A personal overview of the current status of physics results from LEP using $b$-hadrons is presented. Emphasis is placed on those areas where analyses are not yet finalized and there remains significant activity. Results are presented in the areas of $b$-quark fragmentation, $b$-hadron lifetimes, charm counting in $b$-decays and $V_{cb}$.

1 $b$-Quark Fragmentation

Modelling the fragmentation process in Monte Carlo is a source of systematic error to many LEP $b$-physics analyses e.g. $|V_{ub}|$. Constraining this error from data measurements is therefore important and in the last few years precise measurements have begun to appear e.g. from ALEPH using the semi-exclusive reconstruction of $B \to D^{(*)} \ell \bar{\nu}_\ell$ decays and from SLD using a fully inclusive approach.

The fragmentation function of the $b$-quark is commonly parameterised as a function of the variable $x_B^{\text{weak}} = E_B^{\text{weak}} / E_{\text{beam}}$ where $E_B^{\text{weak}}$ is the energy of the weakly decaying $b$-hadron state. Analyses must address the difficult problem of how to unfold the underlying physics fragmentation function $f(x_B^{\text{weak}})$, from the measured $E_B^{\text{weak}}$ distribution which contains all experimental inefficiencies and resolutions. A new, preliminary, DELPHI analysis reconstructs inclusive $B$-decays with advanced neural network techniques to achieve a core $E_B^{\text{weak}}$ resolution of $\sim 4\%$ with non-Gaussian tails. The unfolding problem is solved by employing regularisation techniques to damp down the oscillatory nature of the solution. The result is an extremely robust and statistically precise underlying $f(x_B^{\text{weak}})$ distribution which is presented in Figure 1 along with the ALEPH and SLD result.

*Unless stated otherwise, charge-conjugate states are also implied throughout this note.*
2 $b$-Hadron Lifetimes

Recent theoretical estimates of the ratio $\tau(B^+)/\tau(B_d^0)$ predict a lifetime difference of the order of only 2%. This places a severe demand on the precision required of direct measurements if the framework of the Heavy Quark Effective Theory (HQET) is to be tested. LEP experiments have long dominated the $B$ lifetime world scene using mainly lepton-charm hadron charge correlations or exclusive reconstruction to isolate the different $b$-hadron types. The most precise published measurement of $\tau(B_d^0)$ comes from OPAL in the channel $B \rightarrow D^*\ell\bar{\nu}_\ell$ utilising the charge correlation between the slow pion (from $D^*$ decay) and the lepton to isolate $B_d^0$. For $\tau(B^+)$, where the background from other $B$-species is lower, the most precise measurements come from the inclusive reconstruction of charged secondary vertices.

In a new preliminary analysis from DELPHI the inclusive approach is taken further and neural networks are trained to identify the $b$-hadron type based on information from the hadron fragmentation and decay in both hemispheres of a $Z^0 \rightarrow b\bar{b}$ event. For the case of the neural network trained to recognise $B^+$ hadrons, a sample which is 70% pure with an estimated efficiency of around 14% is achieved. Neural networks are also used to optimally estimate the $B$-momentum which, when combined with a measurement of the distance travelled before decay, give a measure of the $B$ proper time. The analysis reports measurements for $\tau(B^+)$ and $\tau(B^0)$ and their ratio from this method and the results, quoted below, are currently the most accurate from the $Z^0$ factory experiments:

$$\tau_{B^+} = 1.631 \pm 0.012 \text{ (stat)} \pm 0.021 \text{ (syst) ps}$$
$$\tau_{B^0} = 1.546 \pm 0.018 \text{ (stat)} \pm 0.035 \text{ (syst) ps}$$
$$\frac{\tau_{B^+}}{\tau_{B^0}} = 1.054 \pm 0.017 \text{ (stat)} \pm 0.027 \text{ (syst)}$$

The situation worldwide is summarized in Figure 2 which shows the current average of lifetime ratios for the various $B$-species, as compiled by the B-Lifetime Working Group. The solid bands represent the theoretical expectation. It is clear that the predicted lifetime hierarchy is observed and that the largest discrepancy with theory comes from the $b$-baryon measurements. It is rather too early to conclude whether this represents a problem for the current theory although results from the lattice are beginning to appear that suggest spectator quark effects...
could account for, at most, half of the present discrepancy.

