SLAC-PUB-14693

Recent results on semileptonic decays at BABAR

J. Serrano[a], representing the BABAR Collaboration

[a]Laboratoire de l'accélérateur Linéaire,
Bâtiment 208, BP34, 91898 Orsay Cedex, France

Some recent BABAR results on semileptonic decays are presented. They focus on the determination of the CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$ in inclusive and exclusive $b \to u\ell\nu$ and $b \to c\ell\nu$ decays, and on form factors measurement in exclusive $c \to s\ell\nu$ decays.

1. Introduction

Semileptonic decays play a crucial role in the determination of the unitarity triangle parameters: decays of the b quark give access to the CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$, while charm decays provide a way to validate lattice QCD computations through form factors measurements. Such calculations provide theoretical inputs that are used, especially, in the b sector. A lot of new results have been obtained by the BABAR collaboration during the last years, thanks to the large $b\bar{b}$ and $c\bar{c}$ production cross-sections and to the large recorded statistics. Some of these measurements are presented here.

2. $\bar{B} \to X_c \ell^- \bar{\nu}_\ell$ decays

2.1. Inclusive analysis: measurement of moments of the hadronic-mass and of the lepton energy spectrum

In the context of Heavy Quark Expansion (HQE), measurements of moments of the hadronic-mass and of the lepton-energy spectra in inclusive $\bar{B} \to X_c \ell^- \bar{\nu}_\ell$, and measurements of moments of the photon-energy spectrum in $\bar{B} \to X_s \gamma$ decays, are used to determine precisely $|V_{cb}|$, the quark masses m_b and m_c and the heavy-quark parameters. In the analysis presented here [1], 232 millions of $B\bar{B}$ pairs are used to obtain a new measurement of hadronic mass moments $\langle m_X^k \rangle$ with $k = 1, ..., 6$ as well as a first determination of mixed hadron mass-energy moments $\langle n_X^k \rangle$ with $k = 2, 4, 6$. All moments are given for different cuts on the minimum momentum of the charged lepton, varying between 0.8 GeV/c^2 and 1.9 GeV/c^2, in the rest frame of the B meson. Events with one B meson fully reconstructed in a hadronic decay are used, the semileptonic decay of the second B meson is identified by the presence of an electron or a muon. The hadronic system X_c is reconstructed from the remaining particles in the event and the hadronic mass is calculated from the reconstructed four-momenta as $m_X = \sqrt{p^2_{X_c}}$. To extract unbiased $\langle m_X^k \rangle$ moments, correction functions defined from the simulation are used. They relate moments of the measured mass and moments of the true underlying mass and depend on the resolution and total multiplicity of the hadronic system X_c. The same procedure is used to extract the mixed moments $\langle n_X^k \rangle$. The measured hadronic mass moments shown in [1] agree with previous measurements and present significantly smaller statistical uncertainties, which are smaller than the systematic uncertainties, than the previous BABAR measurements. A combined fit in the kinetic scheme to hadronic mass moments, to measured moments of the lepton-energy spectrum [2] and to moments of the photon energy spectrum in $\bar{B} \to X_s \gamma$ [3,4] , yields preliminary results for $|V_{cb}|$, m_b, m_c, the total semileptonic branching fraction $\mathcal{B}(\bar{B} \to X_c \ell^- \bar{\nu}_\ell)$ and perturbative HQE parameters in agreement with previous determinations. In particular, the following values are found: $|V_{cb}| = (41.88 \pm 0.81) \cdot 10^{-3}$ and $m_b = (4.552 \pm 0.055)$ GeV/c^2.

Work supported in part by US Department of Energy contract DE-AC02-76SF00515.

SLAC National Accelerator Laboratory, Menlo Park, CA 94025

2.2. Exclusive analysis: $B^0 \to D^{*-}\ell^+\nu_\ell$

The study of the $B^0 \to D^{*-}\ell^+\nu_\ell$ decay allows the simultaneous determination of $|V_{cb}|$ and of the form factors parameters characterizing the effects of strong interaction in this decay. There are two axial form factors, A_1 and A_2, and one vector form factor, V, which depend on q^2, the mass squared of the $\ell^+\nu_\ell$ system. The heavy quark effective theory (HQET) predicts that these form factors are related to each other through heavy quark symmetry (HQS), but HQET leaves three free parameters, which must be extracted from experiment. This decay depends on four kinematic variables: w, which is related to q^2 by $w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$; and the three decay angles (θ_ℓ, θ_V, χ) defined in Fig. 1.

