LEP $|V_{\rm cb}|$ and $|V_{\rm ub}|$ measurements

Richard Hawkings (CERN, OPAL collaboration)

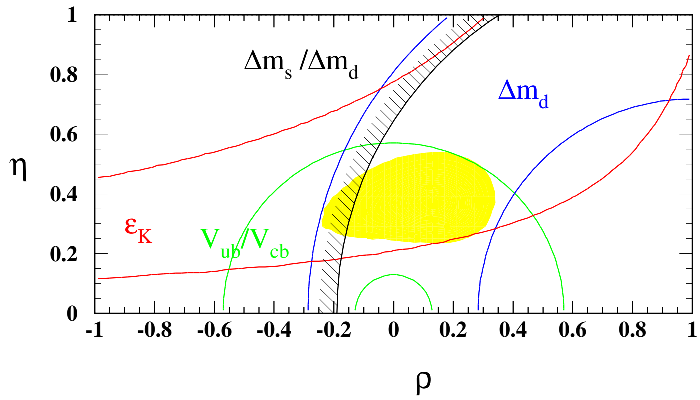
- Introduction—LEP experimental techniques
- Measurement of $|V_{\rm cb}|$ from $\bar{\rm B}^0 \to {\rm D}^{*+}\ell^-\bar{\nu}$ decays.
- Measurement of $|V_{\rm ub}|$ from inclusive ${\rm b} \to {\rm X_u}\ell\bar{\nu}$ decays.
- Summary and conclusions.

Thanks to LEP $V_{\rm cb}$ and $V_{\rm ub}$ groups for combinations used in this talk.

Motivation

CKM matrix elements—fundamental parameters of the Standard Model, involved in the unitarity triangle game…

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

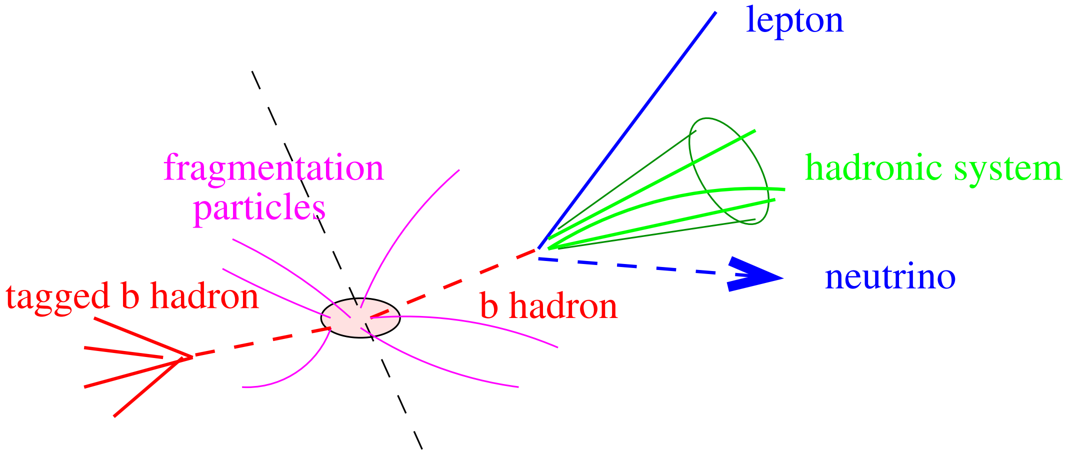


- $|V_{\rm cb}|$ ($\sim A\lambda^2$) the third most precisely known element.
- $|V_{\rm ub}|$ ($\sim A\lambda^3$) very small, important for CKM CP violation.

LEP Experimental Techniques

Each LEP experiment has 0.9 M $Z^0 \to b\overline{b}$ events.

- Clean separation of two b hadrons in event.
- Secondary vertex b-tagging (silicon) allows 90–99 % b event purity.



Large boost of b hadrons ($\langle p \rangle \sim 32$ GeV).

- Separate b-decay and fragmentation particles using kinematic information (+ vertexing for charged particles).
- b-decay products' momenta dominated by boost
- No $E_{\rm b} = E_{\rm beam}$ constraint, but b hadron energy can be determined inclusively from rest of event (resolution 3–5 GeV).
- b direction can be determined inclusively (20-50 mrad).

Neutrino can be reconstructed from missing energy/momentum.

LEP analyses mature: data and MC well understood, sophisticated multivariate techniques, neural networks. . .

$|V_{\rm cb}|$: Theory

$|V_{\rm cb}|$ can be measured from differential decay rate in $\bar{\rm B}^0 \to {\rm D}^{*+}\ell^-\bar{\nu}$.

