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:

- **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*.

Wolfenstein parametrization

4 parameters: $\lambda$, $A$, $\rho$, $\eta$
Visualization of the unitarity of the CKM matrix

Kaon Physics

Radiative decays (future)

Oscillations

B → ππ, ρπ,...

B → ΔK

LEP, SLC
+CLEO and CDF
Played a central role in measuring the sides of the UT

m_c, m_b, \mu_π, Form Factors, F(1), duality...

Moments analysis (b → sγ...) 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

\[ \sigma(Z^0 \rightarrow \text{hadrons}) \approx 30 \text{nb}, \Gamma(bb)/\Gamma(\text{hadrons}) \approx 22\% \]

TAGGING b-hadrons

- displaced vertices
- leptons

- jet charge
- fragments products

B \leftrightarrow B
- leptons
- D mesons

B_i \leftrightarrow B_j
- semileptonic decays
- fragments products

Jetty-like events

- \( \tau(B) \approx 1.6\) ps
- \( E(B) \approx 0.7E(\text{beam}) \approx 35\) GeV

L \approx \beta c \tau \approx 3\) mm
Examples of Historical evolution

b-baryon signals
1990 : ALEPH

Excess of $\Lambda$-$\Gamma$ events
(as compared to $\Lambda$-$\Gamma^+$)
(and charge conjugate final states)

b-baryons in 2002

B-baryons observed using
($\Lambda$,p, $\Lambda_c^+$, $\Xi$)-l events

The b-baryon rate in jets is :
$f(b\text{-}baryons) = (10.5 \pm 1.8)\%$

The b-quark polarization (-0.94) is diluted :
$Pol(\Lambda_b) = -0.45 \pm 0.19(-0.17)$

$\Lambda_b$ lifetime :
$\tau(\Lambda_b) = 1.208 \pm 0.051$ ps

$\Lambda_b$ mass :
$m(\Lambda_b) = 5624\pm9$ 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

7 events: \( \bar{B}^0_s \rightarrow D^+_s \Gamma \bar{\nu} X \ldots \)

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

**B^0_s in 2002**

**B^0_s observed mainly using D^+_s - l^- events**

\[ f(B^0_s) = (9.3 \pm 1.1)\% \]

**B^0_s lifetime**

\[ \tau(B^0_s) = 1.461 \pm 0.057 \text{ ps} \]

**B^0_s mass**

\[ m(B^0_s) = 5369.6 \pm 2.4 \text{ MeV} \]

**B^0_s oscillations**

\[ \Delta m_s > 14.4 \text{ ps}^{-1} \]

**Lifetime difference:**

\[ \Delta \Gamma/\Gamma < 0.31 \text{ @ 95\% C.L.} \]
Interest of measuring the Lifetimes

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

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

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)
Results on B Lifetimes

Averages from LEP/SLD/Tevatron

\[ \tau(B^0_d) = 1.540 \pm 0.014 \text{ ps (0.9\%)} \]
\[ \tau(B^+) = 1.656 \pm 0.014 \text{ ps (0.8\%)} \]
\[ \tau(B^0_s) = 1.461 \pm 0.057 \text{ ps (3.9\%)} \]
\[ \tau(\Lambda_B) = 1.208 \pm 0.051 \text{ ps (4.2\%)} \]

\[ \tau(b) = 1.573 \pm 0.007 \text{ ps (0.4\%)} \]

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

\( \Lambda_B \) Lifetime shorter
Because of W.A.
But the experimental result says the effect is more important

Is there a problem for \( \Lambda_B \)?

\( \frac{\tau(\Lambda_B)}{\tau(B^0)} \)

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 $\Xi_B$ $B_c$, $\Omega_c$
from Tevatron
Determination of $V_{cb}$

Inclusive Method

$$\Gamma_{sl} (b \rightarrow c l^- \nu) \overset{\text{theo.}}{=} \left| V_{cb} \right|^2$$

$$\exp. \quad F = \frac{B_{rs} l}{\tau_b}$$

Based on OPE

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

$$m_b \text{ (also named } \Lambda)$$

$$\mu_\pi^2 \text{ (} \lambda_1 \text{ Fermi movement)}$$

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

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

$$\Gamma_{sl} = (0.434 \times (1 \pm 0.018)) \times 10^{-10} \text{ MeV } 2\% \text{ precision}$$

