B-physics at LEP

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B-physics studies at LEP

$$e^+e^- \to b\bar{b}(\gamma)$$

- **LEP I**: During 5 years $\sqrt{\mathbf{s}} \simeq \mathbf{M_Z}$
- 1995 $\sqrt{s} = \mathbf{130}$ and $\mathbf{136}$ GeV
- 1996 $\sqrt{s} = \mathbf{161}$ and $\mathbf{172}$ GeV
- 1997 $\sqrt{s} = \mathbf{183}$ GeV **LEP II**
- 1998 $\sqrt{s} = \mathbf{189}$ GeV
- 1999 $\sqrt{s} = \mathbf{196}$ and $\mathbf{200}$ GeV

- **Over 7 million b-quark jets recorded by all four LEP experiments up to 1995.**
- **At LEP, B-hadron system is boosted in e^+e^-CM and B-decay vertexes are well-separated from IP**
- **Primary hard-scattering QCD vertex is well-defined**
- **New results use full LEP I statistics, more sophisticated analysis and improved theoretical input.**

Motivation

B-physics is important probe for:

- **Tests of Standard Model (R_b, A^b_{FB}, CKM...)**

- **Tests of QCD (Gluon splitting, HQET...)**

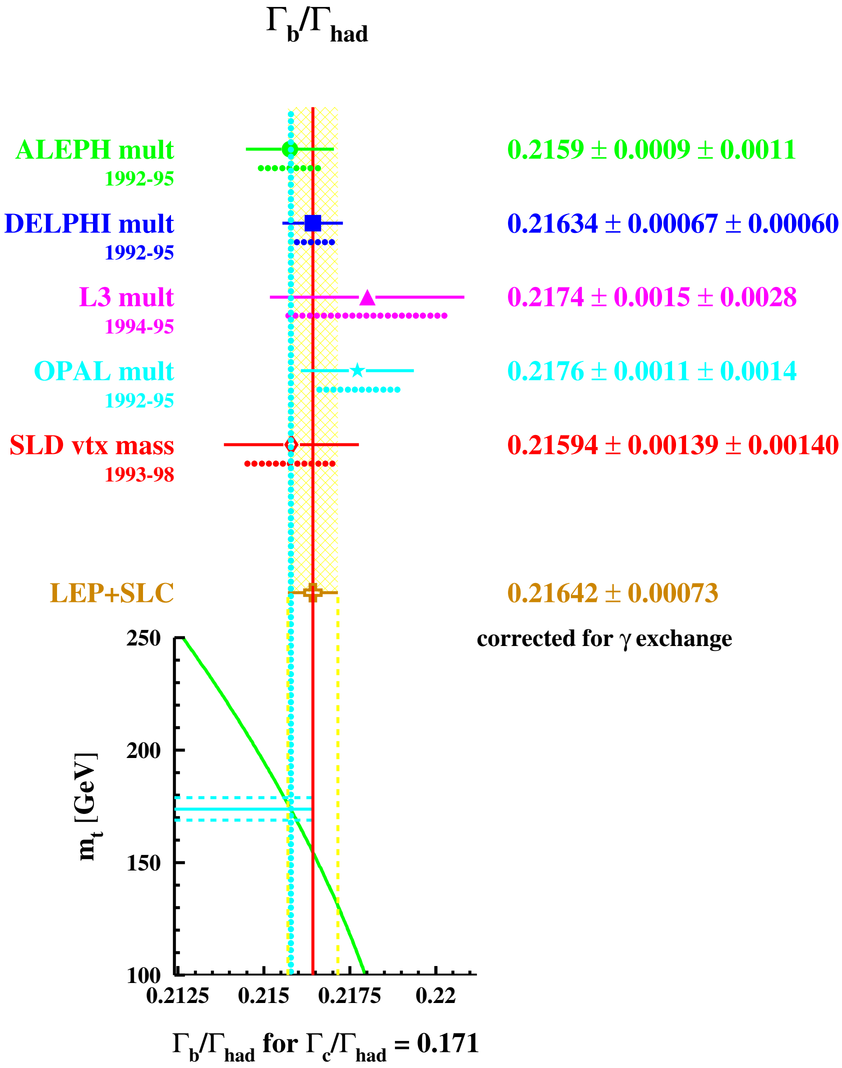
- **CP violation (B-decays, $B^0\bar{B}^0$ mixing, CKM...)**

- **Physics beyond the Standard Model**

R_b and A^b_{FB} measurements

Lifetime (and lepton) double tag used by all four LEP experiments - most precise R_b determination, dominates the combined result:

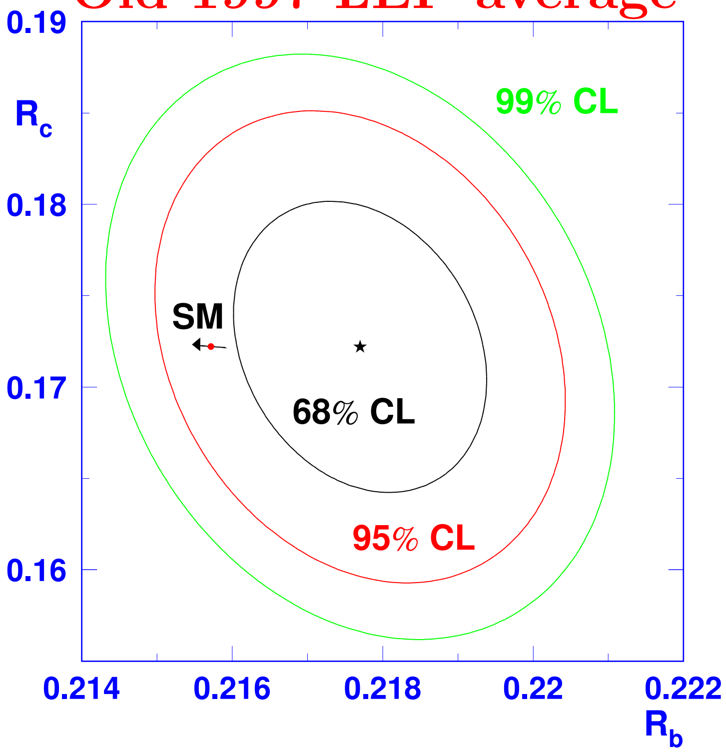
$$\mathbf{R_b} = \frac{\mathbf{\Gamma}(Z \to b\bar{b})}{\mathbf{\Gamma}(Z \to \text{hadrons})} = (\mathbf{0.21678 \pm 0.00076})_{\mathbf{LEP}(\mathbf{R_c}=\mathbf{0.171})}$$



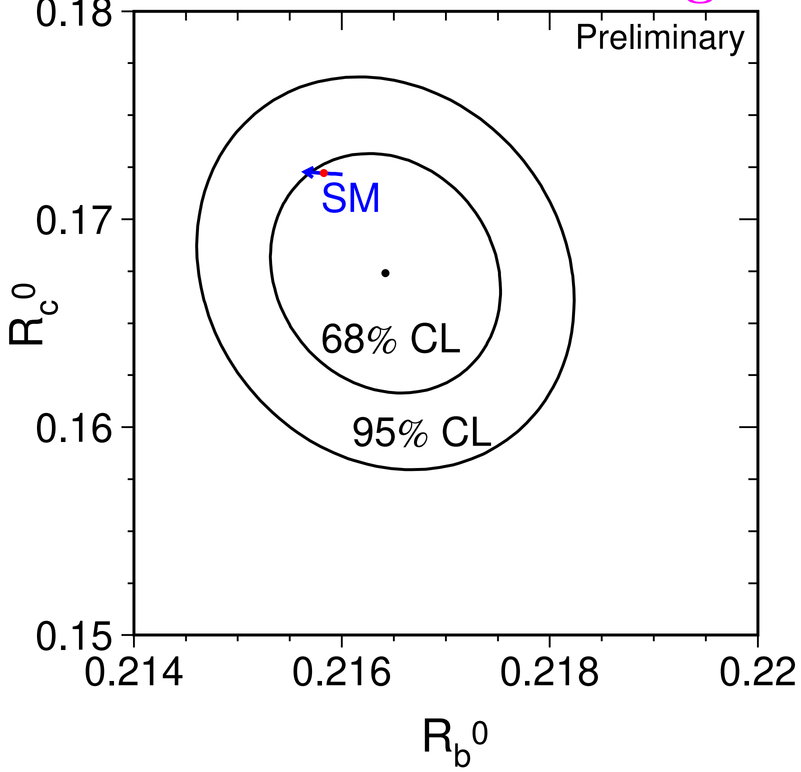
Precision of R_b is still improving (now 0.4%)

R_b and A_{FB}^b measurements

Old 1997 LEP average



New 1999 LEP average

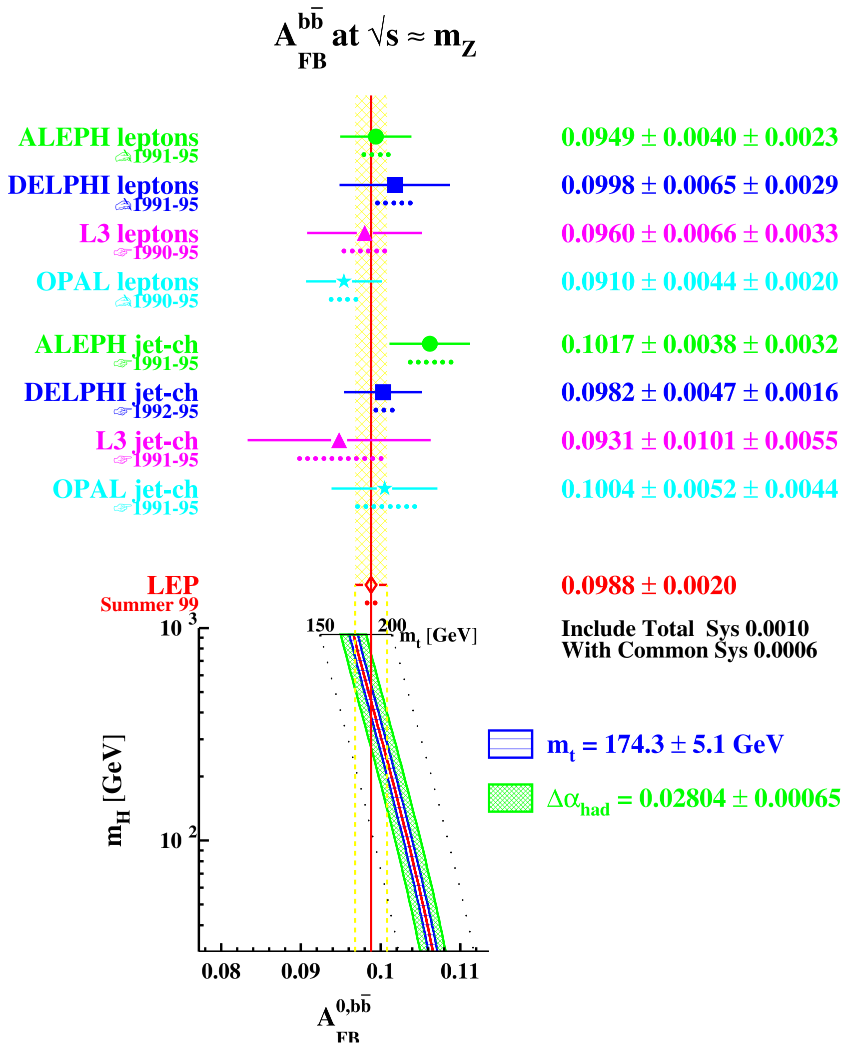


$\mathbf{R_b}$ and $\mathbf{A^b_{FB}}$ measurements

$$\frac{d\sigma}{d\cos\theta_{\mathbf{b}}} \propto \frac{3}{8}(1+\cos^{\mathbf{2}}\theta_{\mathbf{b}}) + \mathbf{A^{b}_{FB}}\cos\theta_{\mathbf{b}}$$