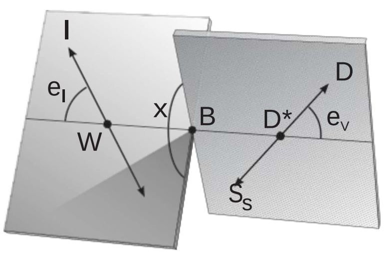

Figure 1. Definition of the kinematic variables for the $B^0 \to D^{*-}\ell^+\nu_\ell$ decay.

The Lorentz structure of the $B^0 \to D^{*-}\ell^+\nu_\ell$ decay amplitude can be expressed in terms of three helicity amplitudes which correspond to the three polarization states of the D^*. For low-mass leptons, these amplitudes are expressed in terms of the three functions $h_{A_1}(w)$, $R_1(w)$ and $R_2(w)$, related to the form factors A_1, A_2 and V. The analysis reported here [5], uses the following expressions for the form factor parameterization [6]:

$$
\begin{aligned}
h_{A_1}(w) &= h_{A_1}(1)\left[1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3\right], \\
R_1(w) &= R_1(1) - 0.12(w-1) + 0.05(w-1)^2, \\
R_2(w) &= R_2(1) + 0.11(w-1) - 0.06(w-1)^2,
\end{aligned}
$$

where $z = [\sqrt{w+1} - \sqrt{2}]/[\sqrt{w+1} + \sqrt{2}]$. The three parameters ρ^2, $R_1(1)$, and $R_2(1)$, cannot be calculated; they must be extracted from data. In BABAR this analysis is performed using a sample of 79 fb^{-1}. Events that contain a D^{*-} candidate and an oppositely charged electron or muon with momentum in the range $1.2 < p_\ell < 2.4$ GeV/c are selected. The D^{*-} is reconstructed in the decay channel $D^{*-} \to \bar{D}^0\pi^-$, with the $\bar{D}^0$ decaying to $K^+\pi^-$, $K^+\pi^-\pi^+\pi^-$, or $K^+\pi^-\pi^0$. About 52,800 $B^0 \to D^{*-}\ell\nu$ decays are reconstructed. The value of $F(1)|V_{cb}|$ and of the three form factors parameters are extracted using a combined fit of three one-dimensional (χ is practically insensitive to the form factors parameters) binned distributions with a bin-by-bin background subtraction. The background is estimated from data independently for each variable. Combining results from this analysis with the ones contained in the previous BABAR publication [7] and taking into account the correlation between them, the following values are obtained:

$$
\begin{aligned}
F(1)|V_{cb}| &= (34.4 \pm 0.3 \pm 1.1) \times 10^{-3} \\
\rho^2 &= 1.191 \pm 0.048 \pm 0.028 \\
R_1 &= 1.429 \pm 0.061 \pm 0.044 \\
R_2 &= 0.827 \pm 0.037 \pm 0.022.
\end{aligned}
$$

The corresponding branching fraction is $\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell) = (4.69 \pm 0.04 \pm 0.34)\%$. These results supersede all previous BABAR measurements of the form factors parameters, of the exclusive branching fraction and of $|V_{cb}|$ extracted from this decay.

3. $\bar{B} \to X_u\ell^-\bar{\nu}_\ell$ decays

3.1. Inclusive analysis

The analysis of inclusive $\bar{B} \to X_u\ell^-\bar{\nu}_\ell$ decays allows the determination of the CKM matrix element $|V_{ub}|$ through the measurement of the decay rate. The experimental challenge for this analysis is to separate the signal from the 50 times larger $\bar{B} \to X_c\ell^-\bar{\nu}_\ell$ decays. Thanks to the mass difference between the u and c quark, several regions of phase space can be defined where this background is suppressed. The measured partial branching fractions, $\Delta\mathcal{B}(\bar{B} \to X_u\ell^-\bar{\nu}_\ell)$, in these selected regions can then be related to $|V_{ub}|$ thanks to QCD calculations in the Operator Product Expansion (OPE) framework. This analysis has been done by the BABAR collaboration using 347.4 fb^{-1} [8]. Events with one of the B meson fully reconstructed in a hadronic decay are selected. The semileptonic decay of the second B meson is identified by the presence of an electron or a muon with momentum in the center of mass frame greater than 1 GeV/c. Three kinematic variables are used to select three different regions of phase space: M_X, the invariant mass of the hadronic system, q^2 and $P_+ \equiv E_X - |\vec{P}_X|$ where E_X and $\vec{P}_X$ are the energy and momentum of the hadronic system in the B rest frame. The distribution of these variables are extracted performing fits to the m_{ES} [1] distribution of the reconstructed B, for subsamples of events in individual bins for each of the kinematic variables. The partial branching ratios are measured for $M_X < 1.55\,\mathrm{GeV}/c^2$, $P_+ < 0.66\,\mathrm{GeV}/c$ and $(M_X < 1.7\,\mathrm{GeV}/c^2, q^2 > 8(\mathrm{GeV}/c^2)^2)$. Actually, in order to reduce systematic uncertainties, ratios of partial branching fractions to the total semileptonic branching fraction are measured. Results of the fitted number of events, $\Delta\mathcal{B}(\bar{B} \to X_u \ell^- \bar{\nu}_\ell)$ and the corresponding values of $|V_{ub}|$ for the three kinematic regions can be found in [8]. The partial branching ratios are translated to $|V_{ub}|$ using recent QCD calculations. The analysis which uses the M_X variable leads to a very accurate determination of $|V_{ub}|$, with a 9% total uncertainty.