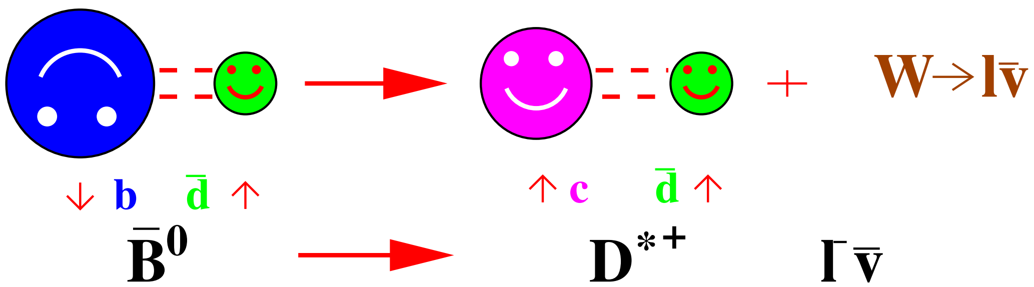
q^2 is 4-mom of leptonic system; recoil ω product of 4-velocities of B and $\rm D^*$.

$$\omega = \frac{m^2_{\rm B^0} + m^2_{\rm D^{*+}} - q^2}{2m_{\rm B^0}m_{\rm D^{*+}}}\ , \quad 1 < \omega < 1.504$$

Differential decay rate:

$$\frac{d\Gamma}{d\omega} = \frac{1}{\tau_{\rm B^0}}\frac{d{\rm Br}({\rm B}^0 \to {\rm D}^{*+}\ell\bar{\nu})}{d\omega} = \mathcal{F}^2(\omega)|V_{\rm cb}|^2\mathcal{K}(\omega)$$

$\mathcal{F}(\omega)$ is the hadronic form factor, $\mathcal{K}(\omega)$ is phase space ($\mathcal{K}(1) \to 0$).



- Heavy Quark Symmetry: With $m_b \to \infty$, $m_c \to \infty$, $\mathcal{F}(1) = 1$.
- Heavy Quark Effective Theory: Corrections to $\mathcal{F}(1)$ with finite quark masses can be calculated: recent estimate $\mathcal{F}(1) = 0.913 \pm 0.042$ (from BaBar physics book)

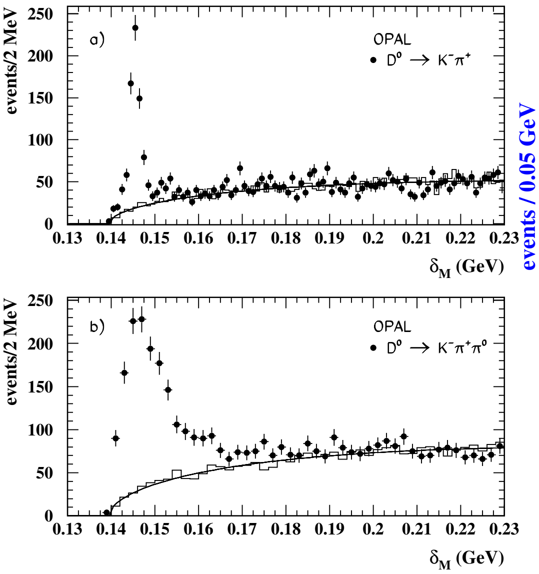
First measurements used linear or quadratic forms for $\mathcal{F}(\omega)$.

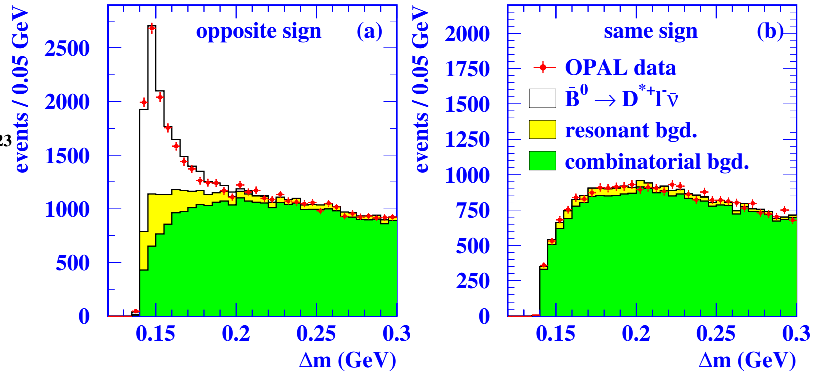
Now parameterise $\mathcal{F}(\omega)$ in terms of form factor ratios R_1 and R_2, and slope ρ^2 at $\omega = 1$ (Caprini, Lellouch, Neubert).

Measuring $|V_{\rm cb}|$

$\bar{\rm B}^0 \to {\rm D}^{*+}\ell^-\bar{\nu}$ events obtained using

- Exclusive reconstruction, e.g. ${\rm D}^0 \to K^-\pi^+, K^-\pi^+\pi^0, \ldots$
- Inclusive reconstruction: only slow pion from ${\rm D}^{*+} \to {\rm D}^0\pi^+$ is found.





