Experimental Review of Exclusive Semileptonic B Meson Decays and Measurements of $|V_{ub}|$

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We review the current status of experimental measurements of the branching fractions for exclusive semileptonic decays of B mesons to charmless hadrons and the determination of the Standard Model CKM parameter $|V_{ub}|$ from these measurements.

1. Introduction

The Standard Model (SM) of particle physics contains a number of parameters whose values are not predicted by theory and must therefore be measured by experiment. In the quark sector, the elements of the 3×3 Cabibbo-Kobayashi-Maskawa (CKM) matrix [1] govern the weak transitions between quark flavours, and precision measurements of their values are desirable. In particular, much experimental and theoretical effort is currently being employed to test the consistency of one of the six "Unitarity Triangles" arising from the CKM formalism, the one most relevant to the decays of B mesons.

Since the first reports of CP violation in the B sector by the B-factory experiments BaBar and Belle in 2001 [2] [3], the precision to which the angle $\sin 2\phi_1$ ($\sin 2\beta$) characterising indirect CP violation in $b \to c\bar{c}s$ transitions has improved to approximately 4%. This makes a precision measurement of the length of the side of the Unitarity triangle opposite to $\sin 2\phi_1$ particularly important as a consistency check of the SM picture. The length of this side is determined to good approximation by the ratio of the magnitudes of two CKM matrix elements, $|V_{ub}|/|V_{cb}|$. Both of these can be measured using exclusive semileptonic B meson decays. Using charmed semileptonic decays, the precision to which $|V_{cb}|$ has been determined is of order 2%. On the other hand $|V_{ub}|$, which can be measured using charmless semileptonic decays, is the most poorly known of the CKM matrix elements. Both inclusive and exclusive methods of measuring $|V_{ub}|$ have been pursued, with the inclusive methods giving a value to something like 7-8% precision. A review of the determination of $|V_{ub}|$ using inclusive methods can be found elsewhere in these proceedings [4]. The exclusive determination of $|V_{ub}|$ currently has a precision poorer than 10%. The aim of the ongoing programme of measurements reviewed here is to improve this precision to better than 5%, for comparison with the inclusive results, which have somewhat different experimental and theoretical systematics, and to provide a sharp consistency test with the value of $\sin 2\phi_1$.

2. Exclusive Charmless Semileptonic B Meson Decays

Measurements of exclusive charmless semileptonic B meson decays, which have branching fractions of the order 10^{-4}, can most readily be made at electron-positron storage rings, where large numbers of $B\overline{B}$ pairs are produced through the process $e^+e^- \to \Upsilon(4S) \to B\overline{B}$. The aim is to measure the rate of the tree level quark transition $b \to u\ell\nu$, whose amplitude depends on V_{ub}. The situation is complicated by strong interaction effects, since the b and u quarks are bound into mesons and form factors depending on q^2, the square of the 4-momentum transferred to the lepton pair, are required. The most promising decays for measuring $|V_{ub}|$ are those where the final state meson is spinless, since in this case only two form factors are required to describe the branching fraction, and one if the mass of the final state leptons is neglected. For example, if the final state meson is a pion, the differential branching fraction can be written in the form

$$\frac{d\Gamma\left(B \to \pi\ell\nu\right)}{dq^2} = \frac{G_F^2}{24\pi^3}|V_{ub}|^2 p_\pi^3 |f_+(q^2)|^2 \qquad (1)$$

where p_π is the pion momentum and $f_+(q^2)$ the form factor. Thus experiment determines the product $|V_{ub}||f_+(q^2)|$, and to extract $|V_{ub}|$, both the shape and normalization of $f_+(q^2)$ are required. Input on $f_+(q^2)$ has come from theory, firstly in the form of quark-model predictions [5]. More recently lattice QCD calculations such as those of the HPQCD [6] and FNAL [7] Collaborations, and calculations based on Light Cone Sum Rules (LCSR) [8] have become available. These latter two approaches are complementary in the sense that lattice predictions are applicable at high $q^2 > 16$ GeV$^2/c^2$, whereas LCSR predictions are applicable at lower $q^2 < 14$ GeV$^2/c^2$. The lattice predictions are now based on unquenched calculations. Experiments have traditionally employed a parametrization of the form factor shapes to extend the predictions to the full q^2 range for which they have data.