$\rightarrow$ Determination of $V_{cb}$ limited by theoretical uncertainties …..
**Measurement of the moments of the distributions of the HADRONIC MASS and LEPTON MOMENTUM**

\[ \bar{\Lambda} = (0.44 \pm 0.04 \pm 0.05 \pm 0.07) \text{ GeV} \]
\[ \lambda_1 = (-0.23 \pm 0.04 \pm 0.05 \pm 0.08) \text{ GeV}^2 \]

Compatible with CLEO result:

\[ \bar{\Lambda} = (0.39 \pm 0.03 \pm 0.06 \pm 0.12) \text{ GeV} \]
\[ \lambda_1 = (-0.25 \pm 0.02 \pm 0.05 \pm 0.14) \text{ GeV}^2 \]

\[ V_{cb}(\text{inclusive}) = (40.7 \pm 0.6 \pm 0.8(\text{theo.})) \times 10^{-3} \]

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

*V_{cb} Working Group*
Exclusive method

Based on HQET

\[
\frac{d\Gamma}{dw} = \frac{G_F^2}{48\pi^2} \left| V_{cb} \right|^2 |F(w)|^2 G(w)
\]

\[
w = \frac{v_B \cdot v_{D^*}}{m_{D^*}^2 + m_B^2 - q^2} \frac{2m_{D^*}m_B}{2m_{D^*}m_B}
\]

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

At zero recoil (w=1), as \( M_Q \to \infty \), \( F(1) \to 1 \)

Strategy: Measure \( d\Gamma/dw \)
extrapolate to \( w=1 \) to extract \( F(1) |V_{cb}| \)
$F(1) = 0.91 \pm 0.04$

$V_{cb}(\text{exclusive}) = (41.9 \pm 1.1 \pm 1.9) \times 10^{-3}$

$V_{cb}(\text{inclusive}) = (40.7 \pm 0.6 \pm 0.8) \times 10^{-3}$

$V_{cb} = (40.9 \pm 0.8) \times 10^{-3}$
Inclusive determination of $V_{ub}$

Challenge measurement from LEP

Using several discriminant variables to distinguish between the transitions:

$b \rightarrow c$

$b \rightarrow u$

$B \rightarrow X_u l \nu$
**Inclusive $b \rightarrow X_u \ell \bar{\nu}$ at LEP**

<table>
<thead>
<tr>
<th>ALEPH</th>
<th>DELPHI</th>
</tr>
</thead>
<tbody>
<tr>
<td>NN Selection</td>
<td>$M_\chi$ Incl.</td>
</tr>
<tr>
<td>Fit NN Output</td>
<td>Fit $E_\gamma^*$ for $M_\chi^2 &lt; 1.6$</td>
</tr>
<tr>
<td>Eff = 11%, S/B = 0.07</td>
<td>Eff = 6.5%, S/B = 0.10</td>
</tr>
</tbody>
</table>

**Results from all the LEP experiments**

<table>
<thead>
<tr>
<th>OPAL</th>
<th>L3</th>
</tr>
</thead>
<tbody>
<tr>
<td>NN Selection</td>
<td>Kinematic Selection</td>
</tr>
<tr>
<td>Fit NN Output</td>
<td>Counting Expt</td>
</tr>
<tr>
<td>Eff = 4.2, S/B = 0.05</td>
<td>Eff = 1.5%, S/B = 0.16</td>
</tr>
</tbody>
</table>

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[Graphs and data plots for ALEPH, OPAL, and DELPHI results are shown here.]

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[Graphs and data plots for L3 results are shown here.]
**V_{ub} Summary**

- Aleph NN: 4.12 ± 0.67 ± 0.62 ± 0.35
- Opal NN: 4.00 ± 0.71 ± 0.59 ± 0.40
- Delphi M_{\chi}: 4.07 ± 0.65 ± 0.47 ± 0.39
- L3 π-l: 5.7 ± 1.0 ± 1.3 ± 0.5
- Cleo E_{l}: 4.12 ± 0.34 ± 0.44 ± 0.33
- Babar Prel. E_{l}: 4.43 ± 0.29 ± 0.50 ± 0.43
- Cleo Prel. M_{\chi}-q^2: 4.05 ± 0.18 ± 0.63 ± 0.60
- Belle Prel. πlv: 3.23 ± 0.14 ± 0.26 ± 0.65
- Cleo Prel. πlv: 3.32 ± 0.21 ± 0.23 ± 0.47
- Cleo πlv: 3.23 ± 0.23 ± 0.25 ± 0.58
- Babar Prel. πlv: 3.69 ± 0.23 ± 0.27 ± 0.50