- Exclusive (ALEPH,OPAL): ~ 1000 signal events, 55–80 % purity.
- Inclusive (DELPHI,OPAL): ~ 5000 signal events, 45–50 % purity.

Recoil ω calculated from $q^2 = (E_{\rm B^0} - E_{\rm D^*})^2 - (\mathbf{p}_{\rm B^0} - \mathbf{p}_{\rm D^*})^2$

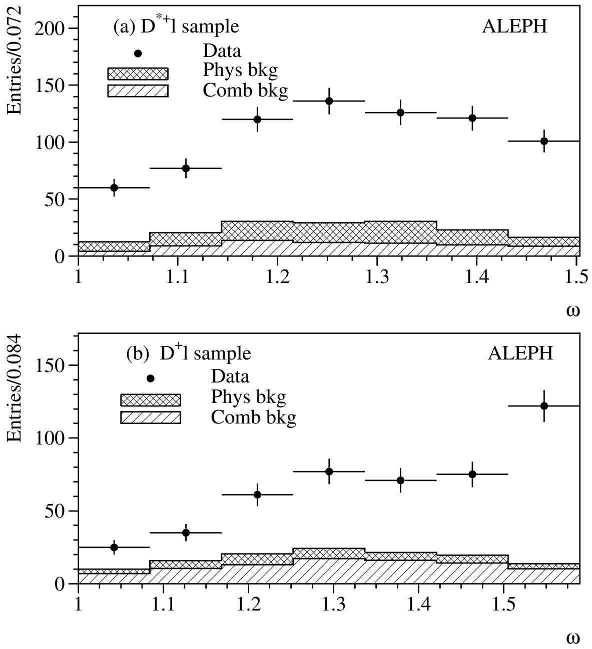
- D direction from decay products or hadronic system direction.
- D energy from decay products or slow pion.
- b direction from decay products (inc. neutrino) or vertex direction.
- b energy from energy/momentum balance in event.

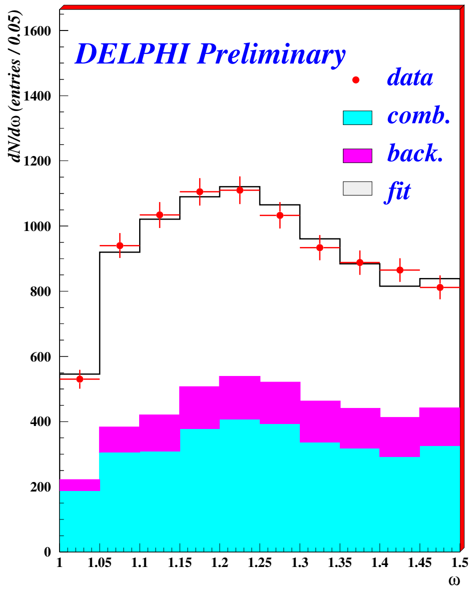
ω resolution typically 0.07–0.1 (exclusive) and 0.12–0.15 (inclusive).

Efficiency is almost flat as function of ω (due to large ${\rm B}^0$ boost).

Fits to $\bar{\rm B}^0 \longrightarrow {\rm D}^{*+}\ell^-\bar{\nu}$ events

Fit ω spectrum of selected events to extract $\mathcal{F}(1)|V_{\rm cb}|$ and ρ^2:

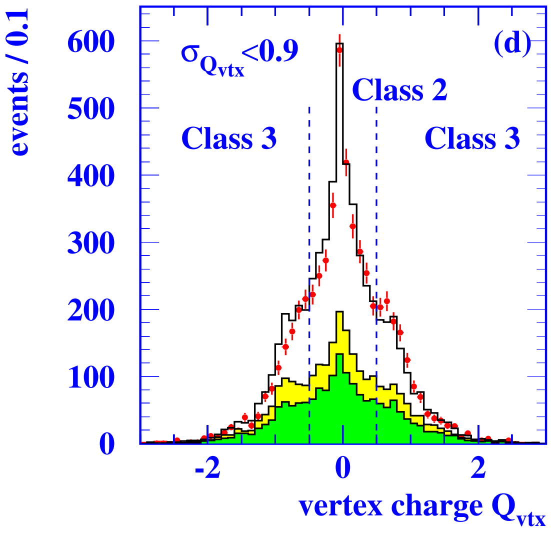




- Signal $\bar{\rm B}^0 \rightarrow {\rm D}^{*+}\ell^-\bar{\nu}$ from form factor $\times$ phase space $\otimes$ resl. function.
- Combinatorial background estimated from mass sidebands/wrong sign.
- Main physics background is $\bar{\rm B} \rightarrow {\rm D}^{*+}{\rm h}\,\ell^-\bar{\nu}$, mainly through ${\rm D}^{**}$.

$$
\begin{array}{lcl}
{\rm B}^- & \rightarrow & {\rm D}^{*+}\pi^-\ell^-\bar{\nu} \\
\bar{\rm B}^0 & \rightarrow & {\rm D}^{*+}\pi^0\ell^-\bar{\nu} \\
\bar{\rm B}_{\rm s} & \rightarrow & {\rm D}^{*+}{\rm K}^0\ell^-\bar{\nu}
\end{array}
$$

From isospin, $\sim 2/3$ from ${\rm B}^-$ decays. Reduced by looking for charged pion or re-constructing charge of secondary vertex. $\bar{\rm B} \rightarrow {\rm D}^{*+}{\rm h}\,\ell^-\bar{\nu}$ rate known to $\sim 20\,\%$.



