CKM matrix elements from tree-level decays and $b$-hadron lifetimes

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We give an updated summary of the topics covered in Working Group I of the 2nd Workshop on the CKM Unitarity Triangle, with emphasis on the results obtained since the 1st CKM Workshop [1]. The topics covered include the measurement of $|V_{ub}|$, of $|V_{cb}|$ and of non-perturbative Heavy Quark Expansion parameters, and the determination of $b$-hadron lifetimes and lifetime differences.

1 Introduction

Uncovering the origin of flavor mixing and CP violation is one of the main goals in elementary particle physics today. As part of this program, the constraining of the CKM unitarity triangle through the redundant measurement of its angles and sides plays a central rôle. The aim of the present summary is to review the state of the art regarding the measurement of the sides $|V_{ub}|$ and $|V_{cb}|$, as it was discussed in Durham at the 2nd Workshop on the CKM Unitarity Triangle, taking into account developments which have occurred since then.

The determination of $|V_{ub}|$ and $|V_{cb}|$ from inclusive decays relies heavily on the Heavy Quark Expansion (HQE). Many of the assumptions underlying these calculations can be tested by comparing HQE predictions for $b$-hadron lifetimes to their experimental values. Such comparisons are also useful for testing lattice calculations of non-perturbative hadronic matrix elements which also enter these predictions. The study of these lifetimes has thus been included in the subjects covered by our working group. Of course, lifetimes are important in themselves. They are required to convert branching fractions into the rates necessary for the determination of $|V_{ub}|$ and $|V_{cb}|$. Moreover, lifetime differences of neutral $B_s$ and $B_d$ mesons may be helpful for uncovering new physics.

Spectral moments of inclusive $B$-decay spectra are also covered, as they too play an important rôle in testing the HQE. They further provide experimental determinations of many of the non-perturbative parameters which appear in these expansions. As the latest spectral moment studies described below show, we are entering a new era, where the currently achieved experimental precisions require a much tighter interplay between experiment and theory. A similar interaction is taking place in the exclusive determination of $|V_{ub}|$, as made clear by the latest CLEO results [2], where non-perturbative methods such as light-cone sum rules and lattice QCD are being put to serious test.

The remainder of this summary is organized as follows. In Section 2 we review inclusive determinations of $|V_{ub}|$. Moments of inclusive $B$-decay spectra are discussed in Section 3, while the measurement of $|V_{ub}|$ from exclusive semileptonic $B$ decays is the subject of Section 4. In Section 5 we review exclusive determinations of $|V_{cb}|$ and $b$-hadron lifetimes and lifetime differences in Section 6. We end with a brief conclusion in Section 7.

2 Inclusive determinations of $|V_{ub}|$

2.1 Inclusive $|V_{ub}|$: theory

The status of theoretical calculations relevant for the determination of $|V_{ub}|$ from inclusive $B \to X_u \ell \nu$ decays is nicely summarized in the contribution by Luke [3]. The main problem is the need for severe phase-space experimental cuts to eliminate the approximately 100 times larger $B \to X_c \ell \nu$ background: these cuts tend to destroy the convergence of the HQE used to describe these decays. Theoretical expressions for a variety of cuts exist:

- $E_\ell > \frac{m_\ell^2 - m_\nu^2}{2m_B}$, where $E_\ell$ is the lepton energy;
- $m_X < m_D$, where $m_X$ is the invariant mass of the final hadronic system;
- $q^2 > (m_B - m_D)^2$, where $q$ is the four-momentum of the leptons;
- combined $(q^2, m_X)$ cuts.

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As detailed in [3], all of these cuts have advantages and disadvantages, some experimental, others theoretical. Because the different methods for measuring $|V_{ub}|$ have different sources of uncertainty, agreement between the measurements (including those obtained from exclusive decays) will give us confidence that both theoretical and experimental errors are under control.

The main theoretical development since the last CKM workshop [1] is the study of $1/m_b$ corrections in ratio of rates such as:

$$R_{s,t}/\gamma = \frac{\Gamma_{X,\ell\gamma}(E_{\ell} \geq E_c)}{\Gamma_{X,\gamma}(E_{\gamma} \geq E_c)},$$

where the cut can be on the lepton energy, as in Eq. (1), or on the hadronic invariant mass. These ratios are important because the dependence of the individual rates on the universal, non-perturbative shape function $f(k_+)$, which describes the distribution of the light-cone component of the residual momentum of the $b$ quark, cancels up to perturbative and subleading-twist corrections. This allows for a model-independent determination of $|V_{ub}|$ (rather $|V_{ub}|/|V_{ts}V_{ts}^*|$) at that order.

Obviously, the accuracy of these methods depends on the size and uncertainty of subleading corrections. Perturbative corrections are dominated by large Sudakov logarithms which were summed to subleading order some time ago [4,5]. $1/m_b$ corrections, on the other hand, have only been studied recently. There are, in fact, two large effects.

The first is a higher-twist correction which arises at $\mathcal{O}(1/m_b)$ [6-9]. For a cut $E_{\ell} > 2.3$ GeV, models indicate that it leads to an order 15% upward shift in the value of $|V_{ub}|$. Though substantial, this correction may be insensitive to the model chosen for the subleading distribution function [9]. Moreover, these effects can be circumvented for a large part in hadronic-mass-cut measurements [10].

