Semileptonic B decays at Belle

Alexei Sibidanov[1]

School of Physics, University of Sydney, NSW 2006, Australia

E-mail: `sibid@physics.usyd.edu.au`

Abstract. Recent results from the Belle experiment on semileptonic decays of B-mesons are reviewed, including their effect on the determination of the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$.

1. Introduction

Precise experimental determinations of the values of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements is the way to test unitarity of the matrix and thus to probe phenomena beyond the Standard Model (SM) of Particle Physics, which can potentially violate this unitarity.

In the most commonly studied Unitarity Triangle (UT) based on the CKM matrix, the well measured angle ϕ_1 (also known as β in the literature) is opposite to the side whose length is proportional to the ratio $|V_{ub}|/|V_{cb}|$, which is currently known much less precisely, as shown in Fig. 1 made by the CKMfitter group [1]. In this ratio, the main contribution to the uncertainty comes from the value of $|V_{ub}|$. The usual way to obtain the values of $|V_{cb}|$ and $|V_{ub}|$ is to extract them from semileptonic decays of B-mesons, in which the decay rate is directly proportional to, to first order, the matrix element squared, and where QCD uncertainties due to hadronic recoil are under control.

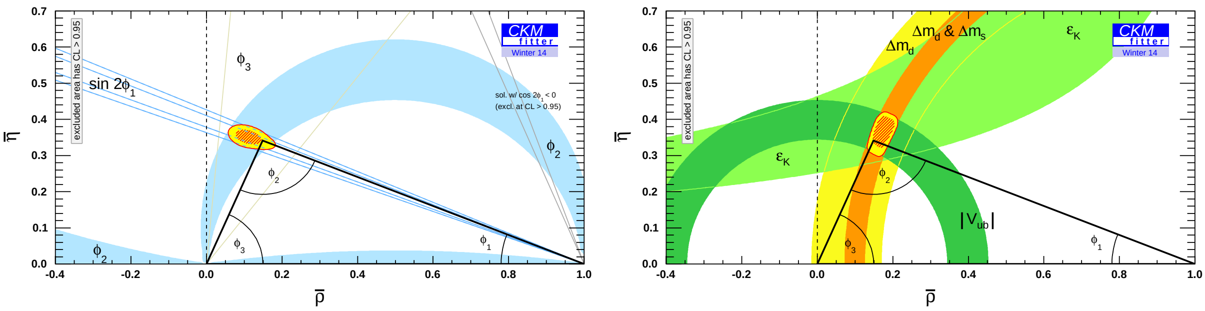

Figure 1. The Unitarity Triangle constraints: left plot – the angle measurements only, right plot – the angle measurements are excluded from the global fit [1].

Vast numbers of B_u^-, B_d^0 and B_s^0 mesons were collected by the Belle experiment at the e^+e^- asymmetric-energy KEKB collider, operating at the $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances. This provides

[1] On behalf of the Belle collaboration

the opportunity to study their properties in great detail using various analysis techniques and theoretical approaches.

2. Semileptonic decays of B_s mesons

2.1. $\bar{B}^0_s \to X^+\ell^-\bar{\nu}_\ell$ *inclusive branching fraction*

The inclusive branching fraction measurement of $\bar{B}^0_s \to X^+\ell^-\bar{\nu}_\ell$ decay, described in more detail elsewhere [2], is based on 121 fb^{-1} of data collected at the $\Upsilon(5S)$ resonance ($\sqrt{s} = 10.87$ GeV) which contains $(7.1 \pm 1.3) \times 10^6$ $B^{0(*)}_s \bar{B}^{0(*)}_s$ pairs. The extracted branching fractions separated by lepton flavor are $\mathcal{B}(\bar{B}^0_s \to X^+e^-\bar{\nu}_e) = (10.1 \pm 0.6_{\rm stat} \pm 0.7_{\rm syst})\%$ and $\mathcal{B}(\bar{B}^0_s \to X^+\mu^-\bar{\nu}_\mu) = (11.3 \pm 0.7_{\rm stat} \pm 0.8_{\rm syst})\%$. The combined branching fraction is $\mathcal{B}(\bar{B}^0_s \to X^+\ell^-\bar{\nu}_\ell) = (10.6 \pm 0.5_{\rm stat} \pm 0.7_{\rm syst})\%$ which matches the theoretical expectations [3, 4] and agrees, and is more precise than, the previous *BABAR* measurement $\mathcal{B}(\bar{B}^0_s \to X^+\ell^-\bar{\nu}_\ell) = (9.5^{+2.5}_{-2.0}(\mathrm{stat})^{+1.1}_{-1.9}(\mathrm{syst}))\%$ [5].

