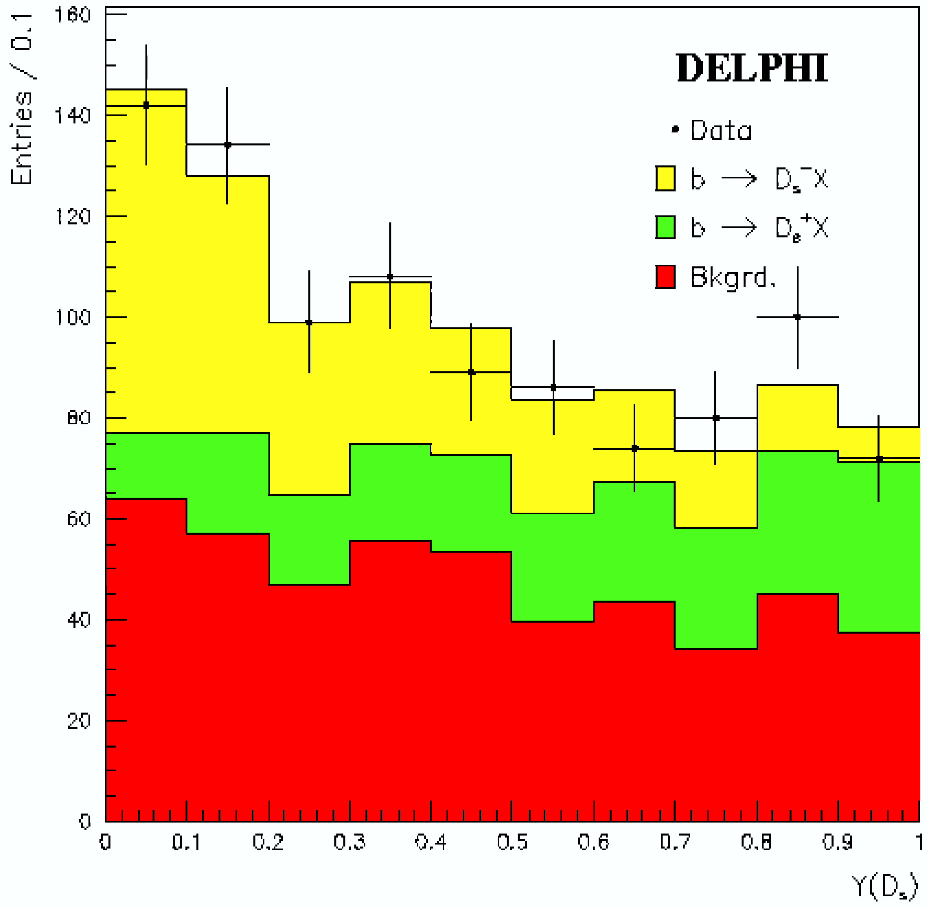
- inclusive production of D^0,D^+,D_s^+,Λ_c^+,Ξ_c^{+0}
- inclusive-topological double-open,single and no-charm measurements
- Charmonium production