The second effect is due to a weak annihilation (WA) contribution and arises at relative order $1/m_b^2$ [11,12]. This contribution is the first of an infinite series which re-sums into a subleading distribution function [8]. For a cut $E_{\ell} > 2.3$ GeV, it is estimated to be roughly 10% with unknown sign [8]. Both this and the higher-twist correction are significantly reduced when the cut on $E_{\ell}$ is lowered below 2.3 GeV.

As emphasized by Luke [3], experiment itself can be used to further reduce theoretical errors in the inclusive measurement of $|V_{ub}|$. Studying the dependence of $|V_{ub}|$ on the lepton cut, for instance, can help test the size of subleading twist contributions. Moreover, comparing the value of $|V_{ub}|$ extracted from inclusive semileptonic decays of charged and neutral $B$ mesons will give a handle on WA contributions. Of course, more precise measurements of the photon spectrum in $B \rightarrow X_s\gamma$ will improve the determination of $|V_{ub}|$ from ratios such as the one in Eq. (1). And for $(q^2, m_X)$ cuts, better determinations of $m_b$ from moments of inclusive $B$ decay rates will reduce the largest source of uncertainty in the corresponding theoretical expressions.

2.2 Inclusive $|V_{ub}|$: experiment

There have been many new results and analyses since the last CKM workshop, notably from BABAR and BELLE [13], as presented by Sarti [14] and Kakuno [15] at this workshop. Precision has been improved and BELLE has tried new methods. The overall situation was very nicely reviewed in Muheim’s presentation [16].

2.2.1 BABAR 2002: endpoint measurement [17,14]

The measurement is based on 20.6 fb$^{-1}$ of on-peak and 2.6 fb$^{-1}$ of off-peak data. The cut on the charged lepton energy is $2.3 \text{ GeV} \leq E_{\ell} \leq 2.6 \text{ GeV}$. They measure a partial branching fraction $\Delta B(B \rightarrow X_u(\ell\nu)) = (0.152 \pm 0.014 \pm 0.014) \cdot 10^{-3}$, where the systematics come from, in order of importance: the estimate of the efficiency; the continuum background subtraction; the variations in the beam energy; the $B\bar{B}$ background modeling. They use CLEO’s determination [18] of the fraction, $f_u$, of the spectrum that falls into their momentum interval to obtain the full rate and the PDG 2002 average $B$ lifetime [19] to measure $|V_{ub}|$. They find:

$$|V_{ub}| = (4.43 \pm 0.29_{\text{exp}} \pm 0.25_{\text{HQL}} \pm 0.50_{f_u} \pm 0.35_{\gamma}) \cdot 10^{-3},$$

where the labelling of errors should be obvious.

2.2.2 BABAR 2003: $m_X$ cut with fully reconstructed $B$’s [14]

This analysis is based on about 88 million $B\bar{B}$ events (82 fb$^{-1}$) in which one of the $B$’s is fully reconstructed through decays of the form $B \rightarrow D^{(*)}\text{hadrons}$ while the semileptonic decay is measured on the opposing $B$ with a cut $p_{\ell} > 1$ GeV and $m_X < 1.55$ GeV, the latter being optimized to reduce the total error. This allows to reconstruct both the neutrino and the hadronic system $X$ and to separate charged and neutral $B$ mesons. It has the advantage of giving a large phase-space acceptance and a high purity of the sample. To reduce systematics due to uncertainties in the efficiency, they normalize the signal by the total semileptonic branching ratio. They use CLEO’s determination of $\Lambda$ and
\[ V_{ub} = \frac{\lambda_1}{\lambda_3} \frac{M_{cb}}{M_{ub}} \]

where again the labelling of errors should be obvious. This determination is the most precise one to date.

### 2.2.3 BELLE 2003: \( m_X \) cut with \( B \to D^{(*)} \ell \nu \) tagging [13,15]

This analysis is based on a sample of approximately 84 million \( BB \) pairs or 78.1 fb\(^{-1}\). Though it leads to a two-fold degeneracy in the decaying \( B \) meson direction which results from the presence of a second neutrino, \( B \to D^{(*)} \ell \nu \) tagging improves on the efficiency of full reconstruction without degrading the \( m_X \) resolution. With a cut on the signal lepton momentum \( p_\ell > 1 \) GeV and on the hadronic recoil mass \( m_X < 1.5 \) GeV, BELLE obtains the preliminary branching ratio, \( B(B \to X_u \ell \nu) = (2.62 \pm 0.63_{\text{stat}} \pm 0.24_{\text{syst}} \pm 0.39_{\text{extrap}}) \cdot 10^{-3} \). This implies

\[ V_{ub} = \frac{\lambda_1}{\lambda_3} \frac{M_{cb}}{M_{ub}} \cdot \frac{1}{2} 
\]