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

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

+ CLEO Exclusive results

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**Next V_{ub} average soon**
Study of the time dependent behaviour of the Oscillation $B^0 \to \bar{B}^0$

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

$\Delta m_q$ can be seen as an oscillation frequency: $1 \text{ ps}^{-1} = 6.58 \times 10^{-4} \text{ eV}$

TextBook Plot

![Graph showing oscillation behavior with proper time in psec on the x-axis and fraction of like-sign events on the y-axis.]
In SM : $\Delta F=2$ process

GIM mechanism (Rate $\sim m_1^2 - m_2^2$)

Dominated by $t$ exchange

Rate LARGE

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

(due to the large phase phase in B decays)

Allow to access fundamental parameters of the Standard Model

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

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

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

$\Delta m_s \approx 20 \Delta m_d$

$\Delta m_s$ oscillations fast

Excellent time resolution required

$\xi$ better know than $f_B B_B$

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

Purity of tagging at production time:

$\mathcal{E}_p$

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

Purity of tagging at decay time:

$\mathcal{E}_d$

Measurement of the decay time

$$\sigma(\Delta m) \approx \frac{1}{\sqrt{N P_s}} \frac{1}{(2\mathcal{E}_d - 1)} \frac{1}{(2\mathcal{E}_p - 1)} e^{-\left(\frac{\sigma_t}{\Delta m_s}\right)^2}$$

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

$\sigma_t$ is the time resolution. As soon as $\Delta m_s$ becomes larger, the precision on the time measurement becomes crucial.
LEP/SLD/CDF measured precisely the $\Delta m_d$ frequency
\[ \Delta m_d = 0.498 \pm 0.013 \text{ ps}^{-1} \text{ LEP/SLD/CDF (2.6 \%)} \]

B-factories confirmed the value improving the precision by a factor 2
\[ \Delta m_d = 0.503 \pm 0.006 \text{ ps}^{-1} \text{ LEP/SLD/CDF/B-factories (1.2\%)} \]
Combine many different analyses which give limits

Combination using the **amplitude method**

**Measurement of A at each Δm_s**

Combination using A and σ_A

At given Δm_s

A = 0 no oscillation
A = 1 oscillation

**Δm_s** excluded at 95% CL

A + 1.645σ_A < 1

**Sensitivity** same relation with A = 0

1.645σ_A < 1

\[
\begin{align*}
P_{B_s^0 \rightarrow B_s^0 (\bar{B}_s^0)} &= \frac{1}{2} e^{-t/\tau_s} (1 \pm A \cos \Delta m_s t) \\
\end{align*}
\]
"Hint of signal" at $\Delta m_s \sim 17.5 \text{ ps}^{-1}$ with significance at 2.3 $\sigma$

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

Sensitivity at 19.2 ps$^{-1}$

Expectation in The Standard Model

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

< 24.6 @ 95% C.L.

Including $\Delta m_s$

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

< 20.9 @ 95% C.L.
What we have learnt about the Unitarity Triangle

Constraints: $V_{ub}$, $V_{cb}$, $\varepsilon_K$, $\Delta m_d$, $\Delta m_s$, $\sin 2\beta$

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

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

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

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

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

$\sin 2\alpha = -0.24^{+0.24}_{-0.20}$
\sin 2\beta = 0.715^{+0.055}_{-0.045} \quad \text{"indirect" sides} + \varepsilon_K

\sin 2\beta = 0.734 \pm 0.054 \quad \text{direct from } B \rightarrow J/\psi K^0_s

Coherent picture of CP Violation in SM
Prediction for $\Delta m_s$

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

$[12.5 - 24.6] \text{ @95\% C.L.}$

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

$[15.2 - 20.9] \text{ @95\% C.L.}$
Conclusions

In 10 years our understanding of the flavour sector of the SM Model improved. 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 $\Lambda_B$)

