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SEMILEPTONIC B DECAYS AT BABAR

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This paper summarizes the content of a talk given by the author at the Lake Louise Winter Institute, on February 21^{st} 2007. It presents recent measurements of the rates for semileptonic B decays using data collected by the BaBar detector at the PEP-II asymmetric-energy collider at the Stanford Linear Accelerator Center.

1. Introduction

Precise measurements of the sides and angles of the Unitarity Triangle are needed to test the description of CP Violation by the Standard Model[1]. In this triangle, the ratio of CKM elements $|V_{ub}|/|V_{cb}|$ determines the length of the side opposite to $\sin(2\beta)$. These CKM elements are best measured with semileptonic B decays. However, as direct measurements of $|V_{ub}|$ and $|V_{cb}|$ currently have precisions[2,3] of $\sim$7.3% and $\sim$1%, respectively, the uncertainty of this side is driven by $|V_{ub}|$. Hence, improving the precision of $|V_{ub}|$ is very important to better constrain the Standard Model. In addition, the $|V_{ub}|$ value obtained with direct measurements now differs by more than two standard deviations from the ones given by global fits of the Unitarity Triangle[4], which generates even more interest for new precise $|V_{ub}|$ measurements.

To determine $|V_{ub}|$ and $|V_{cb}|$, there are two complementary approaches: inclusive and exclusive. Both methods rely on non-perturbative QCD calculations which contribute a large part of the $|V_{ub}|$ and $|V_{cb}|$ uncertainties. However, each method provides an independent cross-check for the uncertainties of the other.

The inclusive approach measures $B \to X_u(X_c)\ell\nu$ decays, where X_u (X_c) denotes any charmless (charmed) meson. These hadron-level measurements

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are interpreted with quark-level $b \to u(c)\ell\nu$ calculations[2] in order to extract $|V_{ub}|$ ($|V_{cb}|$), hence assuming the so-called "quark-hadron duality"[1]. These calculations achieve a relatively good precision by parametrizing the unknown b-quark motion with experimental informations from $B \to X_c\ell\nu$ and/or $B \to X_s\gamma$ decays.

The exclusive approach uses semileptonic B decays to one particular final-state meson. For V_{ub}, the $B \to \pi\ell\nu$ decay is optimal theoretically and experimentally. For V_{cb}, both $B \to D\ell\nu$ and $B \to D^*\ell\nu$ decays are used. The measurements of these exclusive branching fractions now have small experimental uncertainties[2]. However, the form factor(s) calculations needed to determine $|V_{ub}|$ and $|V_{cb}|$ from these measurements currently suffer from relatively large uncertainties.

From the experimental point of view, two complementary approaches are also used: tagged and untagged. The tagged approach requires the reconstruction of both signal and non-signal B mesons. The non-signal B are reconstructed through their $B \to D^{(*)}\ell\nu$ decays (semileptonic tags) or their $B \to D^{(*)}n\pi mK$ decays (hadronic tags). The reconstruction of the two B mesons has a relatively low signal efficiency. However, it allows high signal purity by requiring that no superfluous track and neutral energy remain in the fully reconstructed event.

With the untagged approach, the non-signal B is ignored, but the $B \to X\ell\nu$ signal decay is completely reconstructed, including its neutrino. The neutrino four-momentum is inferred from the event's missing momentum, i.e. the difference between the momenta of the colliding-beam particles and of the sum of all the charged and neutral particles detected in a single event. The untagged approach allows a much higher signal efficiency than the tagged approach, but has a lower signal purity and requires kinematic cuts which reduce the available phase space fraction.

2. Inclusive $b \to u\ell\nu$ and $b \to c\ell\nu$

BaBar has performed several inclusive $|V_{ub}|$ measurements[2]. In these measurements, the experimental uncertainties are minimized by rejecting phase space regions with stringent cuts. On the other hand, the theoretical uncertainties are minimized by using the largest phase space fraction possible. Hence, an optimized balance between experimental and theoretical uncertainties needs to be found. In one tagged analysis[6], we succeeded to keep the experimental uncertainties at an acceptable level while conserving the full phase space, a feature that is promising with more data. Also, the

BaBar untagged lepton endpoint analysis[7] has been recently reinterpreted[8] to benefit from improved theoretical calculations.

In the charmed sector, the combined data from several experiments show an impressive agreement with the theoretical predictions. Fits to these data now measure $|V_{cb}|$ and the b and c quark masses with precisions[3] of 1%.

3. Exclusive $B \to X_u \ell \nu$

BaBar has recently published two analyses of the $B \to \pi \ell \nu$ decay, one tagged and one untagged. Both analyses are based on an integrated luminosity of $\sim 210\ fb^{-1}$.

The tagged measurement[9] is performed in three bins of q^2, the squared invariant mass of the lepton-neutrino system. In this analysis, we used both semileptonic and hadronic tags, to measure 206 $\pm$ 31 signal events for the combined $B^0 \to \pi^- \ell^+ \nu$ and $B^+ \to \pi^0 \ell^+ \nu$ channels. The results of this analysis have small experimental systematics, but a relatively large statistical uncertainty. These uncertainties will reduce with more data, hence this method is promising for the future. We obtained:

$$BF(B^0 \to \pi^- \ell^+ \nu) = (1.33 \pm 0.17 \pm 0.11) \times 10^{-4} \quad (1)$$

$$|V_{ub}| = (4.5 \pm 0.5 \pm 0.3^{+0.7}_{-0.5}) \times 10^{-3} \quad (HPQCD) \quad (2)$$

where the first two uncertainties are experimental (statistical and systematic), and the third uncertainty on $|V_{ub}|$ comes from the form factor calculation of the HPQCD Collaboration[5], in the range $q^2 > 16\ GeV^2$.