Finally, it should be noted that the \( B \)-factory experiments, Babar and Belle, currently match the precision of the best \( Z^0 \)-decay measurements for \( \tau(B_\ell^0) \) and \( \tau(B^+) \) and are still statistically limited. The Tevatron will presumably dominate the future measurements of \( \tau(B_\ell^0) \), where the most precise measurement already comes from CDF based on \( D_\ell \ell \) correlations, and of \( \tau(b - \text{baryon}) \) where ALEPH have currently the best measurement using \( \Lambda \ell \) correlations.

3 Charm Counting

Charm counting, i.e. the measurement of \( n_c = (\text{the mean number of } c \text{ plus } \bar{c} \text{ quarks per } b \text{-quark decay}) \), is important in attempts to resolve whether or not theoretical predictions of the inclusive \( b \)-quark semi-leptonic branching ratio (\( BR_{sl} \)) are consistent with data. The most precise determinations of \( n_c \) come from measurements of the ‘wrong-sign’ branching ratio \( BR(b \rightarrow \bar{c}s(d)X) \) which, up to small corrections for charmonium and \( b \rightarrow \text{no charm production} \), is related to \( n_c \) via \( n_c \sim 1 + BR(b \rightarrow \bar{c}s(d)X) \).

In a new DELPHI analysis, wrong-sign \( D \)-mesons are separated from the ‘right-sign’ background by utilising (a) a high performance neural network that tags the charge of the \( b \)-quark at the decay time and (b) the momentum spectrum of the \( D \)-mesons in the decaying \( b \)-hadron rest frame. The preliminary results are: \( BR(b \rightarrow D\ell X) = 9.3 \pm 1.7 \text{(stat.)} \pm 1.3 \text{(syst.)} \pm 0.4 \text{(BR)\%} \), where \( D = D^+, D^0 \) and \( BR(b \rightarrow D^- X) = 10.1 \pm 1.0 \text{(stat.)} \pm 0.6 \text{(syst.)} \pm 2.8 \text{(BR)\%} \), where in both cases the last error comes from the uncertainty on the branching ratio of the decay channel investigated.

![Figure 3: Preliminary averages from the \( Z^0 \) factories (LEP+SLD) compared to CLEO data at the \( \Upsilon(4s) \) in the \( n_c \) vs \( BR_{sl} \) plane.](image)

4 \( |V_{cb}| \)

The extraction of the CKM matrix element \( |V_{cb}| \) has been, and continues to be, a very active area in LEP \( b \)-physics. There are two approaches where theoretical uncertainties are thought to be well enough under control: the first uses the Operator Product Expansion expression linking \( |V_{cb}| \) with \( BR(b \rightarrow \ell\bar{\nu}_\ell X_c) \) and the inclusive \( B \) lifetime. The second is based on the reconstruction of the exclusive channel \( B_\ell^0 \rightarrow D^{*-} \ell^+ \bar{\nu}_\ell \) and relies on the HQET relationship for the differential cross section \( \frac{d\sigma}{d\omega} \propto F_{D\ell}^2(\omega) \cdot |V_{cb}|^2 \). Here, \( \omega = v(B^0) \cdot v(D^*) \) and \( F_{D\ell}(\omega) \) is the hadronic form factor for the decay.
There are published results from ALEPH\textsuperscript{14}, and OPAL\textsuperscript{15} using the exclusive approach where the technique is to fit the measured differential cross section for $F_{D^*}(\omega) \cdot |V_{cb}|^2$ and then extrapolate the result back to the zero recoil point, $\omega = 1$. The heavy quark prediction for $F_{D^*}(1)$ can then be substituted to yield $|V_{cb}|$.

DELPHI has a new, preliminary, exclusive measurement\textsuperscript{16} where the emphasis has been placed on better controlling the main sources of systematic error from their previous analysis, such as uncertainties linked to the $\omega$ spectrum of $D^{**}$ states coming from excited $D^{**}$ decays. By simultaneously fitting the $D^{**}$ rate, the impact on the analysis is greatly reduced and the result is, $F_{D^*}(1) |V_{cb}| = 0.0357 \pm 0.0024_{\text{(stat.)}} \pm 0.0018_{\text{(syst.)}}$.

The current world status is summarised in Figure 4, as compiled by the $V_{cb}$ Working Group\textsuperscript{17}, which illustrates the nice compatibility between results from the inclusive (including LEP results only) and exclusive approach (which includes the preliminary DELPHI result discussed above).

5 Conclusions

It is fair to say that LEP has made an enormous contribution to $b$-physics over the last ten years or so in all areas ranging from $b$-quark production and hadronisation through lifetimes and oscillations to hadronic decay properties and spectroscopy. Although many analyses are now finalised, there are still many areas of $b$-physics activity at LEP and this review has highlighted those where new publications can be expected shortly.

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