$V_{cb}$ 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
$\Delta m_d$ precisely measured (2.6% $\rightarrow$ 1.2% with B-factories)

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

UT parameters knowledge much improved
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: $\frac{\Delta \Gamma}{\Delta m_s} \approx \frac{3}{2} \pi \left( \frac{m_s^2}{m_\pi^2} \right)$ (naively)
  - possible visibility for $\Delta \Gamma_s$
  - $\Delta m_s$ accessible via $\Delta \Gamma_s$ (important if $\Delta m_s$ is too high)
- Caveat: Theory still uncertain....

![CDF, LEP average](image)

Assuming $\tau(B^0) - \tau(B_s^0)$

- $\Delta \Gamma_s / \Gamma_s = 0.15^{+0.09}_{-0.09}$
- $\Delta \Gamma_s / \Gamma_s < 0.31$ 95% C.L.

No assumptions

- $\Delta \Gamma_s / \Gamma_s = 0.24^{+0.16}_{-0.12}$
- $\Delta \Gamma_s / \Gamma_s < 0.53$ 95% C.L.
$n_c$ versus $Br(b \rightarrow \ell \nu)$

$Br_{st}: b \rightarrow c \ell^- \bar{\nu}$ is on the low side of the theo. expectation. A possible explanation is that the $c$-quark effective mass is low $\rightarrow$ large decay rate for $b \rightarrow c \bar{c}s(d)$

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

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

Many different ways of measuring $n_c$:

- **inclusive production of** $D^0, D^+, D_s^+, \Lambda_c^+, \Xi_c^{+0}$

- **inclusive-topological double-open, single and no-charm measurements**

- **Charmonium production**
Exclusive wrong-sign measurements: $b \rightarrow D\bar{D}_s X$

Previous measurements from ALEPH (CLEO)

Technique:

- Reconstruct 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 $\mu$**: $\frac{\mu}{m_b} \simeq 0.35$
  ( $\mu =$ scale at which the QCD corrections have to be evaluated )
Inputs for the CKM fit

Standard set:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Gaussian $\sigma$</th>
<th>Uniform half-width</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>0.2210</td>
<td>0.0020</td>
<td>-</td>
</tr>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>$(excl.)</td>
<td>$42.1 \times 10^{-3}$</td>
</tr>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>$(incl.)</td>
<td>$40.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>$(ave.)</td>
<td>$40.6 \times 10^{-3}$</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>$(excl.)</td>
<td>$32.5 \times 10^{-4}$</td>
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<tr>
<td>$</td>
<td>V_{ub}</td>
<td>$(incl.)</td>
<td>$40.9 \times 10^{-4}$</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>$(ave.)</td>
<td>$36.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>/</td>
<td>V_{cb}</td>
</tr>
<tr>
<td>$\Delta M_d$</td>
<td>0.503 ps$^{-1}$</td>
<td>0.006 ps$^{-1}$</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta M_s$</td>
<td>$&gt; 14.4$ ps$^{-1}$ at 95% C.L.</td>
<td>sensitivity 19.2 ps$^{-1}$</td>
<td>-</td>
</tr>
<tr>
<td>$m_t$</td>
<td>167 GeV</td>
<td>5 GeV</td>
<td>-</td>
</tr>
<tr>
<td>$\sin 2\beta$</td>
<td>0.734</td>
<td>0.054</td>
<td>-</td>
</tr>
<tr>
<td>$B_K$</td>
<td>0.86</td>
<td>0.06</td>
<td>0.14</td>
</tr>
<tr>
<td>$f_{B_d}\sqrt{\hat{B}}_{B_d}$</td>
<td>230 MeV</td>
<td>30 MeV</td>
<td>15 MeV</td>
</tr>
<tr>
<td>$\xi$</td>
<td>1.18</td>
<td>0.03</td>
<td>0.04</td>
</tr>
</tbody>
</table>

New lattice QCD parameters with "chiral logarithms"

$$f_{B_d}\sqrt{\hat{B}}_{B_d} = 235 \text{ MeV}$$

$$\xi = 1.18 \quad 0.04$$

$$+0_{-24}^{+12} \text{ MeV}$$