### 2.2.4 BELLE 2003: \( q^2, m_X \) cut with advanced neutrino reconstruction [13,15]

This method is introduced to increase efficiency while avoiding the degradation in \( (q^2, m_X) \) resolution brought about by hermiticity based neutrino reconstruction. Events with only one charged lepton (\( e \) or \( \mu \)) are retained. The neutrino momentum is then calculated by subtracting the four-momenta of all reconstructed particles from that of the \( \Upsilon(4S) \). This calculation is improved by reconstructing the other \( B \) decay through a simulated annealing technique. The signal region is then defined by \( m_X < 1.5 \) GeV and \( q^2 > 7 \) GeV. The resulting branching fraction is \( B(B \to X_u \ell \nu) = (1.64 \pm 0.14_{\text{stat}} \pm 0.46_{\text{syst}} \pm 0.22_{\text{extrap}}) \cdot 10^{-3} \), yielding

\[ V_{ub} = \frac{\lambda_1}{\lambda_3} \frac{M_{cb}}{M_{ub}} \cdot \frac{1}{2} 
\]

### 2.2.5 Summary of inclusive \( |V_{ub}| \) measurements [16]

M"uhlem combined the above results with the CLEO and BABAR endpoint measurements as well as

### 3 Moments of inclusive \( B \) decay spectra and \( |V_{cb}| \)

Since different moments depend differently on the various parameters or non-perturbative quantities which appear in the HQE that describe inclusive \( B \) decays, a measurement of moments allows a determination of these quantities and numerous consistency checks of the HQE. One should not forget, however, that there is an assumption behind these determinations: in order to be sensitive to non-perturbative \( 1/m_b \) corrections which are formally smaller than any term in perturbation theory, one must assume that the former are larger than the perturbative terms neglected.

The moments which have been considered most frequently up to now are moments of the photon energy spectrum in \( B \to X_u \gamma \) decays, moments of the charged lepton energy spectrum and of the hadronic recoil mass in \( B \to X_u \ell \nu \) decays. Moments analyses were pioneered by CLEO [22]. Today, a sufficient variety of moments have been measured to allow a global
fit to the corresponding HQE expressions up to and including $1/m^2_\ell$ terms [23,24].

Experimental aspects of the subject were reviewed very nicely by Calvi [25] at this workshop and Luke [3] and Uraltsev [26] provided very interesting discussions of some of the theoretical issues involved. Results from BABAR were presented by Luth [27] and from CLEO by Cassel [28]. The subject was also covered quite extensively in the proceedings of the 1st CKM workshop [1].

The main novelty since the last workshop are the global fits mentioned above, whose results were actually summarized in the proceedings [1]. In [24] the authors use preliminary DELPHI measurements of the first three moments of the hadronic mass and charge lepton energy spectra [29] and obtain

$$m_b(1 \text{ GeV}) = 4.59 \pm 0.08 \text{ GeV}$$
$$m_c(1 \text{ GeV}) = 1.13 \pm 0.13 \text{ GeV}$$
$$|V_{cb}| = (41.1 \pm 1.1) \cdot 10^{-3}, \quad (7)$$

where no expansion in $1/m_c$ is performed and matrix elements up to $O(1/m^3_\ell)$ are also obtained. The masses given here are the running kinetic masses. The corresponding $1S$ mass for the $b$ is $m^S_b = 4.69 \pm 0.08 \text{ GeV}$. The quality of their fit indicates the consistency of the HQE description of these moments at the order considered. In [23], the authors use a total of 14 moment measurements from CLEO [30], BABAR [31] and DELPHI [29]. Imposing the constraint on $m_b - m_c$ given by the $B(+)\ell$ and $D(+)\ell$ masses, thereby introducing an $1/m_c$ expansion, they obtain

$$m^S_b = 4.74 \pm 0.10 \text{ GeV}$$
$$|V_{cb}| = (40.8 \pm 0.9) \cdot 10^{-3}, \quad (8)$$

along with matrix elements up to $O(1/m^3_\ell)$. The 2-3% accuracy of these $|V_{cb}|$ measurements is impressive. They are currently limited by the accuracy of the moments measurements and should therefore be improved in the near future with additional data from the $B$ factories.

It is important to note that the results of [23] include the $m_X^2$ moment measurement of BABAR presented at this workshop by Luth [27], whose dependence on the charge lepton energy cut appears to be in contradiction with the HQE. This measurement is based on a sample of 55 million $\bar{B}B$ pairs. In these events, one of the $B$‘s is fully reconstructed while the semileptonic decay of the second is identified by a high momentum charged lepton. The discrepancy arises when the HQE parameters are fixed at $E^\text{cut}_\ell = 1.5 \text{ GeV}$ and the predicted moment is compared with data for lower values of $E^\text{cut}_\ell$, as shown in Figure 2.

A possible resolution was proposed by Luke and collaborators [23]. The measurement depends on the assumed spectrum of excited $D$ resonances, in which there are no contributions from excited states with masses below $\sim 2.4 \text{ GeV}$. The addition of a non-negligible fraction of excited $D$ states with masses less than $2.45 \text{ GeV}$ could help reconcile the discrepancy.

Another solution to this problem was put forward by Uraltsev [26]. He emphasized that the convergence of the HQE is governed by the maximum energy release or hardness of the moment considered. For $E_\ell = 1.5 \text{ GeV}$, the hardness is only $1.25 \text{ GeV}$ and smaller than $1 \text{ GeV}$ for $E_\ell > 1.7 \text{ GeV}$, implying rather poor convergence in this region of phase space. And the hardness only decreases for higher moments. Thus, the problem with the BABAR moment measurement is not at low $E_\ell$, but rather at high $E_\ell$, where the matching to the HQE is actually performed. His recommendation is therefore to perform comparisons to the HQE at the lowest practical value of $E_\ell$.