More discussion on the issue of the calculation of form factors, the need or otherwise for extrapolation and the effect of form factors on the determination of $|V_{ub}|$ can be found in [9] [10]. Since experiments are reaching the point where they can begin to provide information on the form factor shapes, the dominant issue in extracting $|V_{ub}|$ is the form factor normalization.

3. Experimental Methods for Determining Branching Fractions

All recent results on exclusive charmless semileptonic B meson decays have come from the e^+e^- machines CESR at Cornell, PEP-II at SLAC and KEKB at KEK, and their respective experiments CLEO, BaBar and Belle. In each case, the required decay must be identified in final states which also contain the decay products of the other B meson, and without direct detection of the neutrino. Suppression of combinatorial backgrounds, backgrounds from the $b \to c\ell\nu$ process, and backgrounds from the underlying continuum to the $\Upsilon(4S)$ resonance is the major challenge. Three methods of signal extraction have been used in the measurements tabulated here, which we now briefly describe.

3.1. Untagged Method

The pioneering CLEO measurements developed the untagged method which was the only method available given the size of their dataset and the rareness of the decays under study. Since the total 4-momentum of the final state is fixed by the decaying $\Upsilon(4S)$, the 4-momentum of the escaping neutrino is estimated by subtracting the visible 4-momentum from the known total, attributing this missing 4-momentum to a neutrino. Candidate $B \to X_u\ell\nu$ decays are then selected on the basis of two variables, the beam constrained mass m_{BC} and ΔE, defined as follows

$$m_{BC} = \sqrt{E^2_{\rm beam} - p^2_B} \quad (2)$$

$$\Delta E = E_B - E_{\rm beam} \quad (3)$$

Here $E_{\rm beam}$ is the beam energy in the center of mass frame of the $\Upsilon(4S)$, and E_B and p_B are the energy and magnitude of momentum of the B candidate in the same frame. For $B \to X_u\ell\nu$ decays these will ideally have values close to the B meson mass and zero respectively, whilst for background this is not the case. The method is denoted untagged since the B meson recoiling against the signal candidate B is not explicitly reconstructed.

The major advantage of this method over the two to be described below is a relatively high efficiency (of the order of several percent). The major disadvantage is that the resolution of the neutrino 4-momentum is relatively poor, and this results in a lower purity and signal to background ratio.

3.2. Semileptonic Tagging

Semileptonic tagging involves the partial reconstruction of a semileptonic B meson decay to charm recoiling against the signal $B \to X_u\ell\nu$ candidate. Several D and D^* decay modes are used for the tagging. Since the final state contains a neutrino from both signal and tagging B, kinematic constraints must be employed to separate signal events from background. Backgrounds are lower than for the untagged method, but so is efficiency.

3.3. Full Reconstruction Tagging

In this method the B meson recoiling against the signal B candidate is fully reconstructed in a selected set of hadronic B decay modes containing a charmed meson. A sizeable number of modes are used for the tagging. In this case neutrino 4-momentum resolution is excellent and very low backgrounds result. The major disadvantage of the method over the two just described is very low tagging efficiency (typically a fraction of a percent).

The B-factory experiments Belle and BaBar have collected of order 500×10^6 and 300×10^6 $B\overline{B}$ pairs respectively to date. These represent very large datasets, which will continue to grow in the next few years. This will offset the disadvantage of low efficiency for the full reconstruction tagging method, and it will become the method of choice.

4. $B \to \pi\ell\nu$ Branching Fractions

Table I lists the current measurements of the branching fraction for $B \to \pi\ell\nu$, for both charged and neutral pion modes. These are displayed in Figure 1, which is reproduced from the HFAG Winter 2006 compilation [17]. In this figure, results for the $\pi^0\ell\nu$ mode have been multiplied by a factor of two to reflect isospin expectations, and corrected for the difference in lifetimes of charged and neutral B mesons. Note that presently at least, the untagged methods still give the best experimental precision for the branching fraction.

The $B \to \pi\ell\nu$ branching fraction averaged over all of these measurements is quoted by HFAG to be $[1.34 \pm 0.08(stat) \pm 0.08(syst)] \times 10^{-4}$, which represents an experimental precision of around 8%.