The untagged measurement[10] is performed in twelve bins of q^2, using the $B^0 \to \pi^- \ell^+ \nu$ channel only. In this analysis, we obtained a very high signal efficiency by using an innovative loose neutrino reconstruction technique. We extracted the signal and background yields with a multi-parameter fit of the B meson mass and energy (M_{ES} and ΔE), in each bin of q^2, which reduced our sensitivity to the backgrounds simulation. We measured a signal yield of 5072 $\pm$ 251 events. Then, we characterized the shape of the measured q^2 spectrum with complete covariance matrices, that we used to derive χ^2 probabilities for various theoretical predictions of the $B^0 \to \pi^- \ell^+ \nu$ form factor. We obtained:

$$BF(B^0 \to \pi^- \ell^+ \nu) = (1.46 \pm 0.07 \pm 0.08) \times 10^{-4} \quad (3)$$

$$|V_{ub}| = (4.1 \pm 0.2 \pm 0.2^{+0.6}_{-0.4}) \times 10^{-3} \quad (HPQCD) \quad (4)$$

where the first two uncertainties are experimental (statistical and systematic), and the third error on $|V_{ub}|$ comes from the form factor calculation[5] used in the range $q^2 > 16\ GeV^2$. This analysis has the smallest statistical and systematic uncertainties of the exclusive $B \to X_u \ell \nu$ measurements.

4. Exclusive $B \to X_c \ell \nu$

BaBar has performed an exclusive measurement of $|V_{cb}|$ by studying the $B^0 \to D^{*-}\ell^+\nu$ decay with two untagged analyses, using an integrated luminosity of 79 fb^{-1}. In addition, three form factors which effectively describe the $B^0 \to D^{*-}\ell^+\nu$ decay have also been measured by the two analyses. To do so, the form factors have been parametrized by three constants: R_1, R_2 and ρ^2, whose values are related to the measurable kinematic variables w, θ_ℓ, θ_V and χ, through the differential decay rate:

$$\frac{d\Gamma(B^0 \to D^{*-}\ell^+\nu)}{dw\ d\theta_\ell\ d\theta_V\ d\chi} = |V_{cb}|^2 \cdot f(w, \theta_\ell, \theta_V, \chi;\ R_1, R_2, \rho^2). \tag{5}$$

In the first analysis[11], we measured the w, θ_ℓ, θ_V and χ distribution of $B^0 \to D^{*-}e^+\nu$ decays, in a four-dimensional binning. Then, we extracted the values of R_1, R_2 and ρ^2, but not $|V_{cb}|$, with a fit of this four-dimensional distribution to the Eq. 5. In the second analysis[11], we measured the three one-dimensional projections of the w, θ_ℓ and θ_V variables. Then, we extracted the values of R_1, R_2, ρ^2 and $|V_{cb}|$ with a simultaneous fit of these three distributions to the partially integrated Eq. 5. From the average of the two measurements, we obtained[12]:

$$R_1 = 1.417 \pm 0.061 \pm 0.044 \tag{6}$$
$$R_2 = 0.836 \pm 0.037 \pm 0.022 \tag{7}$$
$$\rho^2 = 1.179 \pm 0.048 \pm 0.028 \tag{8}$$
$$|V_{cb}| = (37.74 \pm 0.35 \pm 1.25^{+1.23}_{-1.44}) \times 10^{-3} \tag{9}$$

where the first two uncertainties are experimental (statistical and systematic), and the third uncertainty on $|V_{cb}|$ comes from the form factor calculation[13]. The precision achieved for R_1, R_2 and ρ^2 is five times better than the former result by CLEO[14].

That said, the complete understanding of $B \to D^*\ell\nu$ decays remains an unsolved puzzle. First of all, the values of $BF(B^0 \to D^{*-}\ell^+\nu)$ measured by various experiments[2] have a relatively large spread, with a modest χ^2 probability of 6.8%. Also, the ratio of the $B^0 \to D^{*-}\ell^+\nu$ and $B^+ \to D^{*0}\ell^+\nu$ decay rates measured at the B-factories gives an unexpected value[15] of $R = 1.27 \pm 0.09$, where one would expect $R = 1.0$. Finally, the sum of the exclusive $B \to X_c\ell\nu$ branching fractions measured so far does not add up to the inclusive measurement[1]. This calls for new experimental studies of semileptonic B decays to higher-mass charmed states, the so-called D**.

BaBar has recently performed two such $B \to D^{**}\ell\nu$ analyses. One of them is a tagged measurement of the relative $D^0/D^{*0}/D^{**0}$ composition of $B^+ \to X_c\ell^+\nu$ decays[16]. The other one is the first (untagged) measurement of the exclusive $B \to D_1\ell\nu$ and $B \to D_2^*\ell\nu$ branching fractions[17]:

$$BF(B^+ \to D_1^0\ell^+\nu) = (4.48 \pm 0.26 \pm 0.35) \times 10^{-3} \tag{10}$$

$$BF(B^+ \to D_2^{*0}\ell^+\nu) = (3.54 \pm 0.32 \pm 0.54) \times 10^{-3} \tag{11}$$

$$BF(B^0 \to D_1^-\ell^+\nu) = (3.64 \pm 0.32 \pm 0.49) \times 10^{-3} \tag{12}$$

$$BF(B^0 \to D_2^{*-}\ell^+\nu) = (2.70 \pm 0.35 \pm 0.43) \times 10^{-3}. \tag{13}$$

The results of these two new measurements are in agreement with previous data. More studies will be needed to solve the $B \to D^*\ell\nu$ puzzle.

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