The main message of this discussion is that experimental groups should strive as much as possible to obtain model-independent measurements of these spectral moments and the applicability of the HQE in dangerous regions of phase space should be considered with care.

Since this discussion took place, new measurements of hadronic moments as a function of lepton-energy cut have been presented by BABAR [33] and CLEO [34]. Both these measurements are preliminary. CLEO derives the $m_X^2$ moment for a number of $E^\text{cut}_\ell$ in the range of 1 to 1.5 GeV, from the branching fractions and average hadron mass distributions of a number
of charm meson resonant and non-resonant states, as advocated in \cite{22}. They obtain,

\[
\langle m_X^2 - m_D^2 \rangle_{E_l > 1.0 \text{ GeV}} = 0.456 \pm 0.014_{\text{stat}} \\
\pm 0.045_{\text{det}} \\
\pm 0.109_{\text{model}} \text{ GeV}
\]

(9)

\[
\langle m_X^2 - m_D^2 \rangle_{E_l > 1.5 \text{ GeV}} = 0.293 \pm 0.012_{\text{stat}} \\
\pm 0.033_{\text{det}} \\
\pm 0.048_{\text{model}} \text{ GeV}
\]

(10)

BABAR has inaugurated a new method in which the \(m_X\) and \(m_X^2\) moments are extracted directly from the measured \(m_X\) and \(m_X^2\) distributions. This analysis reduces dependence on the mass distributions and branching fractions of individual charm states which are poorly known for higher mass states. Combining their results for \(\langle m_X^2 \rangle\) with their earlier measurements of semileptonic branching ratios and \(B\) lifetimes, they obtain

\[
m_b^{1S} = 4.638 \pm 0.094_{\text{exp}} \pm 0.090_{\text{th}b} \text{ GeV}
\]

\[
|V_{cb}| = (42.10 \pm 1.04_{\text{exp}} \pm 0.72_{\text{th}b}) \cdot 10^{-3},\]

in good agreement with the results of Eqs. (7) and (8). They also find \(\lambda_1 = -0.26 \pm 0.06_{\text{exp}} \pm 0.06_{\text{th}b} \text{ GeV}^2\).

As a result of several changes to their analysis and data selection, BABAR find that their new results for \(\langle m_X^2 \rangle\) vs. \(E_l^{\text{cut}}\) fall substantially below those reported in \cite{27} and depicted in Figure 2 at low \(E_l^{\text{cut}}\). This has the effect of reconciling experiment with theory as shown in Figure 3, where BABAR and CLEO’s results are plotted together with the theoretical prediction constrained by CLEO’s measurement at \(E_l^{\text{cut}} = 1.5 \text{ GeV}\) (Eq. (10)) and the first \(B \to X_s \gamma\) photon energy moment \cite{32}. Agreement between the two experiments is excellent.

4 \(|V_{ub}|\) from exclusive semileptonic \(B\) decays

Many new measurements of exclusive \(b \to u\ell\nu\) decays using new techniques have been presented recently, with more to come. These were very nicely reviewed by Gibbons/Cassel \cite{35}, with presentations from BABAR, BELLE and CLEO by Schubert \cite{36}, Schwanda \cite{37} and Gibbons/Cassel \cite{35}. The improving statistics of experiments are beginning to permit the measurement of partial rates as a function of lepton recoil squared, \(q^2\), allowing reduction of the dependence of the measured rates and \(|V_{ub}|\) on the still rather poorly known theoretical form factor shapes. Such measurements also help eliminate incorrect form factor models. The overall normalizations of the form factors, however, cannot be tested experimentally and dominate the extraction of \(|V_{ub}|\) from measured rates. One therefore needs model-independent determinations of these form factors such as those which upcoming, unquenched lattice QCD calculations should provide.

4.1 Exclusive \(|V_{ub}|\): theory

The theory of exclusive, semileptonic \(b \to u\ell\nu\) has evolved little since the publication of the proceedings from the last CKM workshop \cite{1}. The status of lattice QCD (LQCD) calculations of \(B^0 \to \pi^- (\rho^-) \ell^+ \nu\) form factors was very nicely reviewed by Onogi \cite{38} and that of light-cone sum-rule (LCSR) calculations by Ball \cite{39}. One important feature of lattice calculations is that they are currently limited to smaller recoils \((q^2 \gtrsim 10 \text{ GeV}^2)\) while LCSR calculations are more reliable at larger recoils \((q^2 \lesssim 15 \text{ GeV}^2)\).

The current situation regarding quenched lattice calculations of \(B^0 \to \pi^-\) form factors is summarized in Figure 4. There is good agreement amongst the different methods used to obtain \(f^0(q^2)\), which determines the rate in the limit \(m_l = 0\), with errors at the level of 15-20%. Agreement is also good with the recent LCSR results of \cite{40} (see also \cite{41}). Agreement is less clear for the lattice results for \(f^0(q^2)\), due to sensitivity of this form factor on light and heavy quark masses.