Most of the measurements of $\mathcal{B}(B \to \pi\ell\nu)$ now provide some information on the q^2 dependence. By way of illustration, Figure 2 shows the shape dependence of the partial branching fraction for $B^0 \to \pi^-\ell\nu$ obtained by BaBar in 5 q^2 bins using their untagged

Table I Measurements of branching fractions of exclusive $B \to \pi\ell\nu$ decay modes. In each case, the first error is statistical, the second experimental systematic, the third due to form factor uncertainties for the signal mode, and the fourth, when present, due to form factor uncertainties for crossfeed modes. U indicates untagged method, S semileptonic tagging method, and F full reconstruction tagging. The result in the last row of the table combines the previous two, using isospin relations.

Expt/Tag	**Mode**	$B\overline{B}$ $[10^6]$	**Branching Fraction** $[10^{-4}]$
CLEO [11] U	$B^0 \to \pi^-\ell\nu$	9.7	$1.33 \pm 0.18 \pm 0.11 \pm 0.01 \pm 0.07$
BaBar [12] U	$B^0 \to \pi^-\ell\nu$	86	$1.38 \pm 0.10 \pm 0.16 \pm 0.08$
Belle [13] S	$B^0 \to \pi^-\ell\nu$	275	$1.38 \pm 0.19 \pm 0.14 \pm 0.03$
Belle [13] S	$B^+ \to \pi^0\ell\nu$	275	$0.77 \pm 0.14 \pm 0.08 \pm 0.00$
BaBar [14] S	$B^0 \to \pi^-\ell\nu$	232	$1.03 \pm 0.25 \pm 0.13$
BaBar [15] S	$B^+ \to \pi^0\ell\nu$	88	$1.80 \pm 0.37 \pm 0.23$
BaBar [16] F	$B^0 \to \pi^-\ell\nu$	233	$1.14 \pm 0.27 \pm 0.17$
BaBar [16] F	$B^+ \to \pi^0\ell\nu$	233	$0.86 \pm 0.22 \pm 0.11$
BaBar [16] F	$B \to \pi\ell\nu$	233	$1.28 \pm 0.23 \pm 0.16$

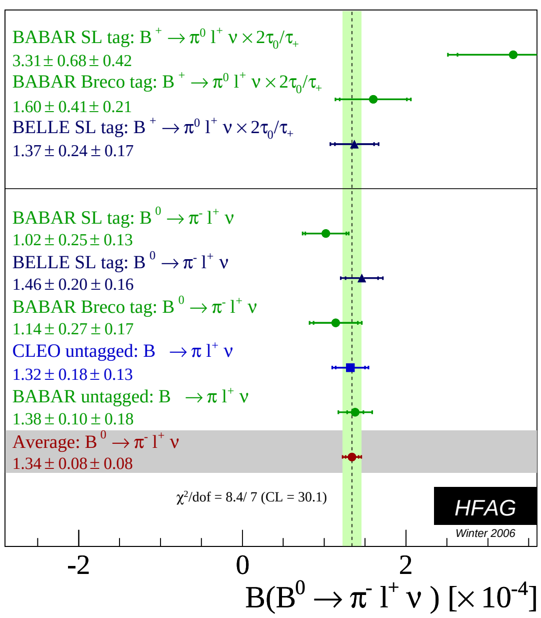

Figure 1: Branching fraction measurements for exclusive $B \to \pi\ell\nu$ decays, reproduced from the HFAG compilation [17] and discussed in this review.

analysis [12] based on $86 \times 10^6 B\overline{B}$ pairs, whilst Figure 3 reproduces the same quantity obtained by Belle in 3 q^2 bins using their semileptonic tag analysis [13] based on $275 \times 10^6 B\overline{B}$ pairs. In each case predictions based on different assumptions about the signal form factor dependence are shown. The BaBar data appears to be able to rule out a form factor shape given by simple quark model calculations. The Belle data also shows the effect of the form factor model on the extracted value of the branching fractions, which enters primarily through the Monte Carlo estimation of the detection efficiency.