D^{**} background

D^{**} background contains narrow (D_1, D_2^*), broad (D_0^*, D_1^*) and non-resonant $\mathrm{D}^*\pi$ decays…composition and ω spectrum is uncertain.

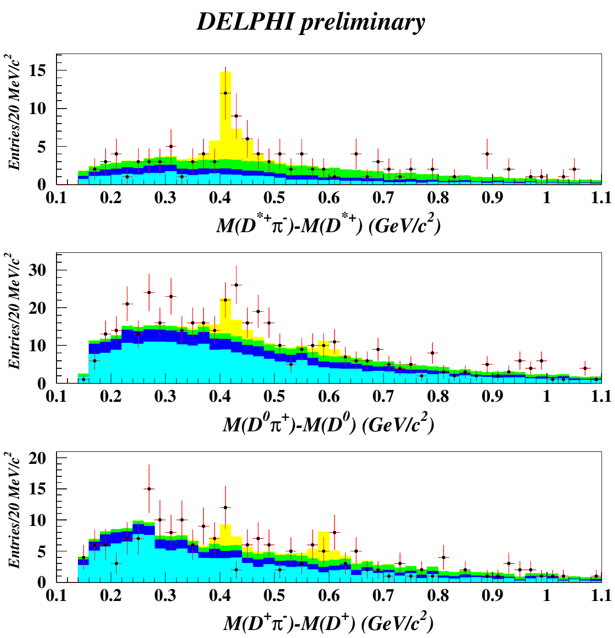
- Model of Leibovich, Ligeti, Stewart and Wise predicts ω distributions.
- Free parameters constrained by measurements from ALEPH and CLEO:

$$\mathrm{Br}(\mathrm{B} \to \mathrm{D}_1 \ell\bar{\nu}) = (0.63 \pm 0.11)\,\%$$
$$R = \Gamma(\mathrm{B} \to \mathrm{D}_2^* \ell\bar{\nu})/\Gamma(\mathrm{B} \to \mathrm{D}_1 \ell\bar{\nu}) = 0.37 \pm 0.16$$

Comparing $B \to (D, D^*, D_1, D_2^*)\ell\bar{\nu}$ and $B \to lX$, some room is left for broad (expected small) and non-resonant states.

New DELPHI analysis of $(\mathrm{D}^{*+}\pi^-$, $\mathrm{D}^0\pi^-$ and $D^+\pi^-)$ combinations in semileptonic b decays.

Fit for contributions from D_1, D_2^* and broad states.

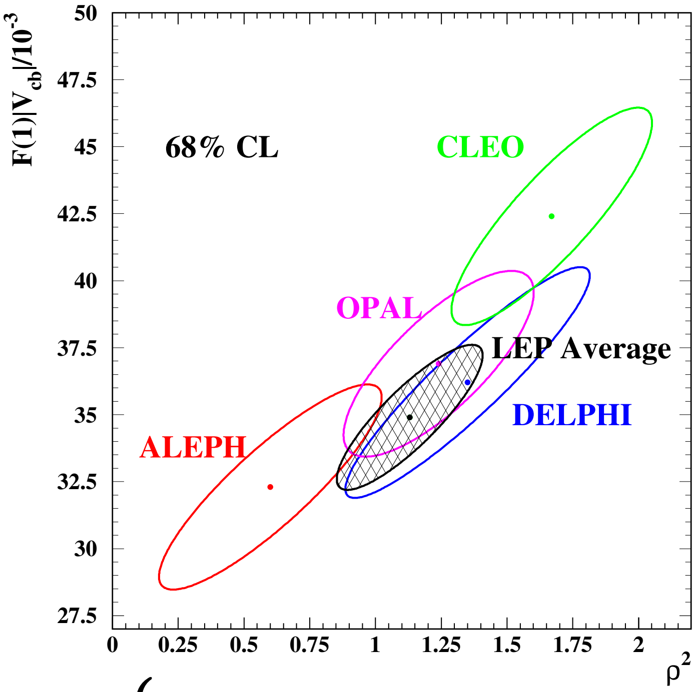


$$\mathrm{Br}(\mathrm{B}^- \to D_1 \ell\bar{\nu}) = (0.67 \pm 0.21)\,\%$$
$$R = 0.66 \pm 0.41$$
$$\mathrm{Br}(\mathrm{B}^- \to D_1^* \ell\bar{\nu}) = (1.63 \pm 0.55)\,\%$$
$$\mathrm{Br}(\mathrm{B}^- \to D_0^* \ell\bar{\nu}) < 1.9\,\%\;(90\,\%\mathrm{CL})$$

Some evidence for broad or non-resonant states.