3.2. Exclusive analysis: $B^0 \to \pi^- \ell^+ \nu_\ell$

The rate of the exculsive $B^0 \to \pi^- \ell^+ \nu_\ell$ is proportional to $|V_{ub} f_+(q^2)|^2$, where the form factor $f_+(q^2)$ depends on the momentum transfered squared q^2. Several theoretical calculations, as light cone sum rules or lattice QCD provide values of this form factors for different q^2 range, which allows the measurement of $|V_{ub}|$ from experimental data. Uncertainties on these calculations still dominate the errors on the computed values of $|V_{ub}|$, but, if a large statistics is available, the data can be used to discriminate between the various calculations by precisely measuring the $f_+(q^2)$ shape. The BABAR collaboration recently published an analysis of the $B^0 \to \pi^- \ell^+ \nu_\ell$ decay [9] using an original method based on a loose neutrino reconstruction technique. Using 206 fb^{-1}, the B meson candidate is reconstructed using $\pi^\pm$ and $\ell^\mp$ together with the event's missing momentum as an approximation to the signal neutrino momentum. The decay of the second B meson is not explicitely reconstructed. This leads to a large signal efficiency while having a good q^2 resolution. A total of 5072 ± 251 signal events are obtained and the partial branching fractions $\Delta\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell, q^2)$ are measured in 12 q^2 bins. The $\Delta\mathcal{B}$ distribution together with theoretical predictions is shown in [9]. Using [10] in the range $q^2 > 16\,\mathrm{GeV}^2$, the value of $|V_{ub}|$ is obtained: $|V_{ub}| = 3.4 \pm 0.2 \pm 0.2^{+0.6}_{-0.4}$, where the last uncertainty is due to the normalization of the form factor. A precise determination of the total branching fraction is also obtained: $\mathcal{B}(B^0 \to \pi^- \ell^+ \nu) = (1.46 \pm 0.07 \pm 0.08) \times 10^{-4}$.

4. $c \to s \ell^+ \nu_\ell$ decays

The BABAR collaboration has obtained precise measurements of the form factors parameters for two charm semileptonic decays: $D^0 \to K^- e^+ \nu_e$ [11] and $D_s^+ \to K^+ K^- e^+ \nu_e$ [12]. The CKM matrix element involved in these decays, V_{cs} is known precisely if we assume the unitarity of the CKM matrix. The analysis technique is similar for both channels, the charm decay is reconstructed in $e^+e^- \to c\bar{c}$ events, the second charm meson is not explicitely reconstructed. The difference of shape between $c\bar{c}$ and $b\bar{b}$ is used to discriminate signal from $b\bar{b}$ background events.

4.1. $D^0 \to K^- e^+ \nu_e$ decay

The rate of this exclusive decay is proportional to $|f_+(q^2)|^2$. The models used to parameterized the q^2 dependence of the form factor are the BK ansatz [13], where the parameter to be fitted is α and the simple pole model, for which the mass of the pole is fitted. This analysis has been done with 75 fb^{-1}. D^0 from $D^{*+} \to D^0 \pi^+$ decays are used, and a sample of about 74,000 signal events is selected. The true q^2 distribu-

[1] $m_{ES} = \sqrt{s/4 - p_B^2}$, where $\sqrt{s}$ is the total energy in the $\Upsilon(4S)$ center-of-mass frame and p_B, the momentum of the B candidate in the same frame.

tion is obtained using an unfolding algorithm. It is then fitted with the different models. The determined pole mass is $m_{pole} = 1.884 \pm 0.012 \pm 0.015\,\mathrm{GeV}/c^2$, which is lower than the expected value ($m_{pole} = m_{D_s^*} = 2.112\,\mathrm{GeV}/c^2$), excluding the simple pole model. The modified pole mass parameter $\alpha = 0.38 \pm 0.02 \pm 0.03$. This value is lower than the lattice QCD determination [14]($\alpha = 0.50 \pm 0.04$). In order to obtain the absolute normalization of the form factor, the $D^0 \to K^- e^+ \nu_e$ branching fraction is measured relative to the reference decay channel $D^0 \to K^- \pi^+$. The extracted value of $f_+(0)$ is found to be $f_+(0) = 0.727 \pm 0.005 \pm 0.007 \pm 0.005$, where the uncertainties are statistical, systematic and from external inputs, repsectively. This value is in agreement with the lattice result [14] ($f_+(0) = 0.73 \pm 0.03 \pm 0.07$).