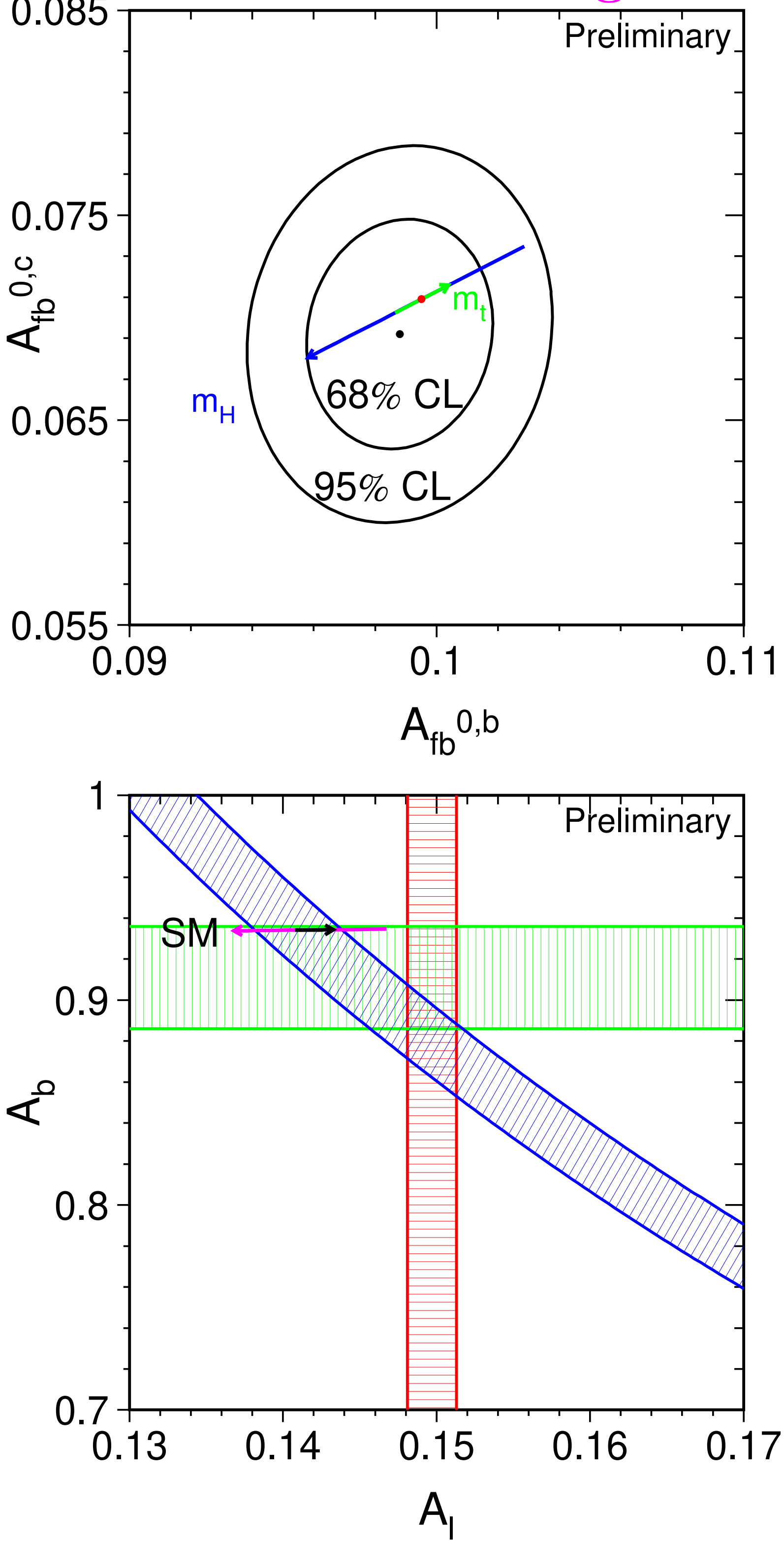
$$A^{\mathrm{b},0}_{\mathrm{FB}} = \frac{3}{4}\frac{2v_{\mathrm{e}}a_{\mathrm{e}}}{v_{\mathrm{e}}^2+a_{\mathrm{e}}^2}\frac{2v_{\mathrm{b}}a_{\mathrm{b}}}{v_{\mathrm{b}}^2+a_{\mathrm{b}}^2} = \frac{3}{4}A_{\mathrm{e}}A_{\mathrm{b}}$$

$\mathbf{A^b_{FB}}$ provides precise determination of $\sin^{\mathbf{2}}\theta^{\mathrm{lept}}_{\mathrm{W,eff}}$



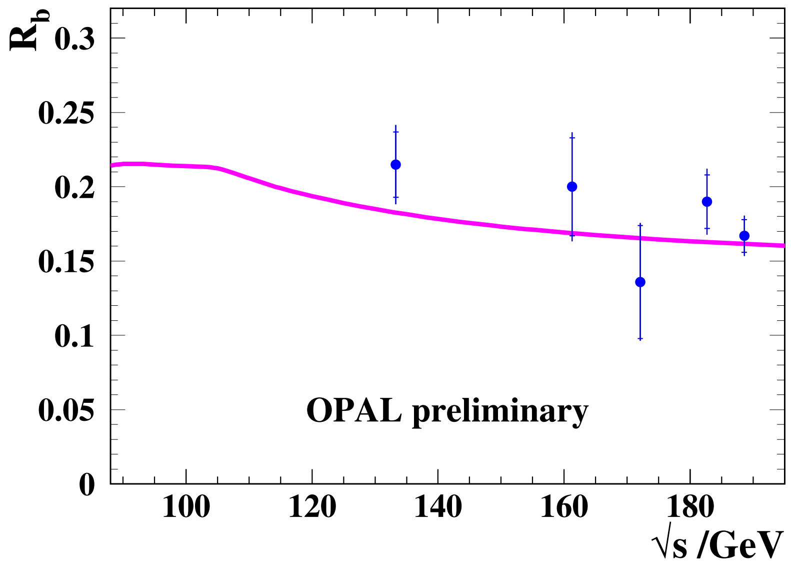
R_b and A_{FB}^b measurements

1999 LEP average



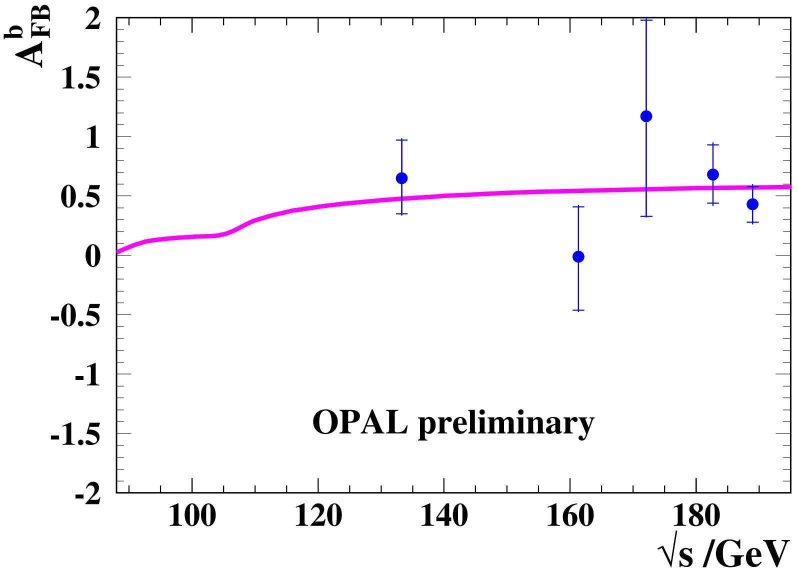
R_b and A^b_{FB} measurements

LEP II high energy measurements



LEP combined (all 4 exp.)

R_b(189 GeV) = 0.161±0.007 ((SM) = 0.168)



LEP combined (ALEPH, L3, OPAL)

A^b_{FB}(189 GeV) = 0.44±0.12 ((SM) = 0.58)

Gluon splitting into $b\bar{b}$

Gluon splitting rate into $b\bar{b}$ definition:

$$g_{b\bar{b}} = \frac{N(Z \to q\bar{q}g, g \to b\bar{b})}{N(Z \to \text{hadrons})}$$

LEP Measured $g_{b\bar{b}}$ values and QCD predictions:

ALEPH	published	$2.77 \pm 0.42 \pm 0.57 \times 10^{-3}$
DELPHI	preliminary	$3.30 \pm 1.00 \pm 0.70 \times 10^{-3}$
OPAL	preliminary	$2.15 \pm 0.43 \pm 0.80 \times 10^{-3}$
Theory	Λ^5_{MS} =150 MeV	$2.00 \pm 0.20 \times 10^{-3}$
Theory	Λ^5_{MS} =300 MeV	$2.60 \pm 0.30 \times 10^{-3}$

Selection of 4-jet topology events.

Analyses benefit from efficient b-tagging.

The limited $g_{b\bar{b}}$ accuracy is one of the main sources of uncerntainty in R_b measurement.

Lifetime of b-hadrons

Expected:

- **In spectator model all B hadrons lifetimes are expected to be equal (due to $b \to cW^-$ only).**
- **Non-spectator effects cause lifetime differences.**

  quark interference
  W exchange
  weak annihilation

- **Heavy Quark Expansion prediction:**

  Baryon-meson differences by $\mathcal{O}(1/m_b^2)$ terms
  Meson-meson differences smaller $\mathcal{O}(1/m_b^3)$

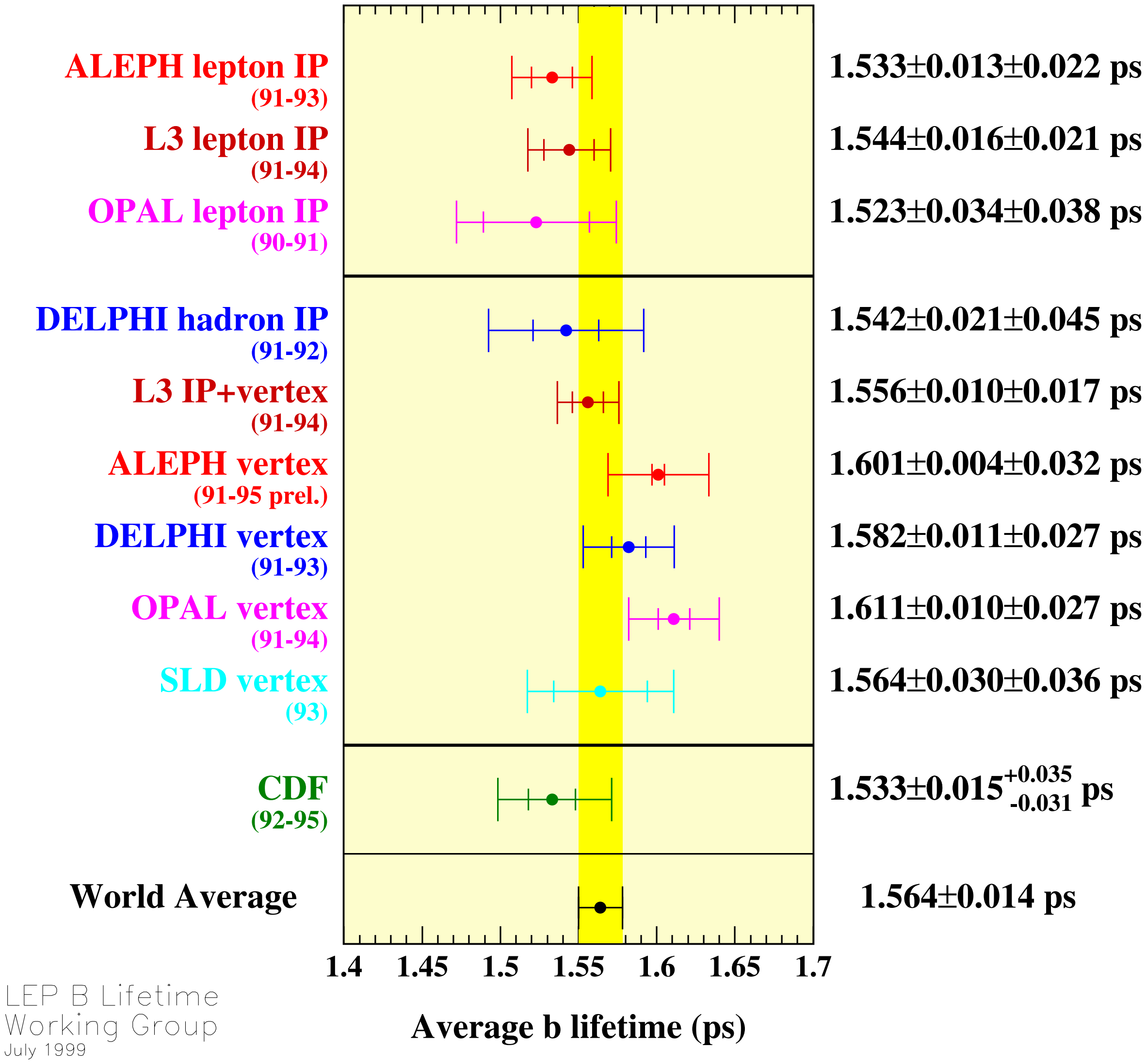
- **Expected hierarchy:** $\tau_{\Lambda_b} < \tau_{B^0} < \tau_{B_s} < \tau_{B^-}$

Measurement

To measure B hadron lifetime one need to reconstruct: B decay lenght , B momentum

Large boost required (LEP average l_d ~3 mm)