D^{**} uncertainties dominate systematic error in LEP $|V_{\rm cb}|$ measurements.

$|V_{\rm cb}|$ results



Combined LEP result: $\begin{cases} \mathcal{F}(1)|V_{\rm cb}| = (34.9 \pm 0.7 \pm 1.6) \times 10^{-3} \\ \rho^2 = 1.12 \pm 0.08 \pm 0.15 \end{cases}$

Using $\mathcal{F}(1) = 0.913 \pm 0.042$, extract

$$|V_{\rm cb}| = (38.2 \pm 1.9({\rm expt}) \pm 1.8({\rm theo})) \times 10^{-3}.$$

c.f. CLEO (Osaka): $\begin{cases} \mathcal{F}(1)|V_{\rm cb}| = (42.4 \pm 1.8 \pm 1.9) \times 10^{-3} \\ \rho^2 = 1.67 \pm 0.11 \pm 0.22 \end{cases}$

- CLEO fits for R_1 and R_2, LEP uses results from HQET/QCD sum rules.
- $\Delta|V_{\rm cb}| = +$(1–2) %, $\Delta\rho^2 = +0.1$ if LEP uses CLEO R_1,R_2 values.

Can also extract $|V_{\rm cb}|$ from ${\rm Br}(b \to lX) = (10.56 \pm 0.11 \pm 0.18)\%$ and theoretical models (e.g. Bigi, Shifman, Uraltsev; Hoang, Ligeti, Manohar):

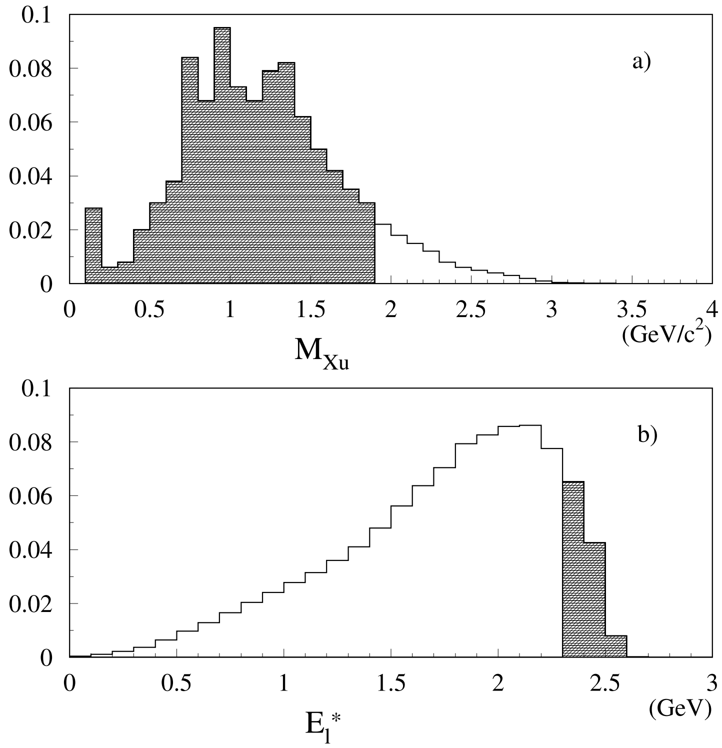
$$|V_{\rm cb}| = 40.7 \pm 0.5({\rm expt}) \pm 2.0({\rm theo})$$

Measuring $|V_{ub}|$

Looking for charmless $b \to X_u \ell \bar{\nu}$ transitions:

- Since $|{V_{ub}}^2/{V_{cb}}^2| \sim 10^{-2}$, have huge background from $b \to c\ell\bar{\nu}$ decays.
- Measure lepton spectrum beyond charm endpoint ($2.3 < p_\ell < 2.6$ GeV)—small fraction of lepton spectrum, large extrapolation error.
- Exclusive $B \to \pi\ell\bar{\nu}$ and $B \to \rho\ell\bar{\nu}$ decays—large model dependence.

LEP analyses try to exploit the hadronic mass—the invariant mass of the hadronic system produced together with the leptons:



Sensitive to a larger fraction of $b \to X_u \ell \bar{\nu}$ decays, but requires good modelling of inclusive $b \to c\ell\bar{\nu}$ decays.

Modelling $\mathrm{b} \longrightarrow \mathrm{X_u}\ell\bar{\nu}$ and $\mathrm{b} \longrightarrow \mathrm{c}\ell\bar{\nu}$

Monte Carlo simulation of signal and background is critical for these analyses.