The situation for \(B^0 \to \rho^- \ell^+ \nu\) decays is quite different. There are far fewer calculations of \(B \to \rho\)
As shown in Figure 6. $B^0 \to \pi^- \ell^+ \nu$ form factors from different lattice groups (UKQCD [42], APE [43], Fermilab [44], JLQCD [45], NRQCD [46]) and from LCSR [40]. The LCSR results for $q^2 \geq 14 \text{GeV}^2$ are obtained using a pole ansatz whose residue is fixed by a LCSR calculation. Figure taken from [38].

form factors, both with LQCD and LCSR. Moreover, quenching effects may be more important here than in $B \to \pi$ decays because the $\rho$ cannot decay into two $\pi$ in the quenched theory. Nevertheless, quenched lattice calculations do provide a first estimate of the relevant matrix elements which is worth considering. While there are a number of older lattice calculations [47–49], for clarity we only show in Figure 5 the recent, preliminary results of the SPQcdR collaboration [50], obtained at two values of the lattice spacing. The small dependence on lattice spacing of $A_1(q^2)$, which dominates the rate at large $q^2$, indicates that discretization errors on this form factor are small. Similar results have been obtained recently by the UKQCD collaboration [51].

Also shown in Figure 5 are the LCSR results of [52]. These results look like a rather natural extension of the lattice results to smaller $q^2$, suggesting rather good agreement between the two methods.

Another interesting feature of the lattice $B \to \rho$ calculations is the agreement with SCET constraints such as [53–56]:

$$\frac{A_1(q^2)}{V(q^2)} = \frac{2E_\rho M_B}{(M_B + m_\rho)^2},$$

as shown in Figure 6.

To extend lattice results to smaller values of $q^2$ in a model-independent way one can make use of dispersive bounds [57,58]. While there are ways of improving these bounds, for the moment they do not provide sufficient accuracy. One may therefore wish to consider a combination of LCSR results at low $q^2$ and quenched LQCD results at high $q^2$. This approach offers a reasonably reliable determination of the form factors over the full kinematic range and has already been used for $|V_{ub}|$ determinations [2]. To avoid the problem “extrapolating” lattice results to lower values of $q^2$ altogether, one can also consider extractions of $|V_{ub}|$ from the partial rates measured for $q^2 > \sim 12 \text{GeV}^2$, as was suggested in [49] and already implemented in [2].

As they stand, quenched LQCD and LCSR results have errors of order 20%, which is not sufficient given the quality of the experimental measurements to come. While significant improvement of LCSR results cannot be expected, lattice predictions can and will be improved. Other than the issue of extending lattice results to smaller values of $q^2$, one of the main issues in these calculations is that of quenching. Indeed, only fully unquenched lattice calculations will provide completely model-independent determinations of the relevant form factors. Partially unquenched results with two flavors of Wilson sea quarks are expected soon from JLQCD and UKQCD and three Kogut-Susskind (KS) flavor calculations based on MILC configurations should also be forthcoming. While JLQCD and UKQCD will be limited to light quark masses $\sim m_s/2$, the MILC configurations extend down to $\sim m_s/8$. This means that the uncertainties associ-
ated with the necessary extrapolations to the physical $u$ and $d$ quark masses should be much smaller in the calculations performed on these configurations. On the other hand, the methods used to produce the MILC configurations may introduce non-localities and KS fermions suffer from flavor violations which can be accounted for but which significantly complicate chiral extrapolations.

Another important avenue to explore to reduce errors in LQCD calculations is ratios of semileptonic $B$ and $D$ meson rates, as many systematic and statistical errors are expected to cancel in such ratios. Results for $B$ mesons can then be recovered by combining these lattice ratios with the high-precision measurements of $D$ decays promised by CLEO-c. For a more complete discussion of both LQCD and LCSR calculations, please see the CKM workshop yellow book [1] and the reviews by Onogi [38] and by Ball [39].

4.2 Exclusive $|V_{ub}|$: experiment

As already mentioned, the last year has seen many new measurements of exclusive $b \rightarrow u \ell \nu$ decays, many of which are still preliminary. All of these measurements make use of detector hermiticity to reconstruct the four-momentum of the neutrino. They are:

- BABAR 2003 [36], reported at this workshop by Schubert: measurement of $B \rightarrow \rho \ell \nu$ rate with an on resonance integrated luminosity of $L_{on} = 50.5 \text{ fb}^{-1}$, an off resonance luminosity of $L_{off} = 7.8 \text{ fb}^{-1}$ and the following cut on the lepton momentum: $2.0 \text{ GeV} < p_{\ell} < 2.7 \text{ GeV}$. They find $B(B^+ \rightarrow \rho^+ \ell^+ \nu) = (1.3 \pm 0.4_{\text{stat}} \pm 0.2_{\text{syst}} \pm 0.3_{\text{model}}) \cdot 10^{-4}$.