Exclusive wrong-sign measurements : $b \to D\bar{D}_j X$

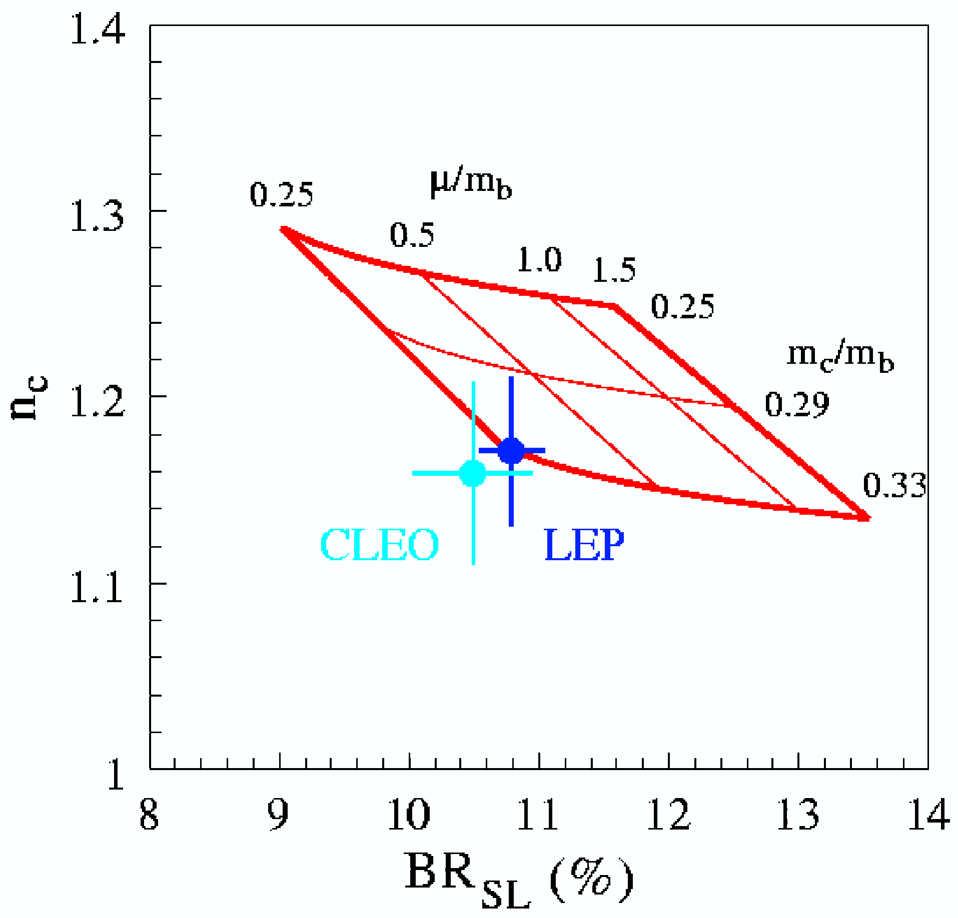
Previous measurements from ALEPH (CLEO)

Technique:

- Recontruct exclusive D mesons
- Correlate the D charge with the initial *b* charge



- The values of B_{sl} at CLEO ($\Upsilon(4S)$) and LEP agree.
- Similar precision on n_c and B_{sl}



- std. value of the c mass : $\frac{m_c}{m_b} = 0.30 \pm 0.02$
  (m_q = pole mass defined at one-loop in perturbation theory)
- low scale μ : $\frac{\mu}{m_b} \simeq 0.35$
  (μ = scale at which the QCD corrections have to be evaluated)

Inputs for the CKM fit

Standard set:

Parameter	Value	Gaussian σ	Uniform half-width
λ	0.2210	0.0020	-
$\|V_{cb}\|$(excl.)	42.1×10^{-3}	2.1×10^{-3}	-
$\|V_{cb}\|$(incl.)	40.4×10^{-3}	0.7×10^{-3}	0.8×10^{-3}
$\|V_{cb}\|$(ave.)	40.6×10^{-3}	0.8×10^{-3} *	
$\|V_{ub}\|$(excl.)	32.5×10^{-4}	2.9×10^{-4}	5.5×10^{-4}
$\|V_{ub}\|$(incl.)	40.9×10^{-4}	4.6×10^{-4}	3.6×10^{-4}
$\|V_{ub}\|$(ave.)	36.3×10^{-4}	3.2×10^{-4} *	
$\|V_{ub}\|/\|V_{cb}\|$(ave.)	0.089	0.008*	
ΔM_d	0.503 ps^{-1}	0.006 ps^{-1}	–
ΔM_s	$>$ 14.4 ps^{-1} at 95% C.L.	sensitivity 19.2 ps^{-1}	
m_t	$167\ GeV$	$5\ GeV$	–
sin 2β	0.734	0.054	-
$\hat{B}_K$	0.86	0.06	0.14
$f_{B_d}\sqrt{\hat{B}_{B_d}}$	$230\ MeV$	$30\ MeV$	$15\ MeV$
ξ	1.18	0.03	0.04

New lattice QCD parameters with "chiral logarithms"

$f_{B_d}\sqrt{\hat{B}_{B_d}}$	$235\ MeV$	$33\ MeV$	$^{+0}_{-24}\ MeV$
$\xi =$	1.18	0.04	$^{+12}_{-0}$