$\mathrm{b} \rightarrow \mathrm{X_u}\ell\bar{\nu}$ decays

Hybrid model with different strategies depending on energy E_h of hadronic system produced in the decay.

- For $E_h < 1.6$ GeV, resonant states $\pi, \rho \ldots$ are used with ISGW2 model.
- For $E_h > 1.6$ GeV, an inclusive approach is used to hadronise the $\mathrm{u\bar{q}}$ state—various different models: DSU, ACCM, parton model, JETSET. . .

Systematics evaluated by varying energy cutoff, mixture of resonant states, different inclusive models, b quark mass . . . .

$\Lambda_b \rightarrow X_u\ell\bar{\nu}$ decays are a particular problem. . . take extreme cases.

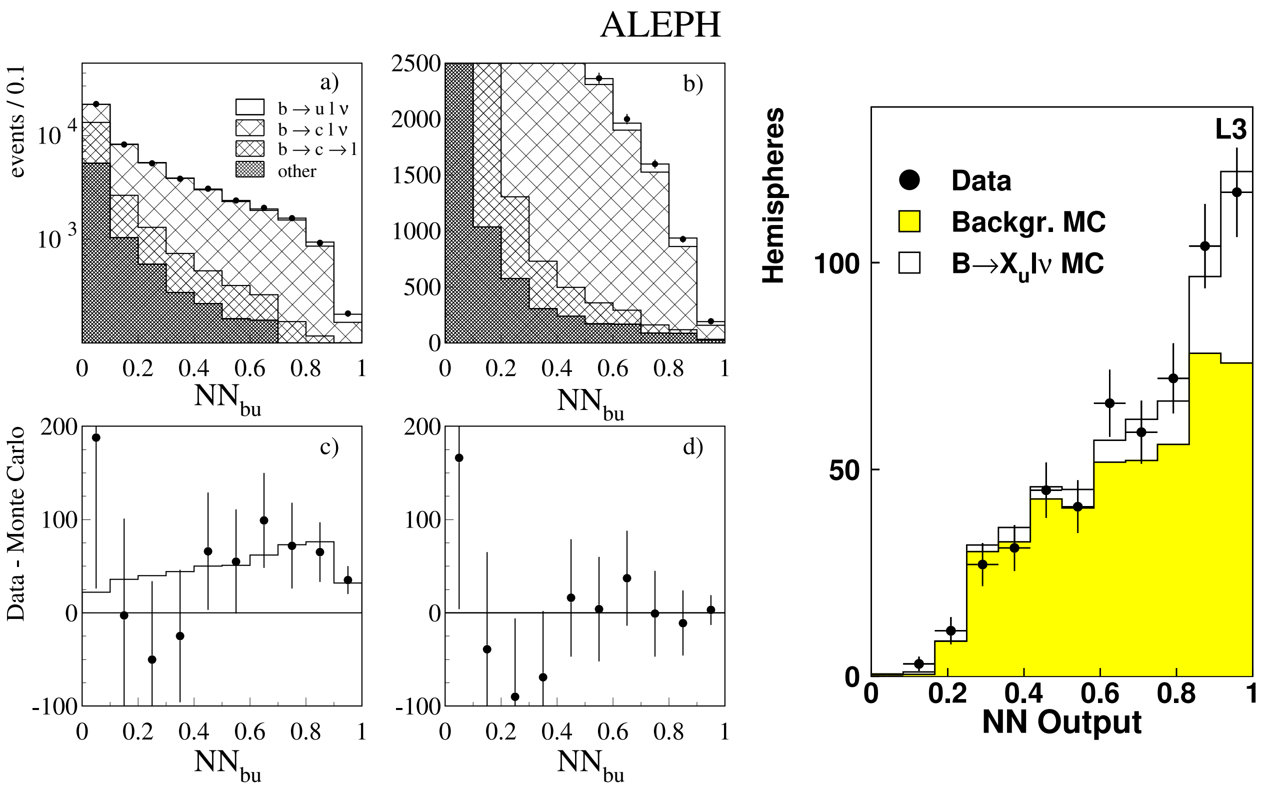
$\mathrm{b} \rightarrow \mathrm{c}\ell\bar{\nu}$ decays

- $\mathrm{b} \rightarrow \mathrm{c}\ell\bar{\nu}$ decays simulated using ACCM, ISGW2 models tuned to CLEO data.
- Vary amount of D^{**}, $\mathrm{D}^{*+}\pi$ production in semileptonic decays.
- Decays of charm hadrons simulated with JETSET, topological branching ratios , K^0 production, lifetimes *etc.* varied as for R_b analyses.