4.2. $D_s^+ \to K^+ K^- e^+ \nu_e$

As for the $B^0 \to D^{*-} \ell^+ \nu_e$, this decay depends on four variables (q^2 and three decay angles) and on three form factors, A_1, A_2 and V, for which we assume a q^2 dependence dominated by a single pole:

$$V(q^2) = \frac{V(0)}{1 - q^2/m_V^2};\; A_{1,2}(q^2) = \frac{A_{1,2}(0)}{1 - q^2/m_A^2}.$$

Events with a K^+K^- mass in the range $1.01 - 1.03\,\mathrm{GeV}/c^2$ are selected, and except for a small S-wave contribution, they correspond to φ meson. Using $214\,fb^{-1}$ of data, the number of selected signal events is 25341, which greatly exceeds any previous measurement and allows the determination of the pole mass m_A in addition to the usual form factors parameters $r_2 = A_2(0)/A_1(0)$, $r_V = V(0)/A_1(0)$. These parameters are extracted using a binned maximum likelihood fit to the four-dimensional decay distribution. The sensitivity to m_V is weak and this parameter is fixed to $2.1\,\mathrm{GeV}/c^2$. The following values are obtained: $r_2 = 0.763 \pm 0.071 \pm 0.065$, $r_V = 1.849 \pm 0.060 \pm 0.095$, $m_A = 2.28^{+0.23}_{-0.18} \pm 0.18\,\mathrm{GeV}/c^2$. BABAR also finds a first evidence for a small S-wave contribution associated with $f_0 \to K^+K^-$ decays corresponding to $(0.22^{+0.12}_{-0.08} \pm 0.03)\%$ of the $K^+K^-e^+\nu$ decay rate. Measuring the $D_s^+ \to K^+K^-e^+\nu_e$ branching fraction relative to the decay $D_s^+ \to K^+K^-\pi^+$, the absolute normalization is obtained and $A_1(0) = 0.607 \pm 0.011 \pm 0.019 \pm 0.018$. Lattice calculations for this channel have been done in the quenched approximation. They agree with the present experimental result of $A_1(0)$, r_2 and m_A, but are lower than the measured value of r_V.

5. Conclusion

This review of recent BABAR measurements, altough non-exhaustive, underlines the great effort ongoing at B-factories in the understanding of semileptonic decays. One can remark that the dominant uncertainties on the determination of the CKM parameters are often coming from theoretical inputs.

REFERENCES

1. B. Aubert *et al* (BABAR collaboration), arXiv:0707.2670[hep-ex]
2. B. Aubert *et al* (BABAR collaboration), Phys. Rev. D 69, 111104 (2004).
3. B. Aubert *et al* (BABAR collaboration), Phys. Rev. D 71, 052004 (2005)
4. B. Aubert *et al* (BABAR collaboration), Phys. Rev. Lett. 97, 171803 (2006)
5. B. Aubert *et al* (BABAR collaboration), Phys. Rev. D. 77, 032002 (2008)
6. I. Caprini, L. Lellouch, M. Neubert, Nucl. Phys. B. 530, 153 (1998)
7. B. Aubert *et al* (BABAR collaboration), Phys. Rev. D. 74, 092004 (2006)
8. B. Aubert *et al* (BABAR collaboration), Phys. Rev. Lett. 100, 171802 (2008)
9. B. Aubert *et al* (BABAR collaboration), Phys. Rev. Lett. 98, 091801 (2007)
10. E. Gulez *et al* (HPQCD collaboration), Phys. Rev. D. 773, 074502 (2006)
11. B. Aubert *et al* (BABAR collaboration), Phys. Rev. D 76, 052005 (2007)
12. B. Aubert *et al* (BABAR collaboration), Phys. Rev. D 78, 051101 (2008)
13. D. Becirevic and A. B. Kaidalov, Phys. Rev. Lett. B478, 417 (2000)
14. C. Aubin *et al*, Phys. Rev. Lett. 94, 011610 (2005)