2.2. Preliminary results of $\bar{B}^0_s \to D^{(*)+}_s X\ell^-\bar{\nu}$ *study*

Using the same data sample as in the previous section 2.1 Belle has studied the semi-inclusive semileptonic decays $\bar{B}^0_s \to D^{(*)+}_s X\ell^-\bar{\nu}$. To select signal decays the D^+_s meson is reconstructed in the mode $D^+_s \to \phi(K^+K^-)\pi^+$ and the D^{*+}_s meson in $D^{*+}_s \to D^+_s\gamma$. The numbers of D^+_s and D^{*+}_s mesons in data are determined from a fit to the $M_{KK\pi}$ invariant mass and $\Delta M = M_{KK\pi\gamma} - M_{KK\pi}$ distributions, respectively. The preliminary branching fractions are $\mathcal{B}(\bar{B}^0_s \to D^+_s X\ell^-\bar{\nu}) = (8.2 \pm 0.2_{\rm stat} \pm 0.8_{\rm syst} \pm 1.5_{N_{B^0_s}})\%$ and $\mathcal{B}(\bar{B}^0_s \to D^{*+}_s X\ell^-\bar{\nu}) = (5.4 \pm 0.4_{\rm stat} \pm 0.5_{\rm syst} \pm 1.0_{N_{B^0_s}})\%$, where the main uncertainty comes from the estimate $N_{B^0_s}$ of the number of B^0_s mesons.

3. Semileptonic decays with a fully reconstructed tag at Belle

In e^+e^- collisions at the $\Upsilon(4S)$ resonance it is possible to fully reconstruct one B-meson decay in a known hadronic "tagging" mode where all decay products are registered by a detector, and by using energy-momentum conservation the kinematic variables of the other B meson can be calculated. This is extremely useful for the exclusive semileptonic decays $B \to X\ell\bar{\nu}_\ell$, where a particular hadronic final state X is reconstructed in the detector and the kinematic properties of the missing neutrino are reconstructed using tag-side information, providing a clean signal sample with very little background.

Recently a new reconstruction procedure for B hadronic decays based on the NeuroBayes neural net package has been introduced in Belle [6]. This procedure tries to reconstruct B mesons in more than 1100 exclusive hadronic decay channels. Compared to the previous cut-based algorithm it offers roughly a factor of two efficiency gain and about 2.1×10^6 (1.4×10^6) fully reconstructed $B^\pm$ (B^0) decays with 711 fb^{-1} collected at the $\Upsilon(4S)$ resonance.

Using this new tagging method Belle has studied the exclusive semileptonic decays $B \to D\ell\bar{\nu}_\ell$, $B^- \to p\bar{p}\ell^-\bar{\nu}_\ell$ [8], $B \to \pi\ell\bar{\nu}_\ell$, $B \to \rho\ell\bar{\nu}_\ell$ and $B^+ \to \omega\ell\bar{\nu}_\ell$ [9]. The study is based on the full data set of 711 fb^{-1} at the $\Upsilon(4S)$ resonance.

3.1. Preliminary study of $B \to D\ell\bar{\nu}_\ell$ *decays*

With the new hadronic tag the Belle study the $B \to D\ell\bar{\nu}_\ell$ decays compliments previous $|V_{cb}|$ evaluation from the $B \to D^*\ell\bar{\nu}_\ell$ decays [7]. To increase the statistical significance of the result D mesons are reconstructed multiple hadronic states. The signal yields in 10 bins of the $w = P_B \cdot P_D/(m_B m_D)$ variable, where m_B and m_D are the masses of the B and D mesons, respectevely, and P_B and P_D are their four-momenta, are extracted from binned maximum likelihood fits to the missing mass squared ($M^2_{\rm miss}$) distributions. The preliminary branching fractions are $\mathcal{B}(\bar{B}^0 \to D^+\ell\bar{\nu}) = (2.49 \pm 0.17) \times 10^{-2}$ and $\mathcal{B}(B^- \to \bar{D}^0\ell\bar{\nu}) = (2.70 \pm 0.19) \times 10^{-2}$.