- BELLE 2002 (preliminary) [59]:
  - measurement of $B \rightarrow \pi \ell \nu$ rate with $L_{on} = 60 \text{ fb}^{-1}$, $L_{off} = 9 \text{ fb}^{-1}$ and $1.2 \text{ GeV} < p_{\ell} < 2.8 \text{ GeV}$, including a measurement of the differential decay rate as a function of $q^2$.
  - measurement of $B \rightarrow \rho \ell \nu$ rate with $L_{on} = 29 \text{ fb}^{-1}$, $L_{off} = 3 \text{ fb}^{-1}$ and $2.0 \text{ GeV} < p_{\ell} < 2.8 \text{ GeV}$.

- CLEO 2003, reported at this workshop by Gibbons/Cassel [35]: measurements of $B \rightarrow \pi \ell \nu$ and $B \rightarrow \rho \ell \nu$ rates based on a sample of 9.7 million $BB$ pairs with $p_{\ell} > 1.0 \text{ GeV}$ for pseudoscalar final states and $p_{\ell} > 1.5 \text{ GeV}$ for vector final states. This study pioneers a new method in which rates are measured independently in three $q^2$ bins, yielding reduced model-dependence and allowing for model discrimination.

CLEO’s results for the $q^2$ dependence of the partial rates for $B^0 \rightarrow \pi^- \ell^+ \nu$ and $B^0 \rightarrow \rho^- \ell^+ \nu$ are shown in Figure 7, as obtained using different form factor calculations to estimate efficiencies. The results for $B^0 \rightarrow \pi^- \ell^+ \nu$ show negligible dependence on the calculation used, indicating that their binning method has essentially eliminated form factor dependence. The situation is less good for $B^0 \rightarrow \rho^- \ell^+ \nu$ decays, likely a result of the cut on the angle between the lepton and the $W$ directions [35]. The poor $\chi^2$ for the ISGWI model [60] fit to the $B^0 \rightarrow \pi^- \ell^+ \nu$ rate and for the Melikhov et al. model [61] and Ball et al. LCSR [52] fit to the $B^0 \rightarrow \rho^- \ell^+ \nu$ rate indicate that these theoretical descriptions of the form factors are disfavored by the data.

BELLE also has a determination of $d\Gamma/dq^2(B^0 \rightarrow \pi^- \ell^+ \nu)$ as a function of $q^2$ as shown in [59]. Unlike CLEO, BELLE determines its efficiency without binning in $q^2$. The model-dependence of their result is therefore expected to be more important, though it has not yet been determined.

A compilation of results for $|V_{ub}|$ obtained from exclusive $B \rightarrow X_u \ell \nu$ decays is shown in Figure 8. Gibbons refrains from giving an average number because the current information provided by the different experiments is insufficient to determine the size of correlations in their results. Indeed, there are a number of common systematics which could lead to large correlations [35]. These include:
Figure 7. The $d\Gamma/dq^2$ distributions obtained in the CLEO '03 analysis for $B^0 \to \pi^- \ell^+ \nu$ (left) and $B^0 \to \rho^- \ell^+ \nu$ (right). Shown are the variations in the extracted rates (points) for form factor calculations that have significant $q^2$ variations, and the best fit of those shapes to the extracted rates (histograms). Plot taken from [35].

Figure 8. Compilation $|V_{ub}|$ measurement from exclusive $B \to X_u \ell \nu$ decays [35].

- the common use of the ISGW2 model [60] and the Neubert-Fazio model [62] to determine the $b \to u \ell \nu$ background coming from feed down modes not considered;
- common GEANT base for detector simulation;
- common signal models: LCSR, LQCD, quark models.

The first item should probably be treated as a correlated systematic. To deal with the issue of common signal models, it seems appropriate to first average the rates and $|V_{ub}|$ obtained by the different experiments for a given model and then combine the measurements.

Nevertheless, the good agreement between the different experiments in their measurements of $|V_{ub}|$ and in the branching ratios from which these measurements were obtained is encouraging. It should be noted, however, that all of these $|V_{ub}|$ determinations are systematically below those obtained from inclusive decays.

With the growing data sets from the $B$ factories, fully reconstructed $B$-tag analyses, such as those used in the study of inclusive $B \to X_u \ell \nu$ decays, will become possible. This will reduce background significantly, allowing for selection criteria which yield a more uniform efficiency. Consequently, systematic uncertainties associated with form factor uncertainties and detector and background modeling will be reduced. At that point, measurement of exclusive $B \to X_u \ell \nu$ decays may yield the most accurate determinations of $|V_{ub}|$.

4.3 Exclusive $|V_{ub}|$ from $B^0 \to X_u^+ D_s^-$

At the workshop, Mikami from BELLE [63] suggested measuring $|V_{ub}|$ from wrong charm exclusive $B^0 \to \pi^+ D_s^-$ decays [64] and semi-inclusive $B^0 \to X_u^+ D_s^-$ decays [65], and presented measurements for the relevant rates and yield. These decays occur through the tree-level $b \to u \bar{c} s$ diagram. The corresponding measurements of $|V_{ub}|$ are meant as consistency checks for the usual semileptonic determinations and for the methods used in the calculation of non-leptonic $B$ decays.

In the semi-inclusive case, the idea would be to obtain $|V_{ub}/V_{cb}|$ from the endpoint of the $D_s$ spectrum in $B^0 \to X_u^+ D_s^-$ decays. The advantage with respect to the semileptonic endpoint measurement is that the signal fraction is larger, with more than 50% of the spectrum for $B^0 \to X_u^+ D_s^-$ beyond the kinematic limit for $B^0 \to X_c^+ D_s^-$ [65]. These semi-inclusive decays also have higher statistics than the exclusive mode.