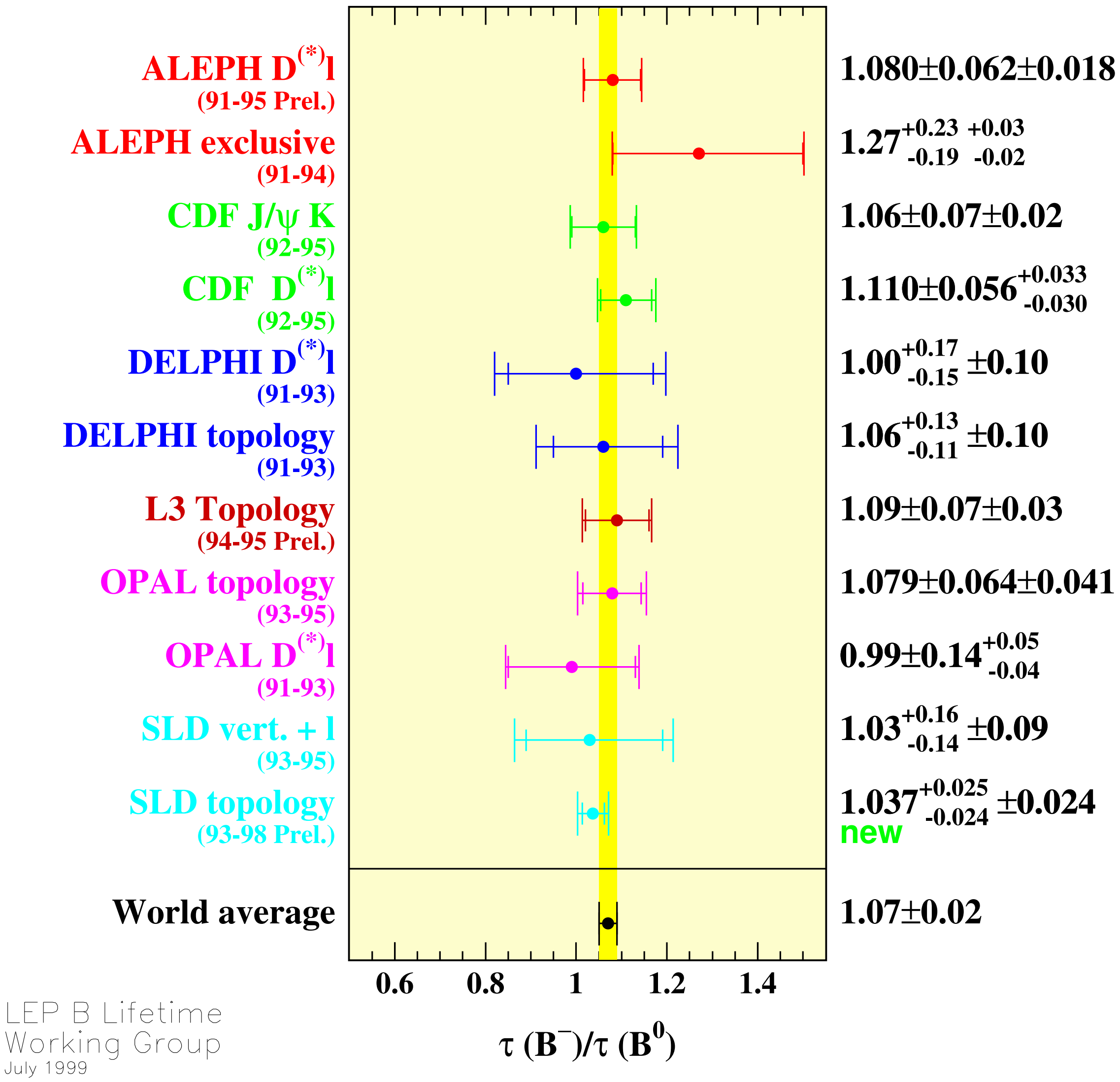
Measured average b lifetime



World combined:

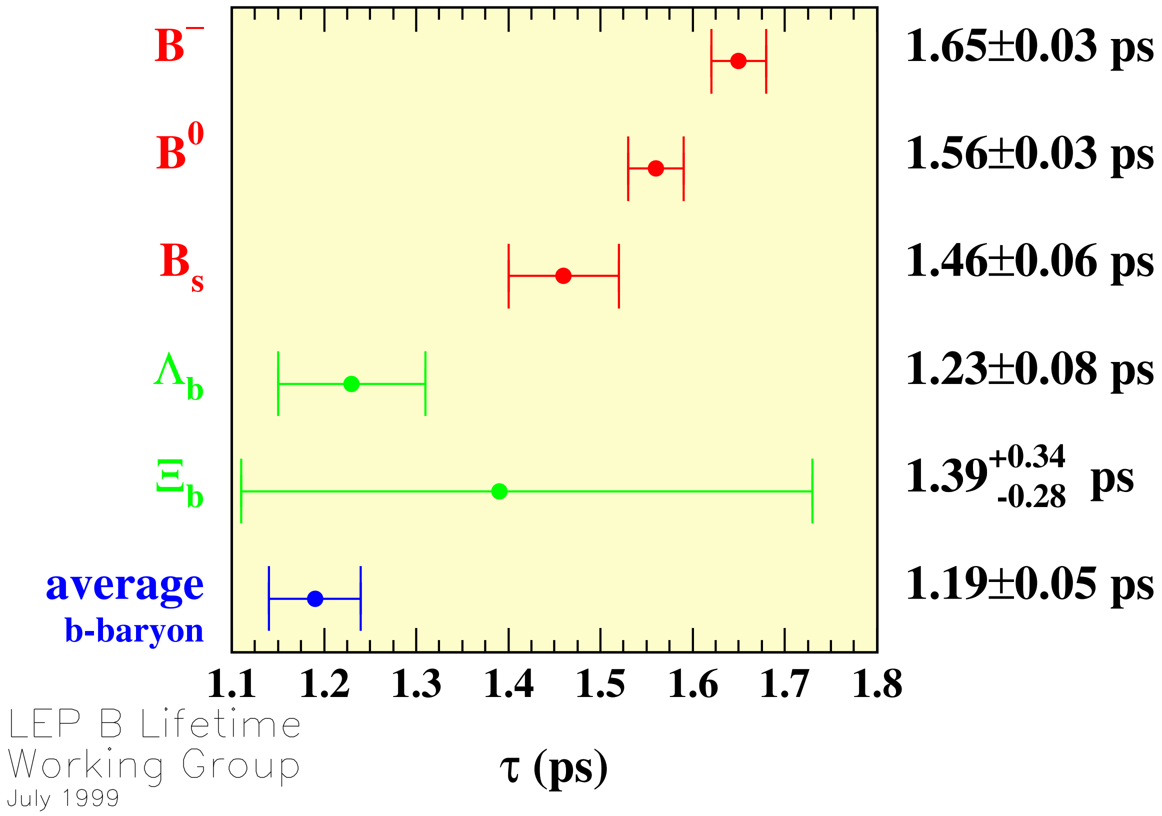
$$\text{average } \tau_b = 1.564 \pm 0.014 \text{ps}$$

Measured B^-/B^0 lifetime ratio



Still compatible with HQE expectations

Summary of B hardon lifetime measurements



$\tau(\mathrm{B_s})/\tau(\mathrm{B^0})$ =0.95±0.04 $\tau(\mathrm{b-barion})/\tau(\mathrm{B^0})$ =0.77±0.04

Low b-barion lifetime is not yet well understood.

Cabibbo-Kobayashi-Maskawa matrix

$\mathbf{V_{CKM}}$ unitary mixing matrix for *down*-type quarks

$$q'_i = \Sigma_j \mathbf{V_{ij}}\, q_j \quad \text{for} \quad \mathbf{I_3} = -1/2$$

The Wolfenstein parametrization valid up to $\mathcal{O}(\lambda^4)$:

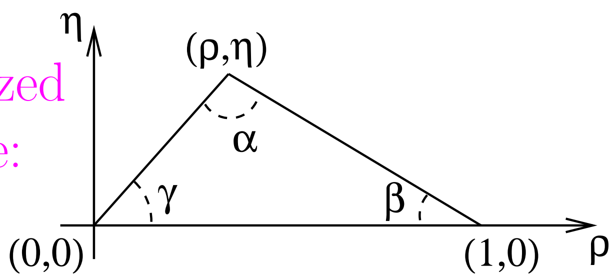
$$\mathbf{V_{CKM}} = \begin{pmatrix} \mathbf{V_{ud}} & \mathbf{V_{us}} & \mathbf{V_{ub}} \\ \mathbf{V_{cd}} & \mathbf{V_{cs}} & \mathbf{V_{cb}} \\ \mathbf{V_{td}} & \mathbf{V_{ts}} & \mathbf{V_{tb}} \end{pmatrix} \simeq \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda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

4 real parameters $\lambda, \mathbf{A}, \rho, \eta$

$$\lambda = \mathbf{\sin}\, \theta_{\mathbf{C}}, \qquad \mathbf{A} = \frac{|\mathbf{V_{cb}}|}{\lambda^{\mathbf{2}}},$$

$$\frac{|\mathbf{V_{ub}}|}{|\mathbf{V_{cb}}|} = \lambda\sqrt{\rho^{\mathbf{2}} + \eta^{\mathbf{2}}}$$

CP violation in b-sector can be visualized by the unitarity triangle in (ρ, η) plane:



Measurements of $|V_{ub}|$

In the context of Heavy Quark Expansion:

$$|V_{ub}| = 0.00445\sqrt{\left(\frac{BR(b \to X_u \ell\nu)}{0.002}\frac{1.55\mathrm{ps}}{\tau_b}\right)}(1 \pm 0.020_{QCD} \pm 0.035_{m_b})$$