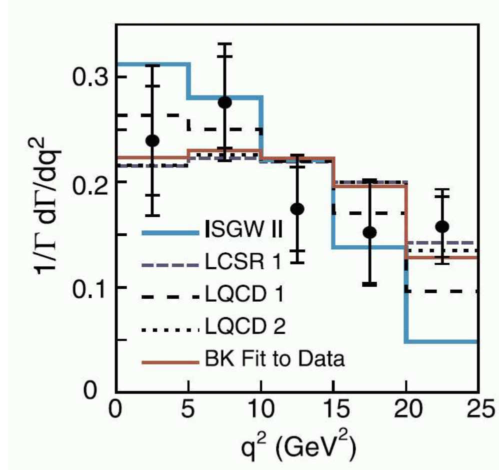

Figure 2: Shape dependence of the partial branching fraction for $B^0 \to \pi^-\ell\nu$ obtained by BaBar using their untagged analysis [12].

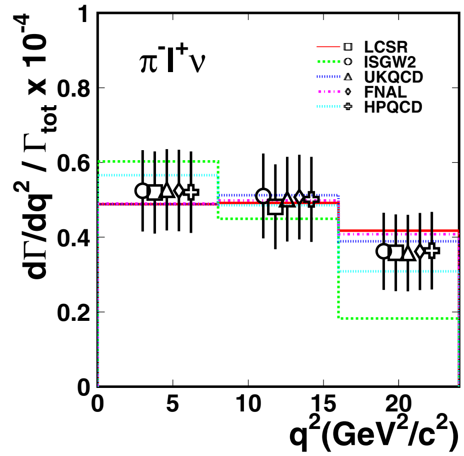

Figure 3: Shape dependence of the partial branching fraction for $B^0 \to \pi^-\ell\nu$ obtained by Belle using their semileptonic tag analysis [13].

5. $|V_{ub}|$ from B $\to \pi\ell\nu$ Decays

Given a branching fraction measurement, $|V_{ub}|$ can be estimated using the relation

$$|V_{ub}| = \sqrt{\frac{\mathcal{B}\left(B \to \pi\ell^+\nu\right)}{\tilde{\Gamma}_{thy}\tau_B}} \tag{4}$$

Table II Measurements of branching fractions of exclusive $B \to X_u \ell\nu$ decay modes other than $B \to \pi\ell\nu$. In each case, the first error is statistical, the second experimental systematic, the third due to form factor uncertainties for the signal mode, and the fourth, when present, due to form factor uncertainties for crossfeed modes. U indicates untagged method, S semileptonic tagging method, and F full reconstruction tagging.

Expt/Tag	**Mode**	$B\overline{B}$ $[10^6]$	**Branching Fraction** $[10^{-4}]$
CLEO [11] U	$B^0 \to \rho^- \ell\nu$	9.7	$2.17 \pm 0.34^{+0.47}_{-0.54} \pm 0.41 \pm 0.01$
CLEO [18] U	$B^0 \to \rho^- \ell\nu$	3.3	$2.69 \pm 0.41^{+0.35}_{-0.40} \pm 0.50$
BaBar [19] F	$B^0 \to \rho^- \ell\nu$	88	$2.57 \pm 0.52 \pm 0.59$
BaBar [20] U	$B^0 \to \rho^- e\nu$	55	$3.29 \pm 0.42 \pm 0.47 \pm 0.60$
BaBar [12] U	$B^0 \to \rho^- \ell\nu$	83	$2.14 \pm 0.21 \pm 0.51 \pm 0.28$
Belle [13] S	$B^0 \to \rho^- \ell\nu$	275	$2.17 \pm 0.54 \pm 0.31 \pm 0.08$
CLEO [11] U	$B^+ \to \eta\ell\nu$	9.7	$0.84 \pm 0.31 \pm 0.16 \pm 0.09$
Belle [13] S	$B^+ \to \rho^0 \ell\nu$	275	$1.33 \pm 0.23 \pm 0.17 \pm 0.05$
Belle [21] U	$B^+ \to \omega\ell\nu$	85	$1.3 \pm 0.4 \pm 0.2 \pm 0.3$

where $\tilde{\Gamma}_{thy}$ is the form factor normalization provided by theory and τ_B is the B proper lifetime.

Most of the analyses listed in Table I have produced values for $|V_{ub}|$, based either on partial branching fraction values over the limited q^2 region for which selected theoretical predictions for the form factor normalizations are applicable, or by using the full q^2 region and an extrapolation of the predictions to the full region. Some analyses quote values for both scenarios. In some cases the charged and neutral pion channels are combined using isospin relations to improve the statistical precision. In general the precision of the extracted $|V_{ub}|$ values is dominated by the form factor uncertainties, with the overall precision for $|V_{ub}|$ tending to be better when a limited q^2 range is employed.