The problem with both the exclusive and semi-inclusive proposals for determining $|V_{ub}|$ is that the theoretical formalism to describe the corresponding
decays does not yet exist. Indeed, BBNS factorization [66] does not apply to $B^0 \to \pi^- D^+_s$, because the $\pi^-$ contains the spectator $d$ quark. The situation is even more complicated for the semi-inclusive case.

More promising, at least theoretically, is the fully inclusive $b \to ucs\bar{s}$, as first proposed in [67]. In [68], it is shown that when the rate is normalized by the inclusive semileptonic rate, the corresponding theoretical expressions have a well behaved HQE. This is, of course, a very challenging measurement to make. However, because it is so theoretically clean, it would be interesting to investigate experimental feasibility.

5 $|V_{cb}|$ from exclusive decays

Experimental aspects of these determinations were reviewed very nicely at this workshop by Oyanguren [69] and lattice results for the relevant decay form factors were very nicely summarized by Onogi [38]. The status of these measurements, as well as the theory behind them, has not evolved significantly since the publishing of the CKM workshop yellow book [1]. There are no new measurement and no new calculations of $F(1)$ and $G(1)$, the values of the $B \to D^* \ell \nu$ and $B \to D \ell$ form factors at zero recoil. Thus, $F(1) = 0.91(4)$ and $G(1) = 1.04(6)$ [1]. And the extrapolation of the measured rate to the zero-recoil point, which is required to obtain $|V_{cb}|$, is still best done with the model-independent, dispersive parameterizations of [70,71], which are given in terms of a single parameter: the slopes $\rho_{D^*}$ and $\rho_D$ of the relevant form factors.

The Heavy Flavor Averaging Group has averaged the results for $|V_{cb}|$ and the slopes $\rho_{D^*}$ and $\rho_D$ obtained by the different experiments, after rescaling them to common input [21]. They find:

$$|V_{cb}| = (42.6 \pm 0.6_{stat} \pm 1.0_{syst} \pm 2.1_{thg}) \cdot 10^{-3}$$

$$\rho_{D^*} = 1.49 \pm 0.05_{stat} \pm 0.14_{syst}$$

from $B \to D^* \ell \nu$ decays and

$$|V_{cb}| = (40.8 \pm 3.6_{exp} \pm 2.3_{thg}) \cdot 10^{-3}$$

$$\rho_D = 1.14 \pm 0.16_{exp}$$

for $B \to D \ell \nu$ decays. These measurements are in good agreement with each other as well as with those obtained using inclusive $B \to X_s \ell \nu$ decays (e.g. Eqs. (7) and (8)), though errors on the exclusive measurements are currently larger. These errors are dominated by the uncertainties in the theoretical determination of the form factors at zero recoil. It is thus important that the quenched lattice calculations [72], which enter the determination of these form factors as explained in [1], be repeated by other groups and be unquenched.

On the experimental side, the limiting systematics are inputs such as the $b \to B^0$ and $\Upsilon(4S)\bar{B}^0$ rates, the contributions of the $D^{**}$ and the $D$ decay branching ratios.

It should be noted that a new set of very interesting lower bounds has been derived for the moduli of the derivatives of the Isgur-Wise function, $\xi(w)$, as explained by Oliver at this workshop [73]. They are based on derivatives of non-zero recoil sum rules à la Uraltsev [74]. In particular, it is shown that the $n$-th derivative at zero recoil, $\xi^{(n)}(1)$, can be bounded by the $(n - 1)$-st one and that one obtains an absolute lower bound on the $n$-th derivative, $(-1)^n\xi^{(n)}(1) \geq (2n + 1)!/2^{2n}$. Moreover, these bounds are compatible with the dispersive parameterizations of [70,71] and reduce the allowed range of parameters, though it should be noted that the latter include finite mass corrections which are absent in the new bounds. It would be interesting to investigate how radiative corrections and subleading corrections in powers of $1/m_c$ affect these bounds.

6 $b$-hadron lifetimes and lifetime differences

The current experimental situation for $b$-hadron lifetimes and lifetime differences was very nicely reviewed by Rademacker at this workshop [75]. The status of both experiment and theory has not changed significantly since the publication of the CKM Workshop yellow book [1].

6.1 Lifetimes

On the theory side, there are no new results and regarding experiment, the halving of errors on $\tau_{B^+}$ and $\tau_{B^0}$ brought about by the measurements of the $B$ factories based on 1999-2001 data were already taken into account in [1]. There are, nevertheless, new measurements from BABAR [76-78], CDF [79] and DELPHI [80] for both $\tau_{B^0}$ and $\tau_{B^+}$ and from D0 for $\tau_{B_s}$ [81]. CDF has also reported new determinations of $\tau_{B_s}$ and $\tau_{B_s}$ [79]. These results are summarized in Table 1. The new BABAR measurements are based on partial reconstruction of the $B$ mesons, either through $B^0 \to D^{*-} (\pi^+, \rho^+)$, where only the $D^0$ in $D^{*-} \to D^0 \pi^-$ is reconstructed [76]; through $B^0 \to D^{*-} \ell^+ \nu$ [77]; and in the di-lepton channel [78]. Partial reconstruction works thanks to the decay kinematics at the $\Upsilon(4S)$.