assuming $\quad m_b = (4.58 \pm 0.06)\ \mathrm{GeV}/c^2$

statistical + detector error

$b \to c$ error

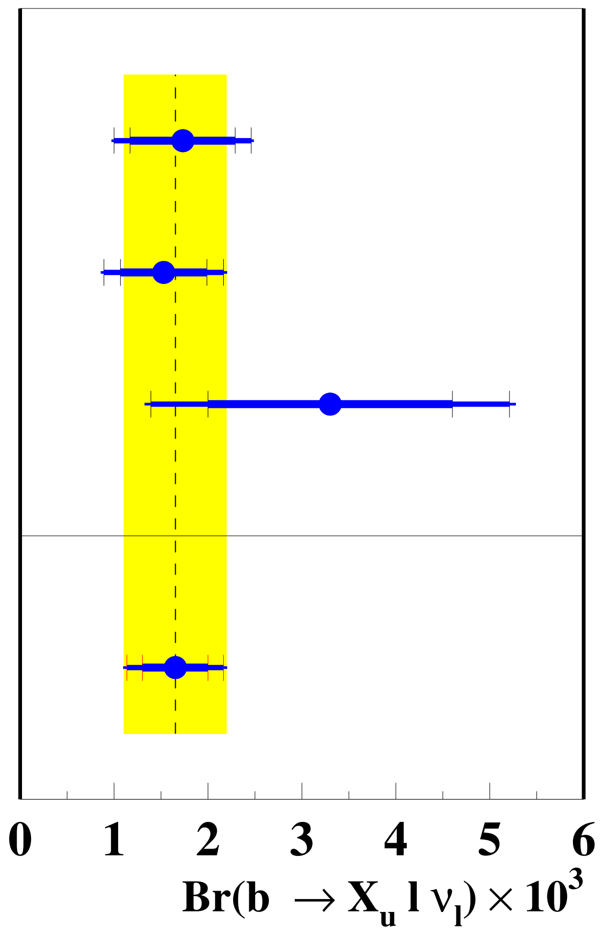
$b \to u$ modelling error

ALEPH
1.73±0.56±0.51±0.21

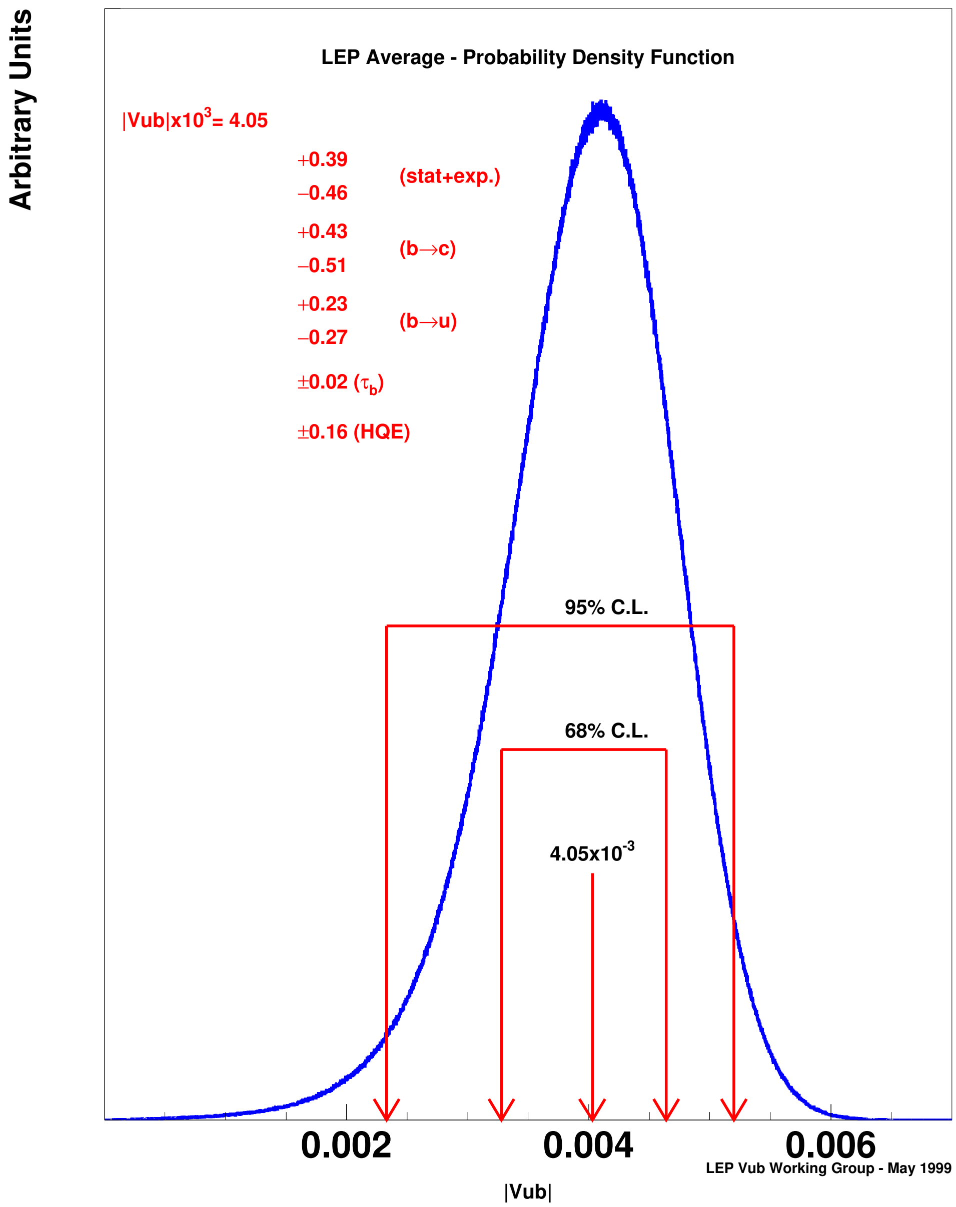
DELPHI
1.56±0.46±0.44±0.22

L3
3.3±1.3±1.4±0.5

LEP average
1.67±0.35±0.38±0.20



Measurements of $|V_{ub}|$



$$|V_{ub}| = (4.05^{+0.62}_{-0.74}) \times 10^{-3} \text{ at } 68\% \text{ C.L.}$$

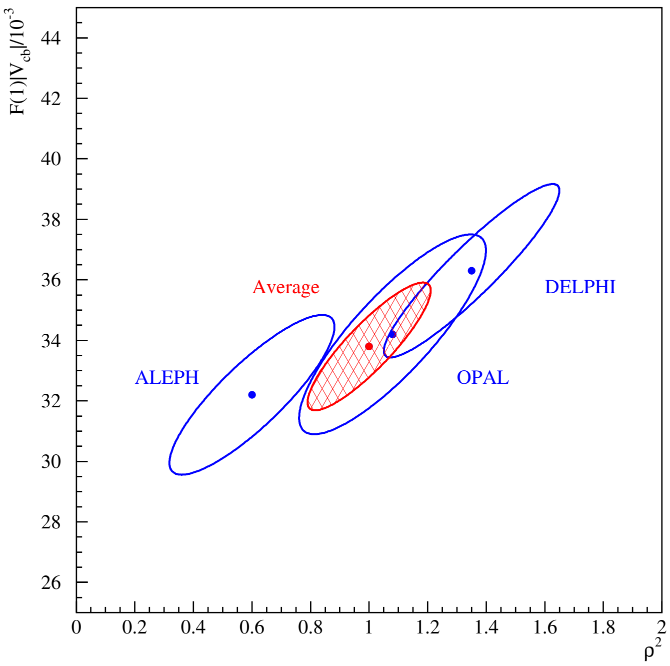
$$|V_{ub}| = (4.05^{+1.17}_{-1.70}) \times 10^{-3} \text{ at } 95\% \text{ C.L.}$$

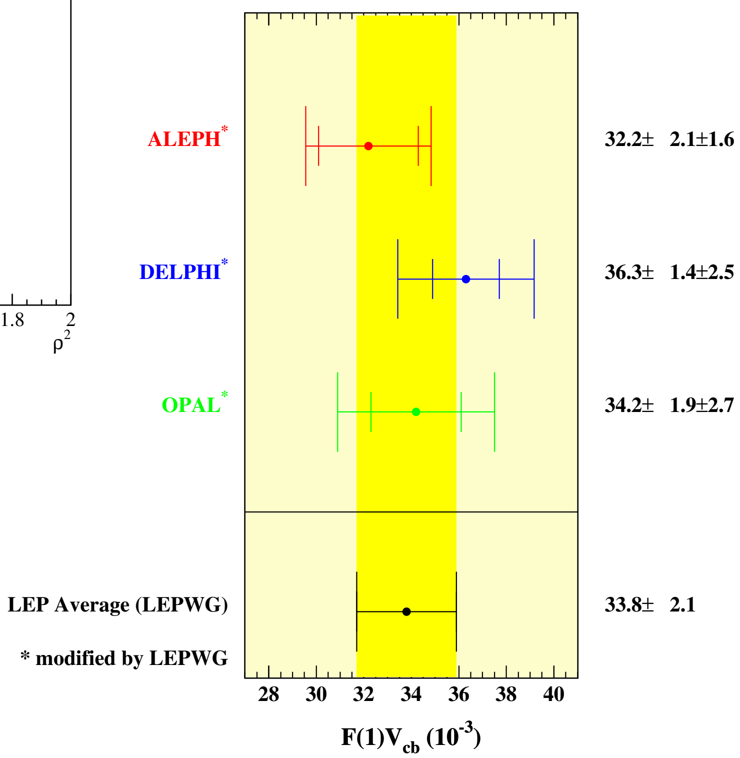
Exclusive method $\overline{\mathbf{B}}^{\mathbf{0}} \rightarrow \mathbf{D}^{*+}\ell^-\overline{\nu}_\ell$

$$\frac{d\Gamma}{dw} = \mathcal{K}(w)\mathcal{F}^2(w)|V_{cb}|^2 \qquad w = \frac{m^2_{D^{*+}} + m^2_{B^0} - q^2}{2m_{B^0}m_{D^{*+}}}$$

ρ : $\mathcal{F}(w)$-slope parameter

at $w = 1$ $\rightarrow$ zero recoil





For $\mathcal{F}(\mathbf{1}) = 0.88 \pm 0.005$

$$|\mathbf{V_{cb}}| = (\mathbf{38.4} \pm \mathbf{1.1}_{\mathbf{stat}} \pm \mathbf{2.2}_{\mathbf{sys}} \pm \mathbf{2.2}_{\mathbf{theo}}) \times \mathbf{10^{-3}}$$

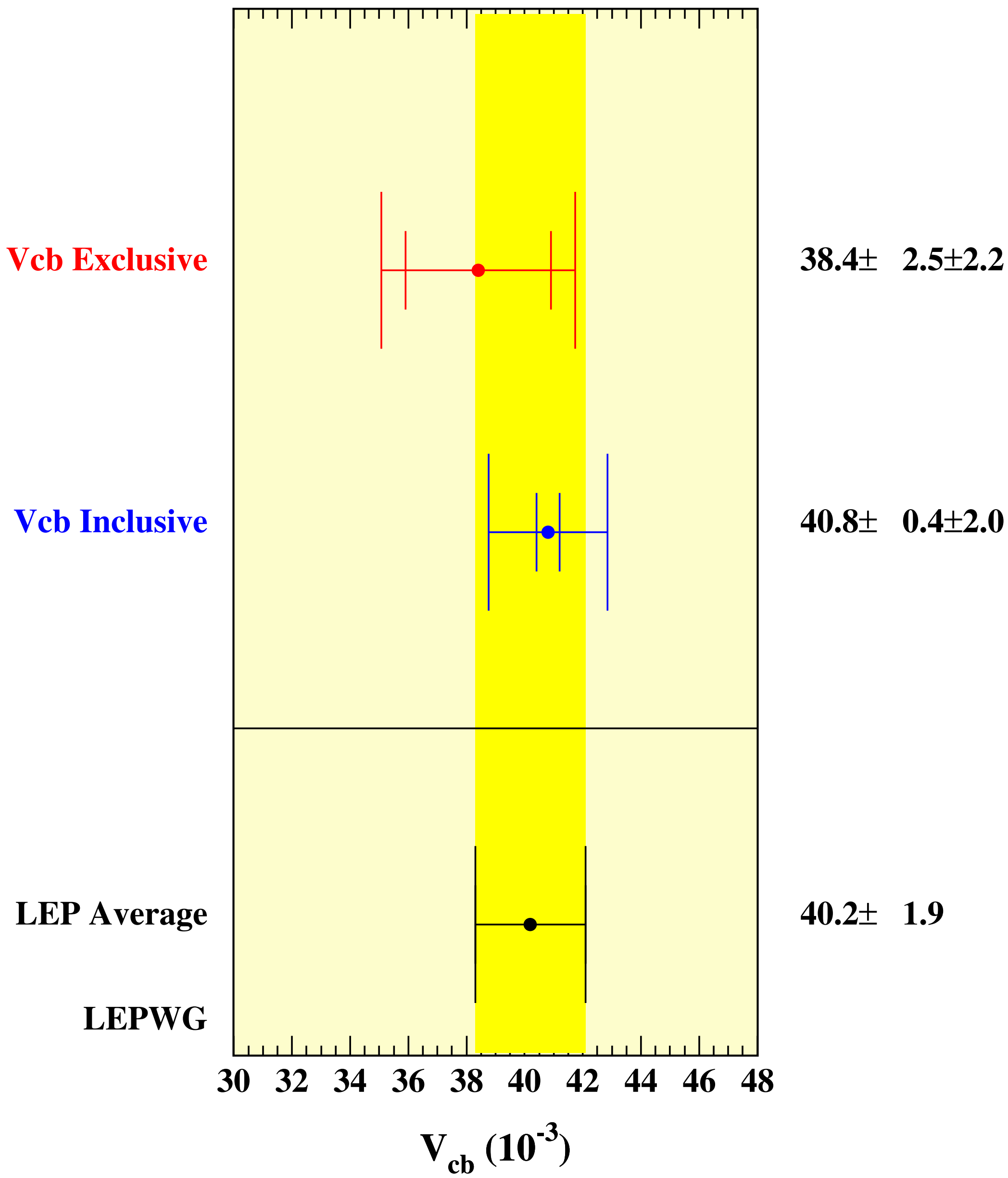
Measurements of $|V_{cb}|$

Inclusive method

$$|V_{cb}| \propto \sqrt{\frac{BR(B \to X_c l \nu)}{\tau_b}}$$

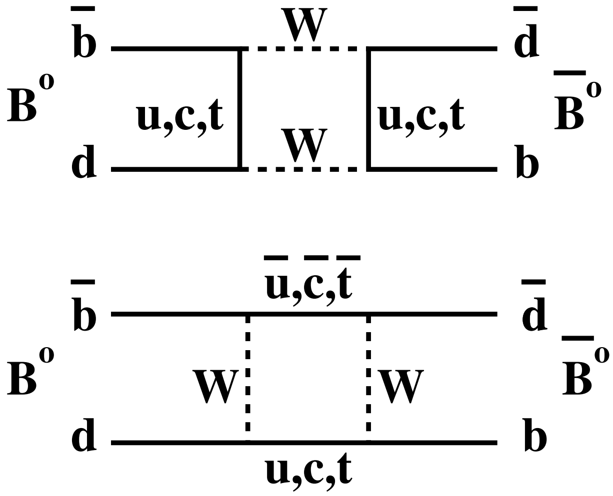
Average ALEPH, DELPHI, L3, OPAL:

$$|V_{cb}| = (40.75 \pm 0.41_{exp} \pm 2.04_{theo}) \times 10^{-3}$$



$$\text{LEP average } |V_{cb}| = (40.2 \pm 1.9) \times 10^{-3}$$

Oscillations of B_d^0 mesons



$$|B_L\rangle = p|B_d^0\rangle + q|\bar{B}_d^0\rangle$$
$$|B_H\rangle = p|B_d^0\rangle - q|\bar{B}_d^0\rangle$$

$$\mathbf{\Delta m_d} = m_{B_H} - m_{B_L}$$

Time dependence of mixing:

$$P(t \mid B_d^0 \rightarrow \bar{B}_d^0) = \frac{1}{\tau}\, e^{-\frac{t}{\tau}}\, \frac{1 - \cos \mathbf{\Delta m_d}\, t}{2}$$