Selecting $\mathrm{b} \longrightarrow \mathrm{X_u}\ell\bar{\nu}$ decays I

$\mathrm{b} \to \mathrm{X_u}\ell\bar{\nu}$ decays are separated from $\mathrm{b} \to c\ell\bar{\nu}$ background by:

- Vertex based b-tag and high momentum lepton selection.
- Assign particles to b decay or fragmentation (kinematics, vertexing).
- Reconstruct b hadron restframe momentum vector.
- Final selection based on neural network using various kinematic variables (event shapes, particle multiplicities, momenta, invariant masses). Both charged and neutral particles used to minimise final state dependence.



Fit to extract $\mathrm{b} \to \mathrm{X_u}\ell\bar{\nu}$ normalises $\mathrm{b} \to c\ell\bar{\nu}$ background in low signal purity region (small neural network values).

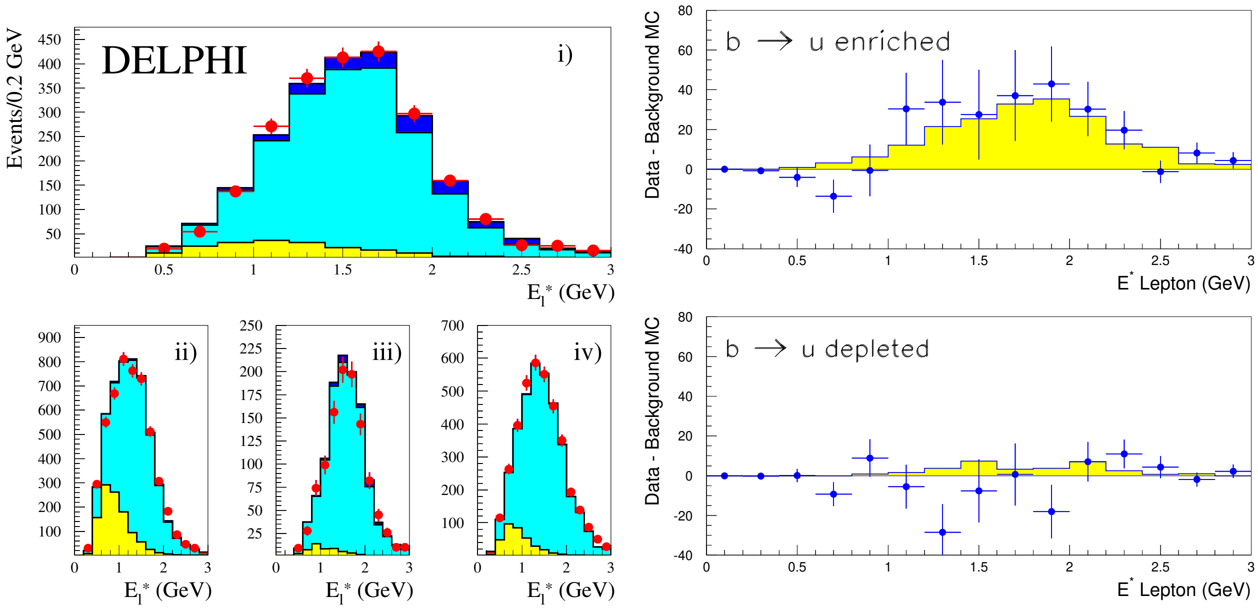
Selecting $b \to X_u \ell \bar{\nu}$ decays II

DELPHI uses slightly different approach: select $b \to X_u \ell \bar{\nu}$ decays using:

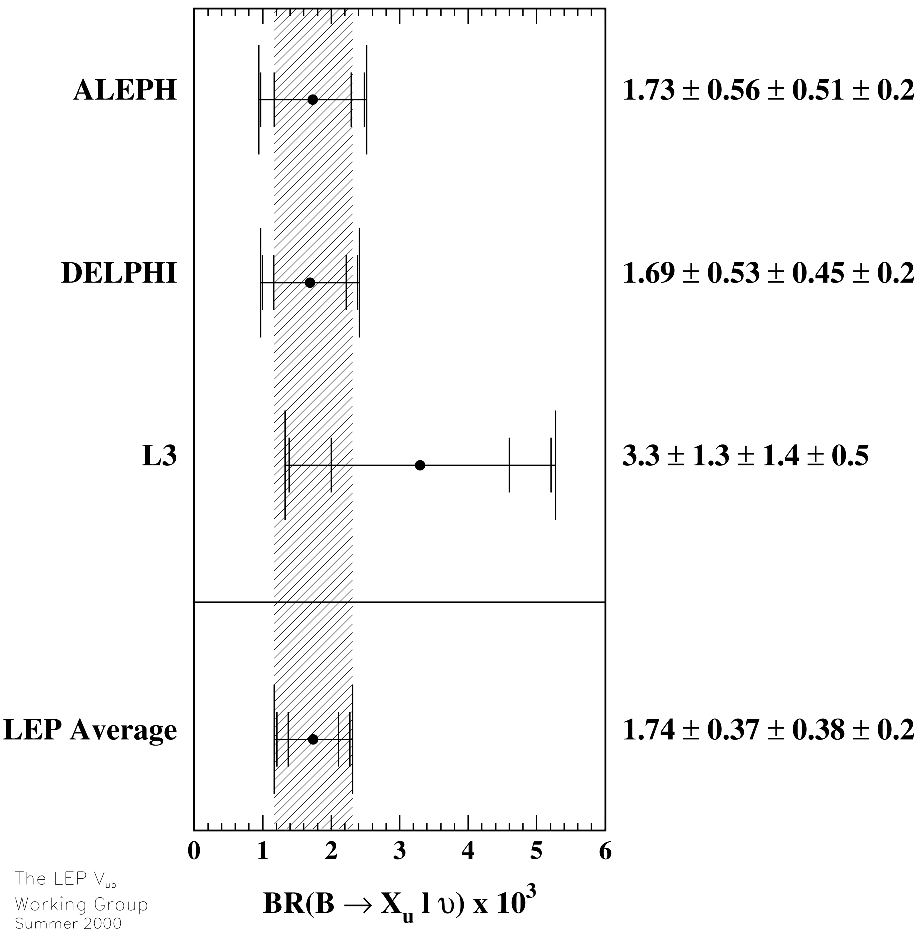
1. Invariant mass of hadronic system $m_X < 1.6$ GeV.
2. $b \to u$ enrichment using absence of $K^{\pm}$, K_s^0 or proton in hadronic system, and lepton impact parameter d^{ℓ} wrt secondary vertex:
   - $d^{\ell} < 0$: vertex from downstream charm decay
   - $d^{\ell} \sim 0$: vertex close to lepton: no charm decay.