Taking these new results of [76,77,79,80] into account, the B Lifetime Group obtains the averages reported in
Agreement for $\tau_{B/B^0}$ results are preliminary. Clear vindication of the HQE approach. Examination of $\tau_{B/B^0}$ and $\tau_{B^+/B^0}$ ratios is less good, though the discrepancy is less than two standard deviations. The Tevatron is currently producing large numbers of $B$ mesons and $B^0$s such that the error on these lifetime ratios are expected to be below 1% by the end of Run IIa [75]. This will provide a stringent test of the HQE and may force theorists to consider penguin contributions, which are absent in $\tau_{B/B^0}$, and which are currently neglected.

### 6.2 Lifetime differences

On the theory side, the preliminary unquenched, two-flavor results of the JLQCD collaboration for one of the two matrix elements relevant for $(\Delta \Gamma/\Gamma)_{B_d,s}$ at leading order in $1/m_b$ have been finalized [83]. These results will not modify the predictions for $(\Delta \Gamma/\Gamma)_{B_d,s}$ reviewed in [1]. Experimentally, the only change comes from the new measurements of the average $B_d$ lifetime, which is used to obtain $(\Delta \Gamma/\Gamma)_{B_d,s}$ from $\Delta \Gamma_{B_d,s}$. The current experimental and theoretical situation for $(\Delta \Gamma/\Gamma)_{B_s}$ is summarized in Table 3.

The status of experimental measurements for $(\Delta \Gamma/\Gamma)_{B_d}$ should change dramatically in the near future: a statistical uncertainty of $\sim 2\%$ is expected by the end of Run IIa. It is not clear, however, that theory will be able to follow. Indeed, the main source of uncertainty comes from $1/m_b$ corrections which are enhanced by a rather large cancellation between the leading-order contributions. A calculation of these corrections requires the non-perturbative estimate of many dimension-7, $\Delta B = 2$ matrix elements which is very challenging. Unfortunately, until these corrections are calculated with reasonable precision, it is unlikely that a measurement of $(\Delta \Gamma/\Gamma)_{B_d}$ will allow detection of physics beyond the Standard Model.

### Table 1. $b$-hadron lifetime measurements which have appeared since the CKM Workshop yellow book [1]. Many of these results are preliminary.

| qty        | expt        | thy        |
|------------|-------------|------------|
| $\tau_{B^0}$ | 1.534(13) ps |            |
| $\tau_{B^+}$ | 1.652(14) ps |            |
| $\tau_{B_s}$ | 1.439(53) ps |            |
| $\tau_{A_b}$ | 1.210(51) ps |            |
| $\tau_{B^+}/\tau_{B^0}$ | 1.081(15) | 1.06(2) |
| $\tau_{B_s}/\tau_{B^0}$ | 0.938(35) | 1.00(1) |
| $\tau_{A_b}/\tau_{B^0}$ | 0.789(34) | 0.90(5) |

### Table 3. World average $(\Delta \Gamma/\Gamma)_{B_s}$ vs. theoretical predictions.

| qty        | expt (summer 2003) [21] | thy [1] |
|------------|--------------------------|---------|
| $(\Delta \Gamma/\Gamma)_{B_s}$ | < 0.29 at 95% CL | 0.09(3) |

### Table 2. World averages of $b$-hadron lifetime measurements, together with the theoretical predictions reviewed in [1]. All averages are from [82], except for $\tau_{B/B^0}$ and $\tau_{A_b}/\tau_{B^0}$ which are taken to be the ratio of the corresponding world average lifetimes.

| qty        | expt        |
|------------|-------------|
| $\tau_{B^0}$ | 1.534(13) ps |
| $\tau_{B^+}$ | 1.652(14) ps |
| $\tau_{B_s}$ | 1.439(53) ps |
| $\tau_{A_b}$ | 1.210(51) ps |
| $\tau_{B^+}/\tau_{B^0}$ | 1.081(15) |
| $\tau_{B_s}/\tau_{B^0}$ | 0.938(35) |
| $\tau_{A_b}/\tau_{B^0}$ | 0.789(34) |
7 Conclusion

We are witnessing very exciting times, with the factories and the Tevatron reducing errors tremendously on all of the quantities studied in our working group. This presents theorist with a great challenge and will allow for very stringent tests, sending many models to the grave. The improved experimental accuracy also permits the exploration of new methods, in which the reliance on non-perturbative calculations is greatly reduced, such as in the spectral-moments determination of $|V_{cb}|$. As this example shows, the close interplay between theory and experiment is crucial to take advantage of the improved accuracies. Further gains should be sought by optimizing comparison between experiment and theory in region of phase space where the combined errors are minimized, such as in the inclusive and exclusive determination of $|V_{ub}|$. It is also important to emphasize the role of CLEO-c, which will not only provide accurate branching ratios necessary for $B$ physics measurements, but will also be very useful for testing non-perturbative approaches such as lattice QCD and for calibrating the predictions of these approaches in $B$ physics.

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