The individual $|V_{ub}|$ values are not tabulated here. Details can be found in the referenced papers. The situation can be summarised by quoting the approach taken by the HFAG. The branching fraction measurements from all of the analyses are combined to give a global average in three q^2 ranges — the full range which extends to approximately 25 GeV$^2/c^2$, and the ranges $q^2 < 16$ GeV$^2/c^2$, to which LCSR apply, and $q^2 > 16$ GeV$^2/c^2$, to which Lattice QCD applies. $|V_{ub}|$ is then calculated using the predictions of LCSR [8], HPQCD lattice [6], FNAL lattice [7] and their stated theoretical errors.

At this point in time a global average based on exclusive decays is not quoted by the HFAG [17]. They obtain the following values in the partial q^2 ranges

$$|V_{ub}| = 3.25 \pm 0.17^{+0.54}_{-0.36} \quad \text{LCSR} \quad q^2 < 16 \text{ GeV}^2/c^2$$
$$|V_{ub}| = 4.44 \pm 0.30^{+0.67}_{-0.46} \quad \text{HPQCD} \quad q^2 > 16 \text{ GeV}^2/c^2$$
$$|V_{ub}| = 3.76 \pm 0.25^{+0.65}_{-0.43} \quad \text{FNAL} \quad q^2 > 16 \text{ GeV}^2/c^2$$

which illustrate the need to reduce the size of the theory errors, quoted second. The first error is a combination of the experimental statistical and systematic errors. The full methodology is described in the HFAG paper. When the full q^2 range is used, the gain from reducing the experimental error tends to be offset by a larger increase in the theory error caused by the extrapolation.

6. Other Exclusive Charmless Semileptonic Meson Decays

Whilst $B \to \pi\ell\nu$ decays have been of most recent interest for the extraction of $|V_{ub}|$, measurements exist for the branching fraction of other charmless semileptonic decays. These are listed in Table II. In many cases these measurements were performed in conjunction with those for $B \to \pi\ell\nu$, since this approach allows for the most consistent treatment of crossfeed between channels.

7. Exclusive Charmed Semileptonic Meson Decays

Alongside improvements in the determination of $|V_{ub}|$ from $B \to X_u \ell\nu$ decays, better knowledge of $B \to X_c \ell\nu$ decays is important for two reasons. Further improvement in the precision of $|V_{cb}|$ helps in constraining the Unitarity Triangle. Secondly, better knowledge of the branching fractions for these decays as a function of q^2 leads to better knowledge of the shapes of the relevant form factors, which when used as input to Monte Carlo simulations of charm backgrounds in $B \to X_u \ell\nu$ measurements will improve systematic errors.

The BaBar Collaboration have recently released an update to their determination of $|V_{cb}|$ from $B \to D^* \ell\nu$ decays [22], based on 86×10^6 $B\overline{B}$ pairs. New values for the parameters ρ^2, R_1 and R_2 characterising the helicity structure of the decays leads to an improvement of order 25% in the systematic error on $|V_{cb}|$, which has the new value $|V_{cb}| = \left[37.6 \pm 0.3(stat) \pm 1.3(syst)^{+1.5}_{-1.3}(theor)\right] \times 10^{-3}$.

8. Summary

The CLEO, BaBar and Belle experiments have between them now provided measurements of the semileptonic branching fractions of B mesons to the following final state mesons: $\pi^{\pm}$, π^0, $\rho^{\pm}$, ρ^0, ω and η, employing three methods of identifying signal decays in the presence of a missing neutrino. The most precise values for $|V_{ub}|$ come from the charged pion channel, with an experimental error approaching 5% precision but with a theory error arising from imprecise knowledge of the form factor normalization dominating the overall precision. Information on the shape of the form factors is now beginning to be provided by experiment. Further increases in the size of the Belle and BaBar datasets will allow full reconstruction tagging techniques to be competitive. Coupled with improvements in lattice calculations, this should in future see the overall precision on $|V_{ub}|$ approach the desired 5% level.

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