Relation of $\mathbf{\Delta m_d}$ with the CKM parameters:

$$\mathbf{\Delta m_d} = \frac{G_F^2}{6\pi^2} m_W^2 m_B \left(f_{B_d}\sqrt{B_{B_d}}\right)^2 \eta_B \frac{m_t^2}{m_W^2} F\left(\frac{m_t^2}{m_W^2}\right) \times$$
$$\times A\lambda^6 \left[(1-\rho)^2 + \eta^2\right]$$

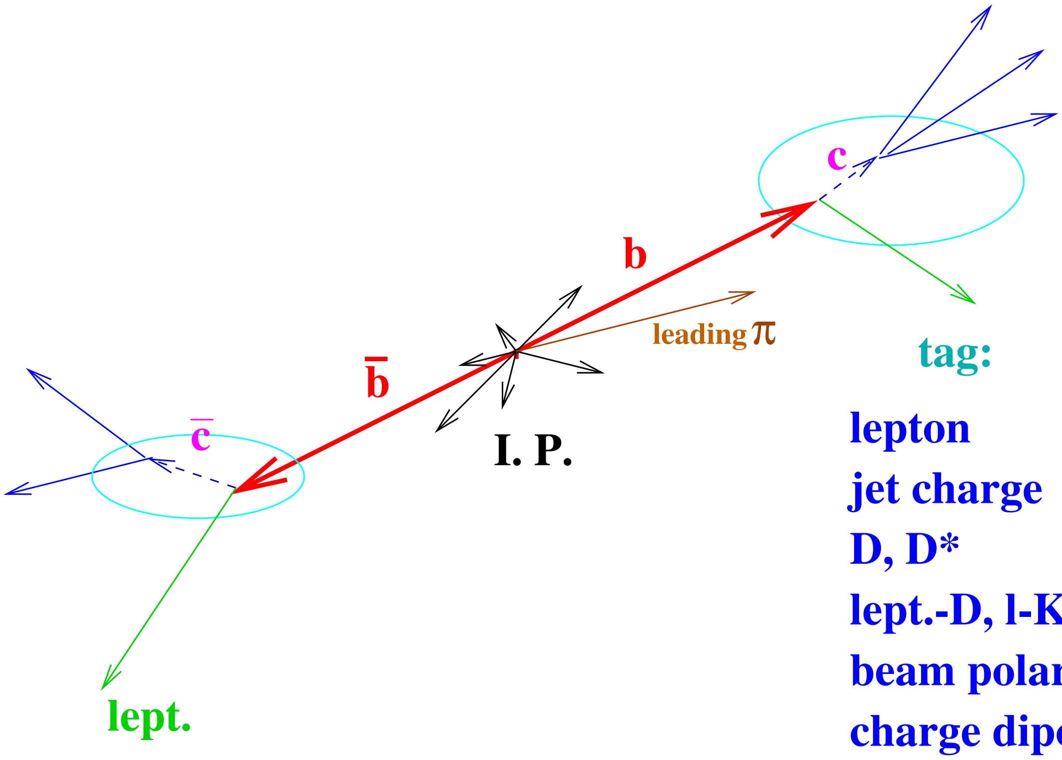
QCD corrections: $\eta_\mathrm{B} = 0.55 \pm 0.01$

"bag" parameter: $\mathrm{B_{B_d}} = 1.35 \pm 0.15$ **(lattice QCD)**

$\mathrm{f_{B_d}}\sqrt{\mathrm{B_{B_d}}} = (223 \pm 13) MeV$

Oscillations of B^0_d mesons

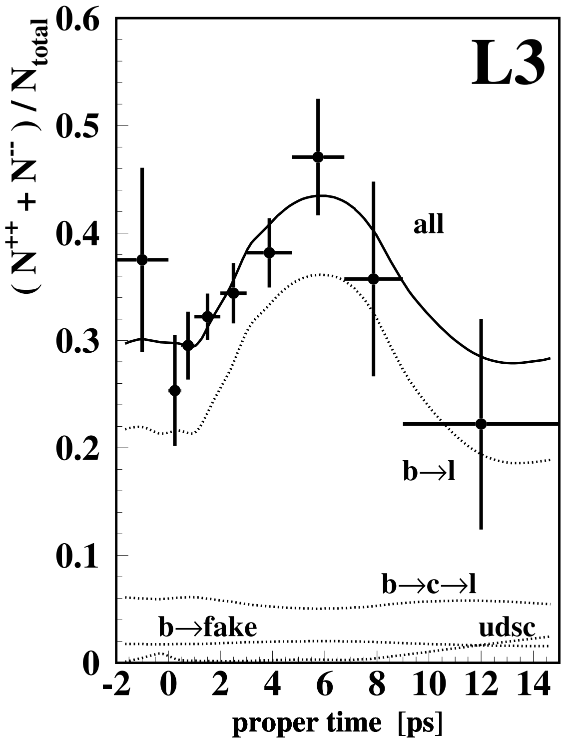
Mixing signature $\Rightarrow$ like ("right") sign leptons,



tag:

lepton
jet charge
D, D*
lept.-D, l-K corr.
beam polarization
charge dipole
. . .

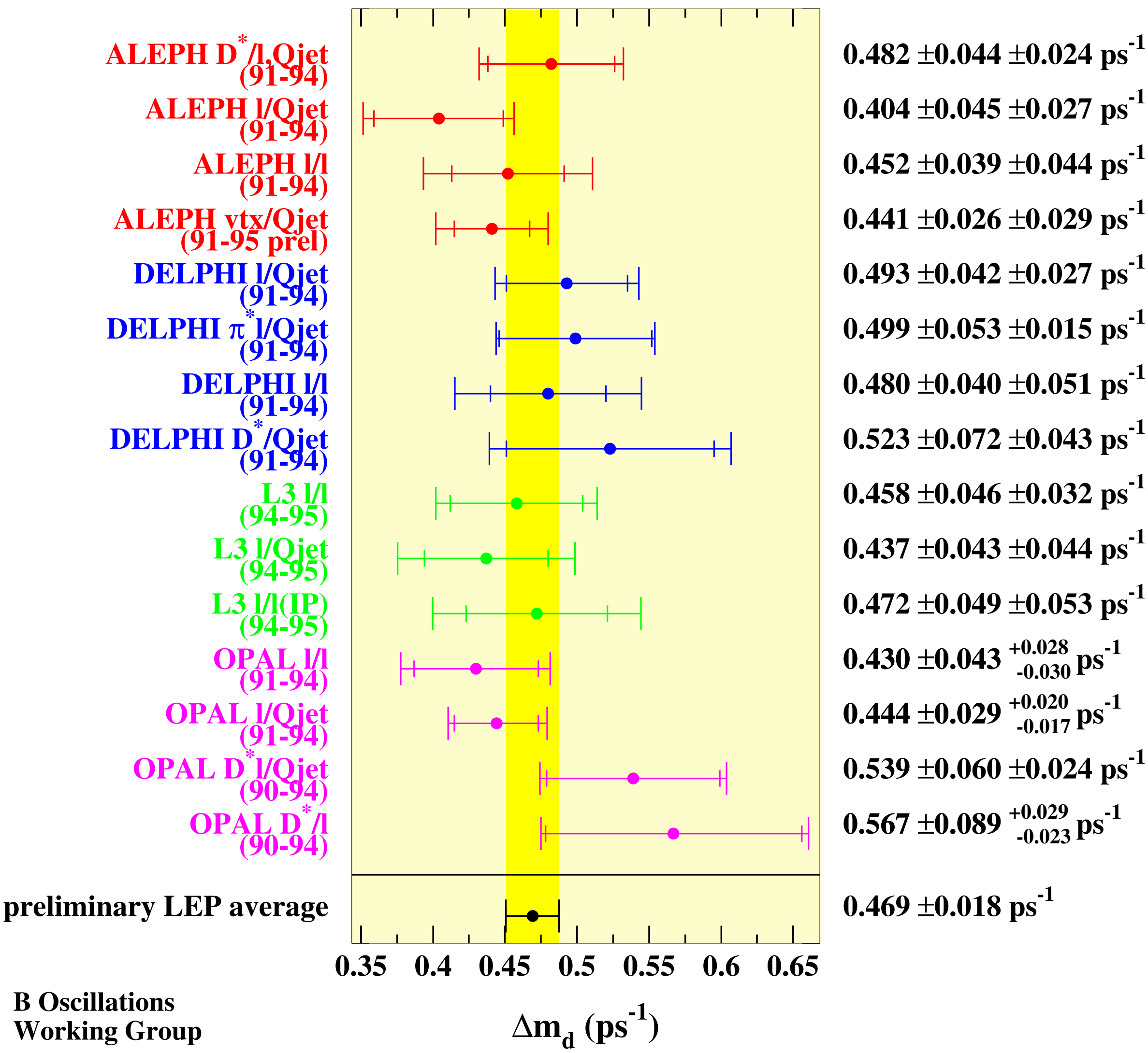
LEP experiments use different tag methods.



$$\frac{N^{like}}{N^{like}+N^{unlike}}(t) = \frac{N^{++}+N^{--}}{N_{total}}(t)$$

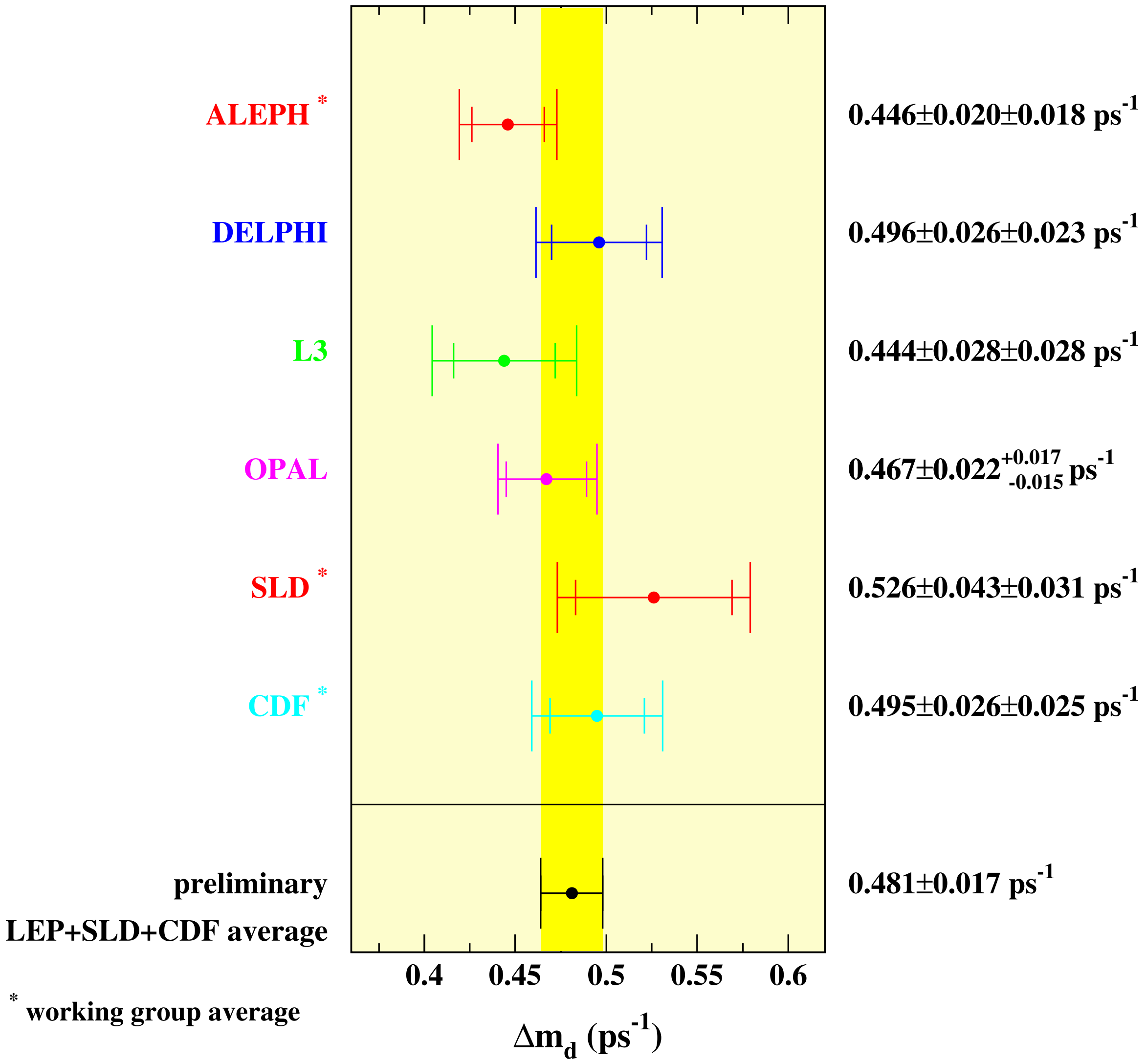
Oscillations of B_d^0 mesons

LEP Δm_d measurement results:



LEP average $\Delta m_d = 0.469 \pm 0.018 \mathrm{ps}^{-1}$

World Δm_d results:



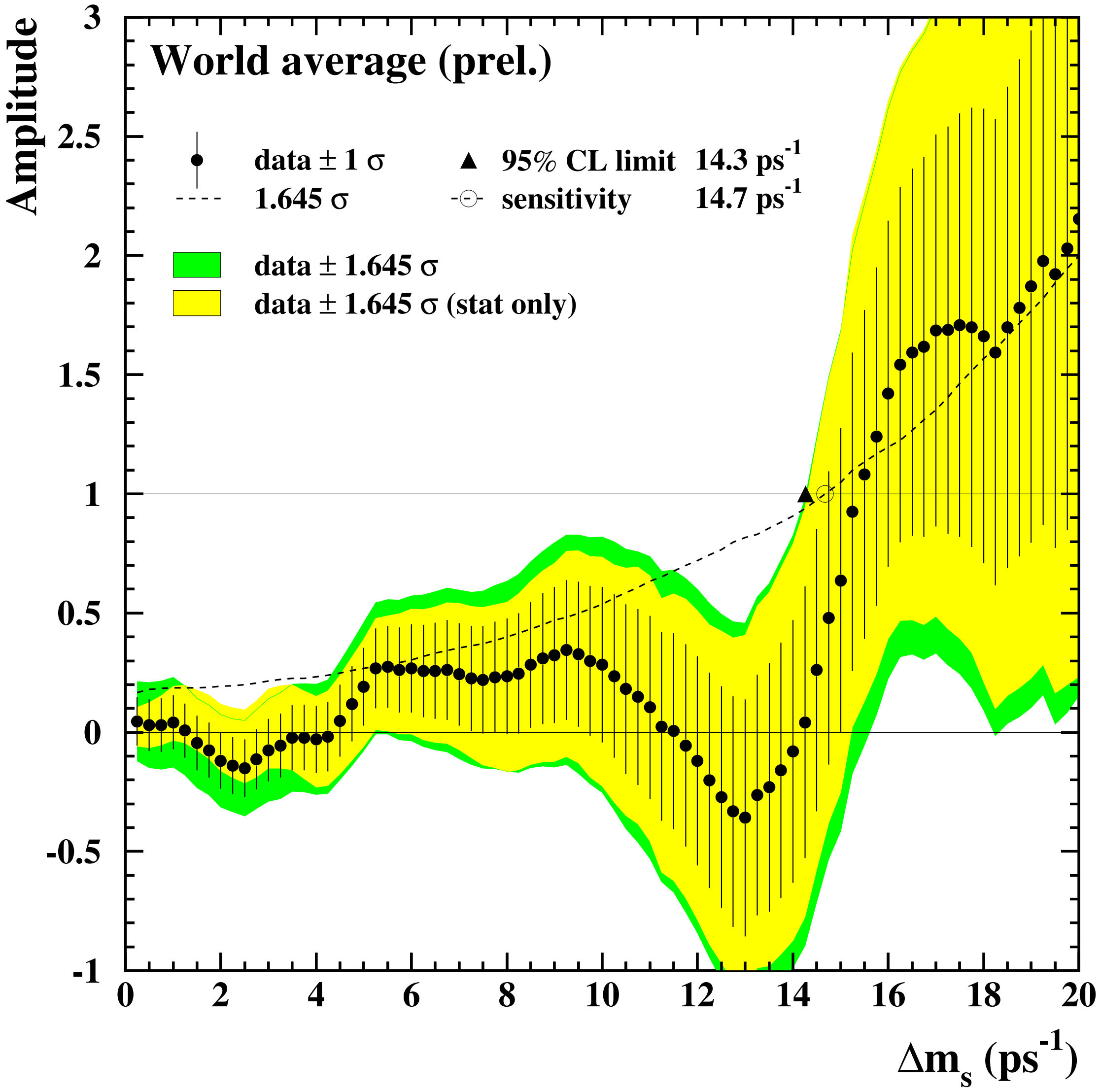
Combined LEP+SLD+CDF+$\Upsilon(4S)$ result

$$\Delta m_d = 0.473 \pm 0.016 \mathrm{ps}^{-1}$$

Oscillations of B_s^0 mesons

No experimet has yet directly observed temporal $B_s^0 - \bar{B}_s^0$ ocillations

Using Amplitude method $P(t) = \frac{e^{-\frac{t}{\tau_s}}}{2\tau_s}(1 \pm A\cos(\Delta m_s t))$:



Combined LEP+SLD+CDF limit on Δm_s

$\Delta m_s > 14.3 ps^{-1}$ at 95% C.L.

Oscillations of B_s^0 mesons

Relation of Δm_s and Δm_d with the CKM parameters:

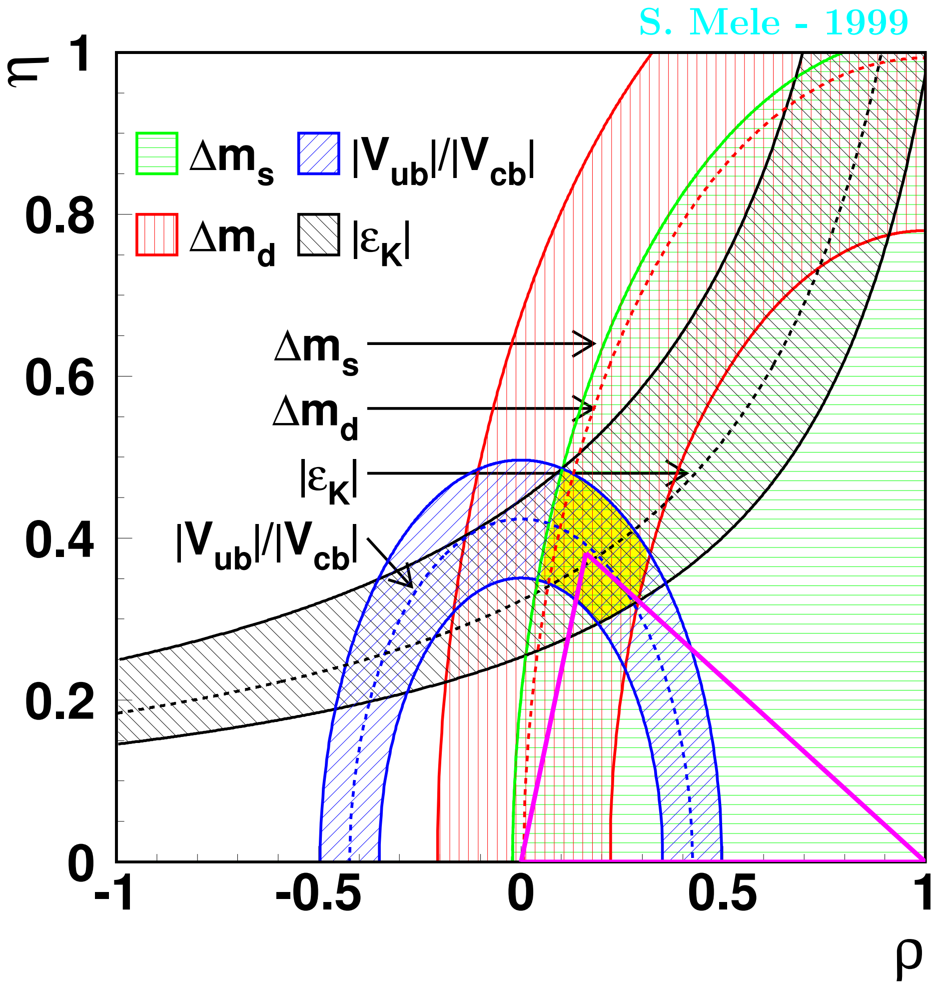
$$\frac{\mathbf{\Delta m_d}}{\mathbf{\Delta m_s}}\frac{m_{B_s}}{m_{B_d}}\xi^2 = \lambda^2((1-\rho)^2+\eta^2)$$

Since the ratio:

$$\xi = \frac{f_{B_d}\sqrt{B_{B_d}}}{f_{B_s}\sqrt{B_{B_s}}} = 1.14 \pm 0.08$$

is computed by lattice QCD with a better precision than the single terms, a measurement of $\frac{\Delta m_d}{\Delta m_s}$ could provide a much stronger constraint on (η,ρ) plane.

Constraints on the unitarity triangle



From the fit to experimental values of all the constraints on (ρ,η)

$$\rho = 0.160^{+0.094}_{-0.070} \quad \eta = 0.381^{+0.061}_{-0.058}$$

$$\sin 2\alpha = 0.06^{+0.35}_{-0.42} \quad \sin 2\beta = 0.75\pm0.09 \quad \gamma = 67^{+11}_{-12}{}^\circ$$

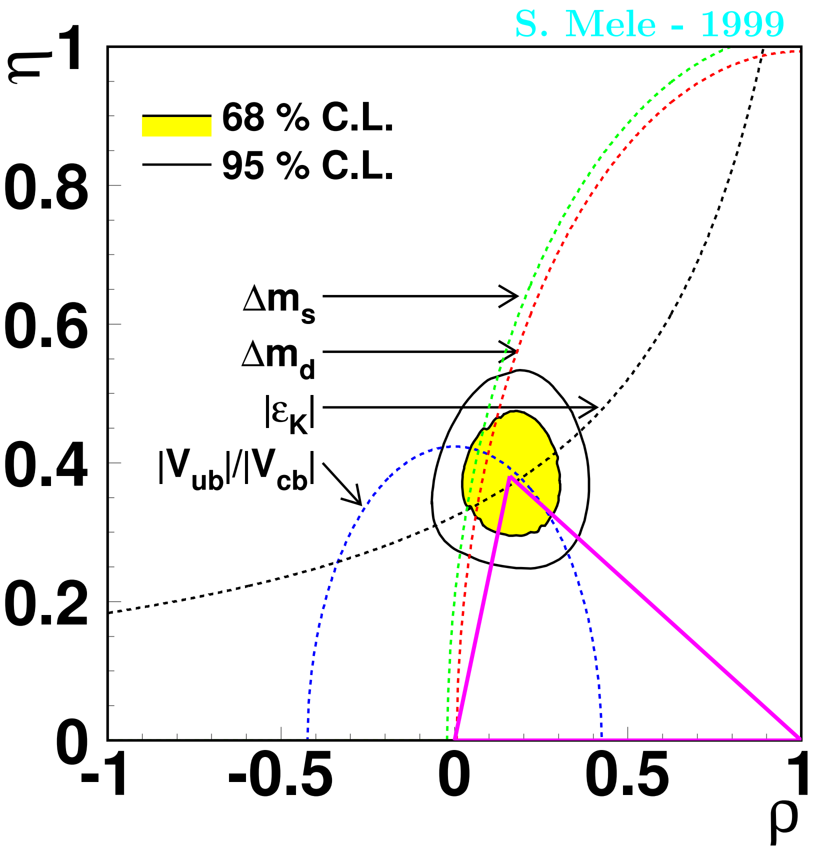
All constraints are compatible

Recent CDF measurement of

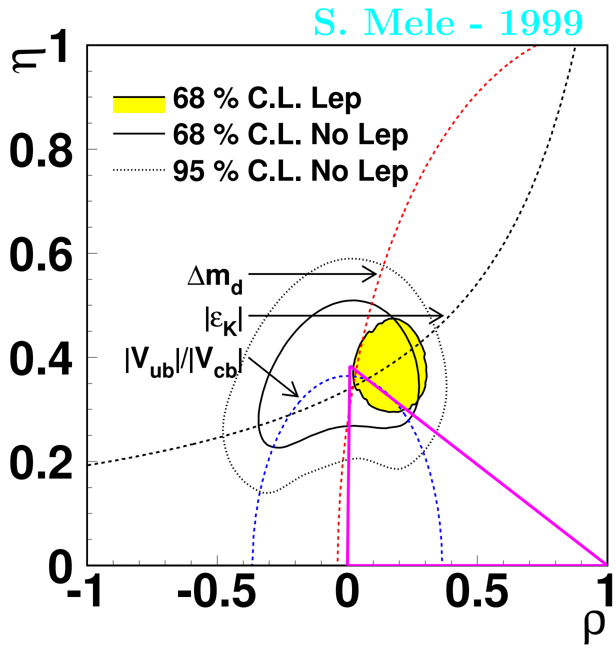
$\sin 2\beta = 0.79\pm0.39(\mathrm{stat})\pm0.16(\mathrm{syst})$