Selection	$b \to u$ enriched			$b \to u$ depleted		
	Data	Background	Signal	Data	Background	Signal
$m_X < 1.6$	2292	2078 ± 30	0.68	1081	1118 ± 19	0.09
$m_X > 1.6$	5017	5019 ± 60	0.17	3744	3618 ± 46	0.06

Signal can be seen e.g. in lepton momentum in B rest frame:



$\mathrm{BR}(\mathrm{b} \to \mathrm{X_u}\ell\bar{\nu})$ and $|V_{\rm ub}|$ results



$|V_{\rm ub}|$ can be extracted from branching ratio using heavy quark expansion:

$$|V_{\rm ub}| = 0.00445 \times \left(\frac{\mathrm{BR}(\mathrm{b} \to \mathrm{X_u}\ell\bar{\nu})}{0.002}\,\frac{1.55\,\mathrm{ps}}{\tau_{\rm b}}\right)^{\frac{1}{2}} \times (1 \pm 0.02(\mathrm{QCD}) \pm 0.035(\mathrm{m_b}))$$

assuming $m_{\rm b} = (4.58 \pm 0.06)$ GeV. With $\tau_{\rm b} = 1.564 \pm 0.014$ ps,

$$|V_{\rm ub}| = \left(4.13^{+0.42}_{-0.47}\,{}^{+0.43}_{-0.48}(\mathrm{b} \to \mathrm{c})^{+0.24}_{-0.25}(\mathrm{b} \to \mathrm{u}) \pm 0.20(\mathrm{theo})\right) \times 10^{-3}$$

Largest systematic is understanding of $\mathrm{b} \to \mathrm{c}\ell\bar{\nu}$ background.

Summary and Outlook

LEP experiments have made a large contribution to $|V_{\mathrm{cb}}|$ and $|V_{\mathrm{ub}}|$:

$|V_{\mathrm{cb}}|$ results from $\bar{\mathrm{B}}^0 \to \mathrm{D}^{*+}\ell^-\bar{\nu}$

$$|V_{\mathrm{cb}}| = (38.2 \pm 1.9(\mathrm{expt}) \pm 1.8(\mathrm{theo})) \times 10^{-3}$$

- Slightly lower than corresponding result from CLEO.
- Consistent with result from inclusive $b \to \ell X$ decays.

A precision measurement, now limited mainly by understanding of D^{**} background and theoretical uncertainties.

Still some updates from LEP to come...

$|V_{\mathrm{ub}}|$ results from $\mathrm{b} \to \mathrm{X_u}\ell\bar{\nu}$

$$|V_{\mathrm{ub}}| = \left(4.13^{+0.42}_{-0.47}\,{}^{+0.43}_{-0.48}(\mathrm{b} \to \mathrm{c})^{+0.24}_{-0.25}(\mathrm{b} \to \mathrm{u}) \pm 0.20(\mathrm{theo})\right) \times 10^{-3}$$

Very challenging measurement using complex techniques.

- Limited by understanding of $\mathrm{b} \to \mathrm{c}\ell\bar{\nu}$ and $\mathrm{b} \to \mathrm{X_u}\ell\bar{\nu}$ decays.
- Consistent with other determinations from lepton endpoint and exclusive decays... a consistent picture is emerging.
- Important for indirect determinations of CKM matrix angles— probing mechanism for CP violation.