is in good agreement with this expectation

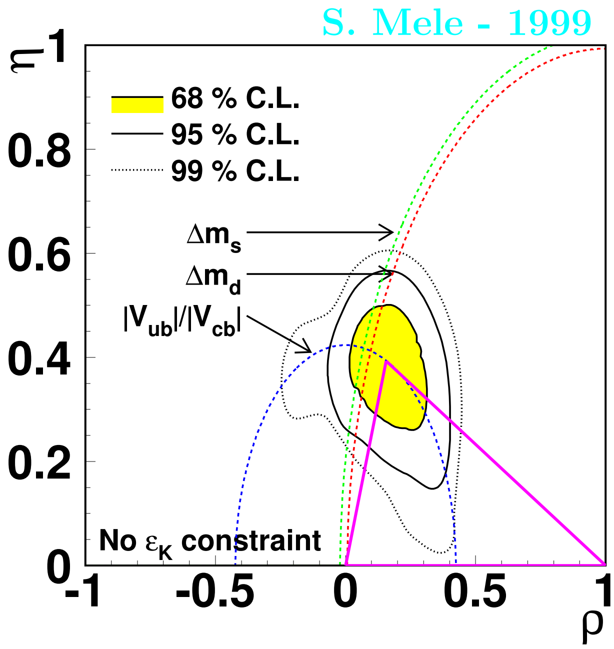
Constraints on the unitarity triangle



With/Without LEP



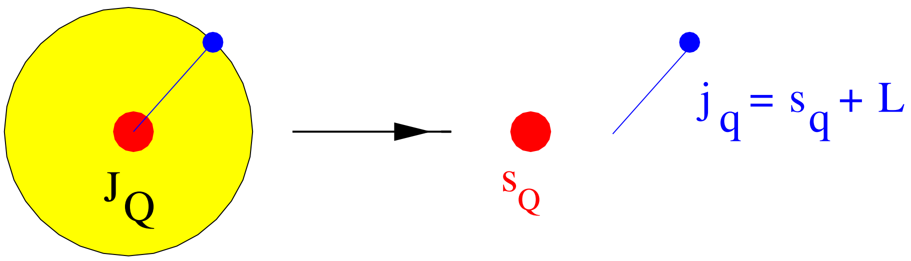
Only B-mesons (No ϵ_k)



B-spectroscopy at LEP

The spectroscopy of B mesons allows to study the underlying QCD potential.

A flavour-spin symmetry works better in B system (at $\Lambda_{QCD}/m_Q \rightarrow 0$):



- Decoupling of heavy quark Q from light degrees of freedom $\Longrightarrow$ $\vec{s}_Q$ and $\vec{j}_q = \vec{s}_q + \vec{L}$ are conserved independently
- Corrections $(1/m_Q, 1/m_Q^2)$ calculable with:

Heavy Quark Effective Theory

Spin counting:

L=0 two possible spin states:

$J^P = 1^-$ **3** B^* **states**

$J^P = 0^-$ **1** B **state**

Expected relative production rate: $\frac{\mathbf{V}}{\mathbf{V+P}} = \frac{\sigma^*_{\mathrm{B}}}{\sigma^*_{\mathrm{B}}+\sigma_{\mathrm{B}}} = \frac{\mathbf{3}}{\mathbf{4}}$

L=1 spin states of $\mathbf{B_{u,d}}$ mesons

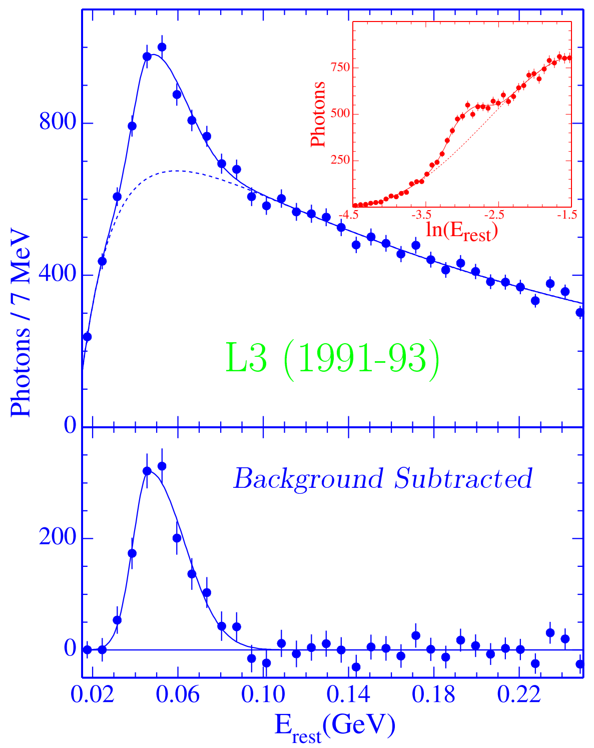
j_q	J^P	$2J+1$	Decay Mode	Transition
1/2	0^+	1	$\mathrm{B}^*_0 \to \mathrm{B}\pi$	S-wave
1/2	1^+	3	$\mathrm{B}^*_1 \to \mathrm{B}^*\pi$	S-wave
3/2	1^+	3	$\mathrm{B}_1 \to \mathrm{B}^*\pi$	D-wave
3/2	2^+	5	$\mathrm{B}^*_2 \to \mathrm{B}^*\pi, \mathrm{B}\pi$	D-wave

HQET predictions e.g. (Eichten, Hill, Quigg - 1994)

J^P	Name	Mass [MeV]	Width [MeV]	Decay
2^+	B^*_2	5771	25	$\mathrm{B}\pi, \mathrm{B}^*\pi$
1^+	B_1	5759	21	$\mathrm{B}^*\pi$
1^+	B^*_1	$M_{\mathrm{B}^*_2} - 100$	~ 150	$\mathrm{B}^*\pi$
0^+	B^*_0	$M_{\mathrm{B}^*_1} - 12$	~ 150	$\mathrm{B}\pi$

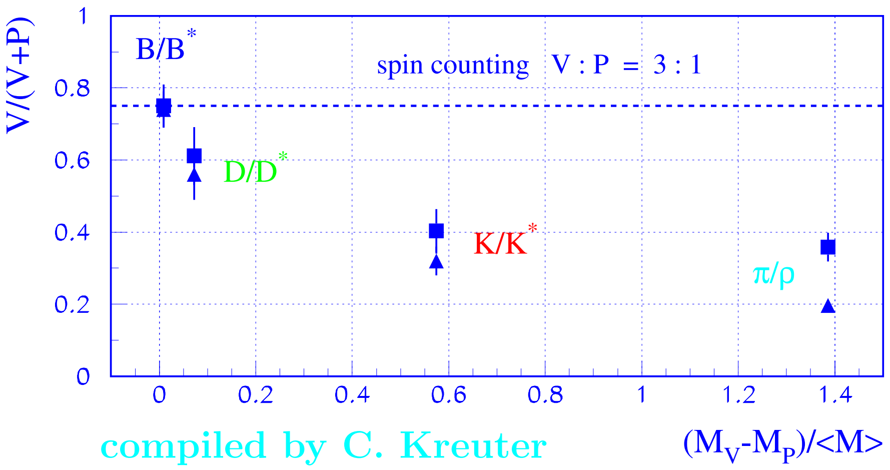
Other papers predict (Isgur, Ebert *et al.* - 1998)
spin-orbit inversion, i.e. $M_{\mathrm{B}^*_2} < M_{\mathrm{B}^*_1}$

LEP measurement of $B^*\gamma$



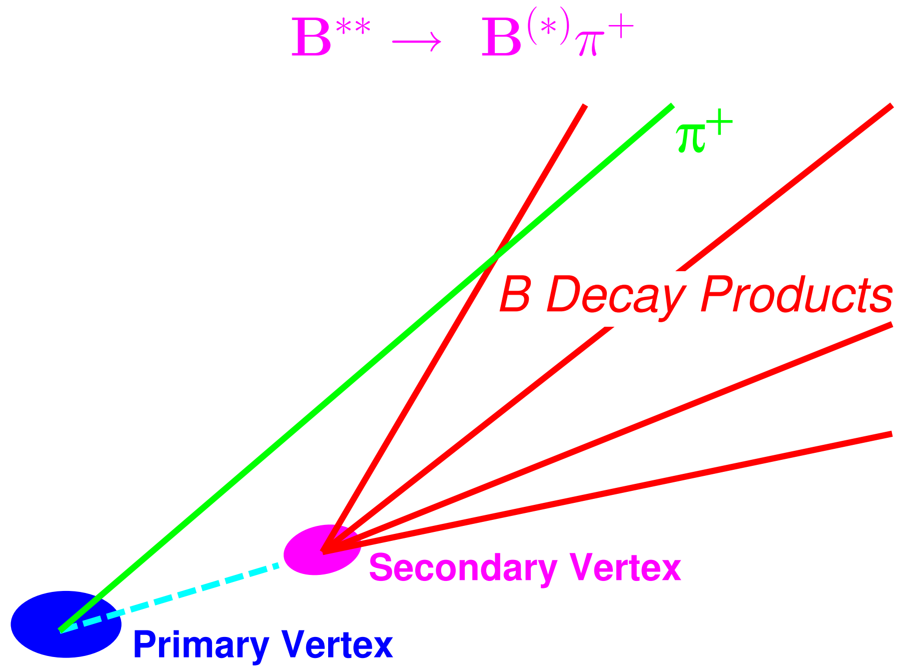
LEP (all 4) combined $\frac{\sigma^*_B}{\sigma^*_B+\sigma_B} = \mathbf{0.75 \pm 0.04}$

Spin counting works well in B system



compiled by C. Kreuter

$B^{**} \to B^{(*)}\pi$ studies



$Z \to b\bar{b}$ selection:

Lifetime based event tag

B mesons reconstruction:

Incusive (vertex charge, rapidity)

Exclusive

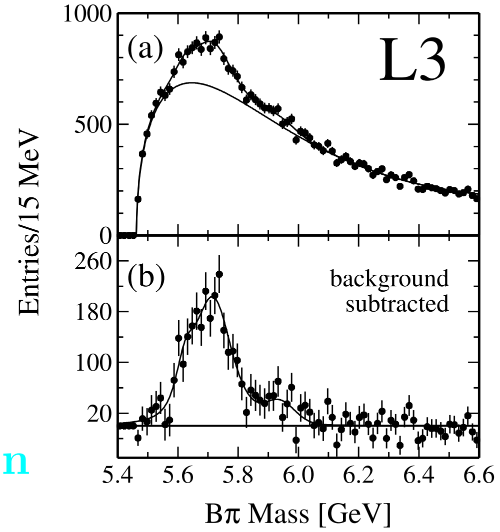
For π^+ required:

Strong decay

Points to primary vertex

Small opening angle vs B direction

Select track with max P_L^B



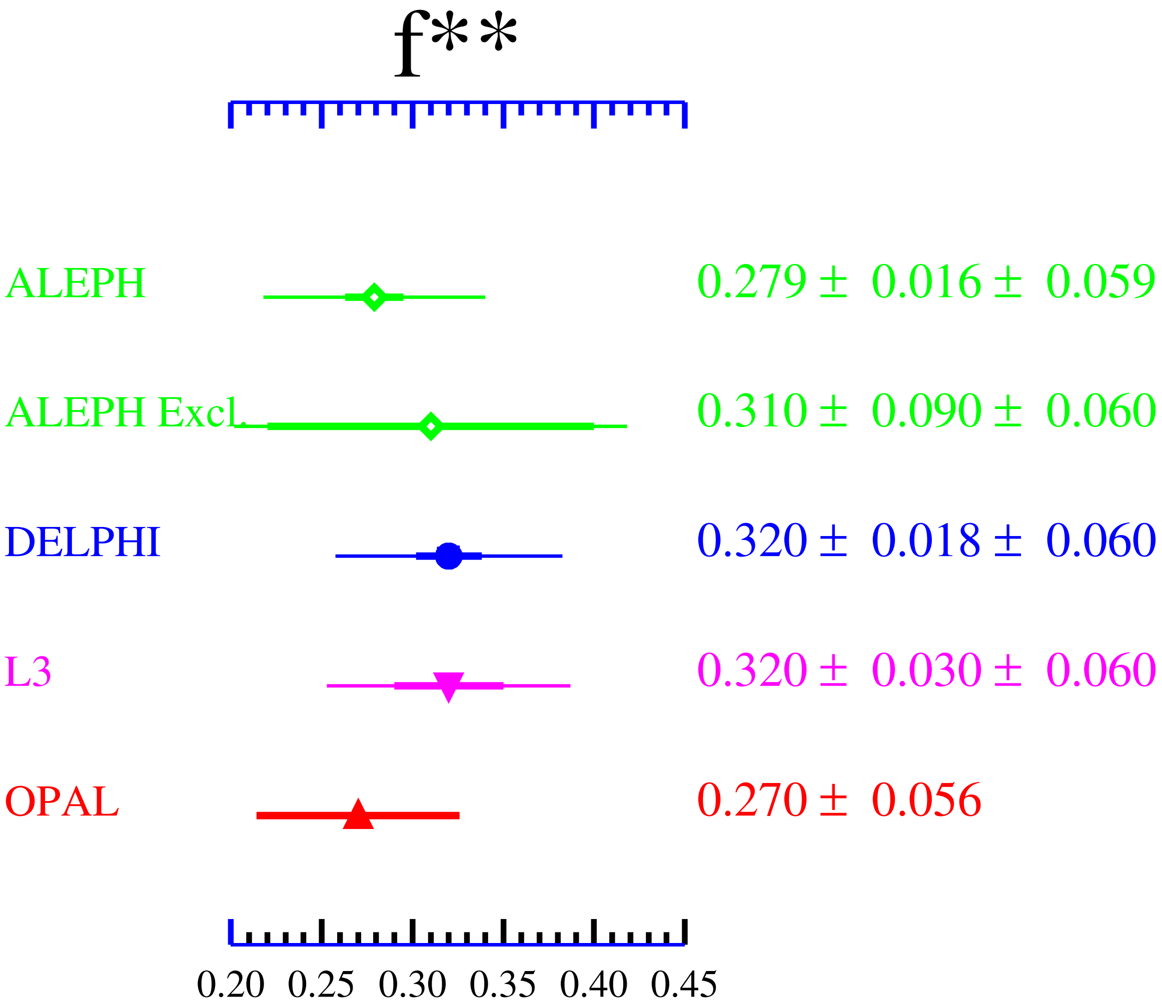
$B^{**} \rightarrow B^{(*)}\pi$ studies

B^{**} Production rate

$$f_{B^{**}} = BR(b \rightarrow B^{**}_{u,d})/BR(b \rightarrow B_{u,d})$$

Expected same as for $f_{D^{**}}$ $(20 \sim 40\%)$

Measured at LEP:



Results

LEP (single bump fit):

$M_{B^{**}_{u,d}}$	$= 5703 \pm 4 \pm 10$ MeV	ALEPH
$M_{B^{**}_{u,d}}$	$= 5734 \pm 5 \pm 17$ MeV	DELPHI
$M_{B^{**}_{u,d}}$	$= 5681 \pm 11$ MeV	OPAL

L3 new result:

$$
\begin{aligned}
M_{\mathrm{B}_2^*} &= 5768 \pm 5 \pm 6 \text{ MeV} \\
\Gamma_{\mathrm{B}_2^*} &= 24 \pm 19 \pm 24 \text{ MeV} \\
M_{\mathrm{B}_1^*} &= 5670 \pm 10 \pm 13 \text{ MeV} \\
\Gamma_{\mathrm{B}_1^*} &= 70 \pm 21 \pm 25 \text{ MeV}
\end{aligned}
$$

No evidence for spin-orbit inversion: $M_{\mathrm{B}_2^*} > M_{\mathrm{B}_1^*}$

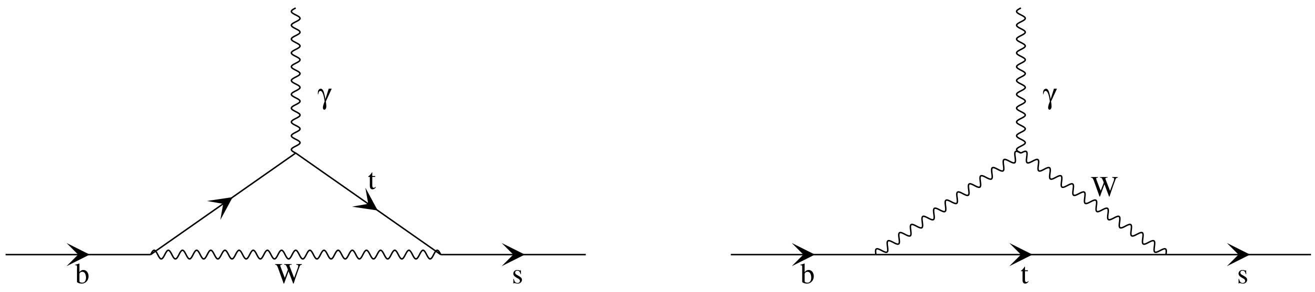
ALEPH (exclusive):

$$M_{\mathrm{B}_2^*} = 5739 \;{}^{+8}_{-11}\;{}^{+6}_{-4} \text{ MeV}$$

Results are consistent with HQET

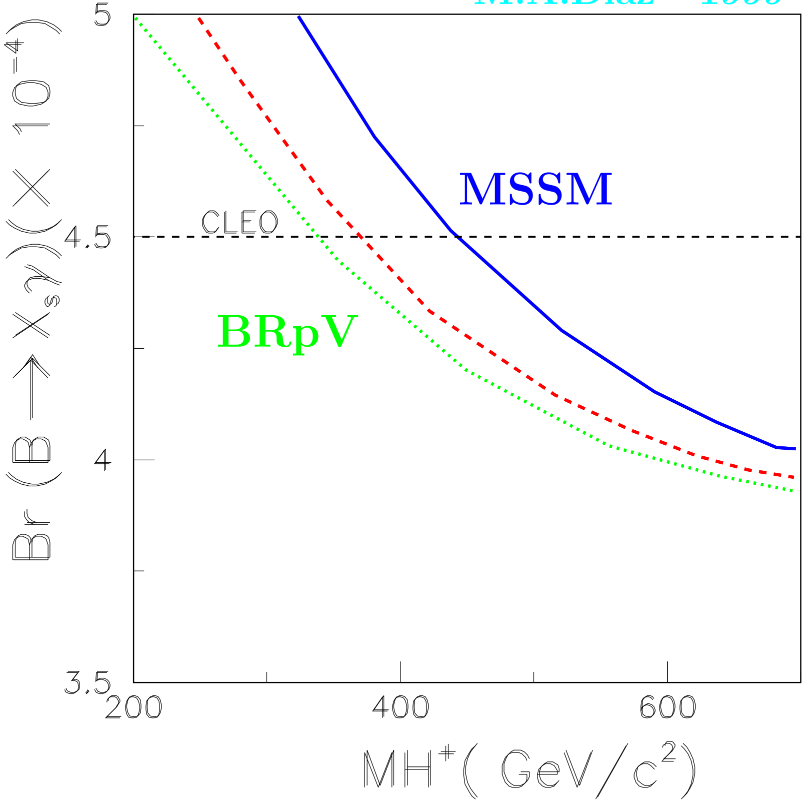
b $\to$ sγ study

The study of flavour changing neutral current provide one of the most stringent test of SM and its extensions.



Lower limit of $Br(b \to s\gamma)$ as a function of the charged Higgs mass

M.A.Diaz - 1999



ALEPH measurement

$\mathbf{Z \to b\bar{b}}$ selected in one hemisphere:

Lifetime based event tag

Hard photon associated with:

System of high momentum, high rapidity hadrons,

originating from a displaced secondary vertex

The extraction of $\mathbf{b \to s\gamma}$ signal is based on HQET:

Monte Carlo incorporating HQET predictions

Measurements and assumptions on exclusive decay rates

ALEPH measured $Br(b \to s\gamma)$ branching ratio:

$$(\mathbf{3.11 \pm 0.80_{stat} \pm 0.72_{syst}}) \times \mathbf{10^{-4}}$$

SM prediction of $Br(b \to s\gamma)$ branching ratio:

$$(\mathbf{3.76 \pm 0.30}) \times \mathbf{10^{-4}}$$

Consistent with both Standard Model and

the only previous CLEO measurement:

$$(\mathbf{2.32 \pm 0.57 \pm 0.35}) \times \mathbf{10^{-4}}$$

Conclusion

- **LEP still produce new results on B physics.**
- **Continious experimental progress improve our knowlege of the Standard Model parameters and sensitivity to the New Physics.**
- **In some cases the theoretical unsertanties are a limitation, despite the good experimental precision.**

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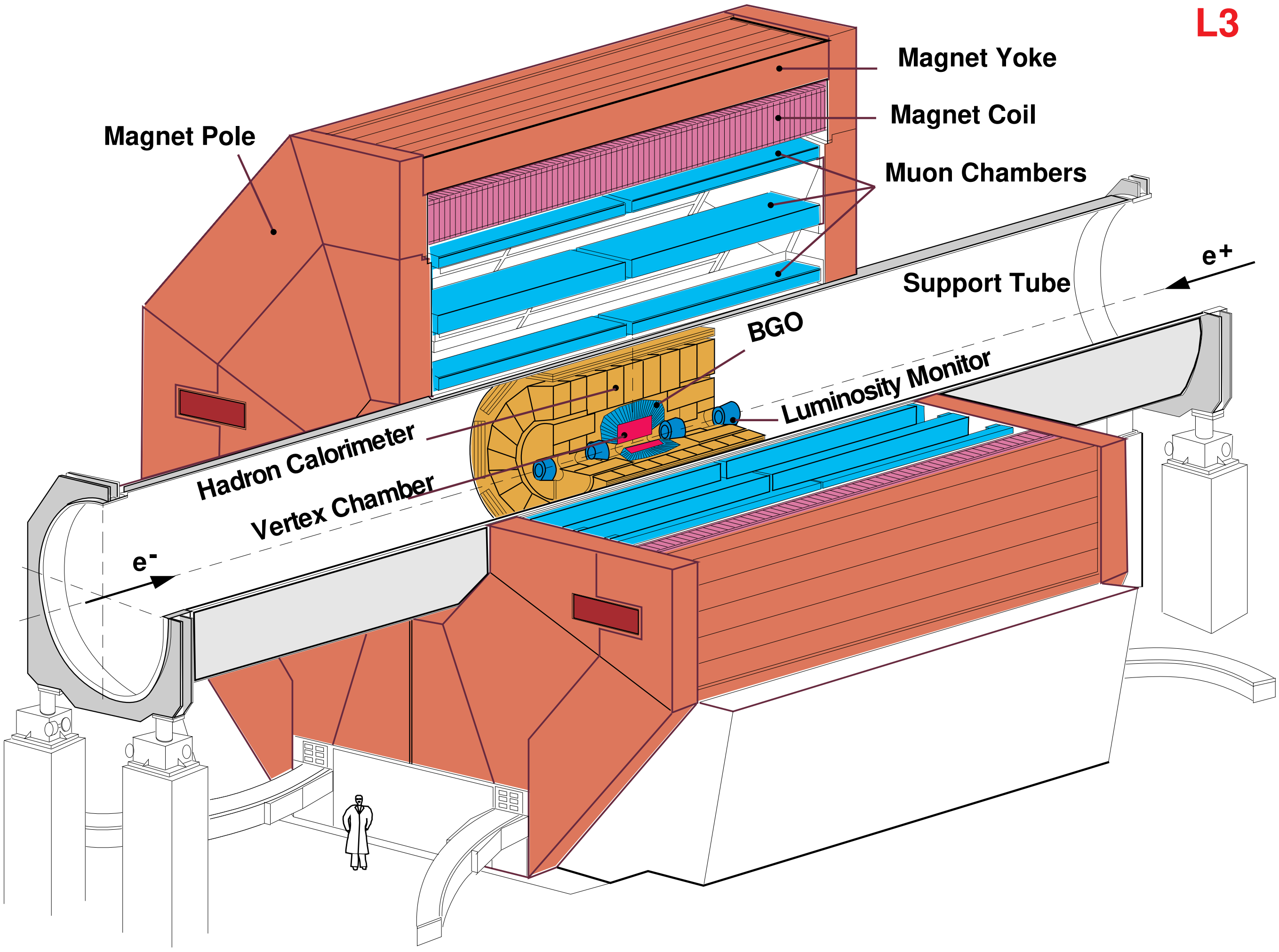

L3 general view