The fit to the w distribution yields $\mathcal{G}(1)|V_{cb}| = (42.6 \pm 1.0 \pm 1.4) \times 10^{-3}$ and the form factor slope $\rho^2_D = 1.00 \pm 0.05 \pm 0.02$, which are the most precise single evaluations of these parameters to date. This result can be compared with the world average value $\mathcal{G}(1)|V_{cb}| = (42.64 \pm 0.72 \pm 1.35) \times 10^{-3}$ and $\rho^2_D = 1.186 \pm 0.036 \pm 0.041$. Currently the exclusive value $|V_{cb}| = (39.5 \pm 0.8_{\rm tot}) \times 10^{-3}$ and inclusive one $|V_{cb}| = (42.2 \pm 0.7_{\rm tot}) \times 10^{-3}$ are marginally consistent [17].

3.2. Evidence for $B^- \to p\bar{p}\ell^-\bar{\nu}_\ell$ decay

The direct experimental search for $B^- \to p\bar{p}\ell^-\bar{\nu}_\ell$ decay at Belle has been triggered by a recent paper [10] which predicts an unexpectedly large branching fraction, $\mathcal{B}(B^- \to p\bar{p}\ell^-\bar{\nu}_\ell) = (1.04 \pm 0.38) \times 10^{-4}$. Previous phenomenological estimations had suggested that the branching fractions of semileptonic B decays with a baryon-antibaryon pair in the final state are at the level of $10^{-5} - 10^{-6}$ [11], which would lead to only a marginal possibility for observing such decays in the data collected by the Belle or *BABAR* experiments.

The measured branching fractions obtained [8], separated by lepton flavor are $\mathcal{B}(B^- \to p\bar{p}e^-\bar{\nu}_e) = (8.2^{+3.7}_{-3.2}(\text{stat}) \pm 0.6(\text{syst})) \times 10^{-6}$ and $\mathcal{B}(B^- \to p\bar{p}\mu^-\bar{\nu}_\mu) = (3.1^{+3.1}_{-2.4}(\text{stat}) \pm 0.7(\text{syst})) \times 10^{-6}$. The combined branching fraction, assuming lepton universality is $\mathcal{B}(B^- \to p\bar{p}\ell^-\bar{\nu}_\ell) = (5.8^{+2.4}_{-2.1}(\text{stat}) \pm 0.9(\text{syst})) \times 10^{-6}$ and has 3.2σ significance. Upper limits at the 90% confidence level are also evaluated: $\mathcal{B}(B^- \to p\bar{p}e^-\bar{\nu}_e) < 14 \times 10^{-6}$, $\mathcal{B}(B^- \to p\bar{p}\mu^-\bar{\nu}_\mu) < 8.5 \times 10^{-6}$ and for the combined mode $\mathcal{B}(B^- \to p\bar{p}\ell^-\bar{\nu}_\ell) < 9.6 \times 10^{-6}$. This result clearly contradicts the prediction from [10] and contributes to a deeper understanding of the baryonic transition form factors in B-meson decays.

3.3. Results for $B \to \pi\ell\bar{\nu}_\ell$ decays

Among charmless semileptonic decays of B mesons, the $B \to \pi\ell\bar{\nu}_\ell$ decay has the most developed theoretical apparatus to describe the $B \to \pi$ hadronic transition form factors. The number of signal events is extracted from an extended binned maximum likelihood fit to the $M^2_{\rm miss}$ distribution. The fit result for the $B^0 \to \pi^+\ell\bar{\nu}_\ell$ decay is shown in Fig. 2 where the signal peak is clearly visible and the signal-to-background ratio is much better in comparison with untagged measurements. The extracted branching fractions are $\mathcal{B}(B^0 \to \pi^+\ell\bar{\nu}_\ell) = (1.49 \pm 0.09(\text{stat}) \pm 0.07(\text{syst})) \times 10^{-4}$ and $\mathcal{B}(B^+ \to \pi^0\ell\bar{\nu}_\ell) = (0.80 \pm 0.08(\text{stat}) \pm 0.04(\text{syst})) \times 10^{-4}$ [9].

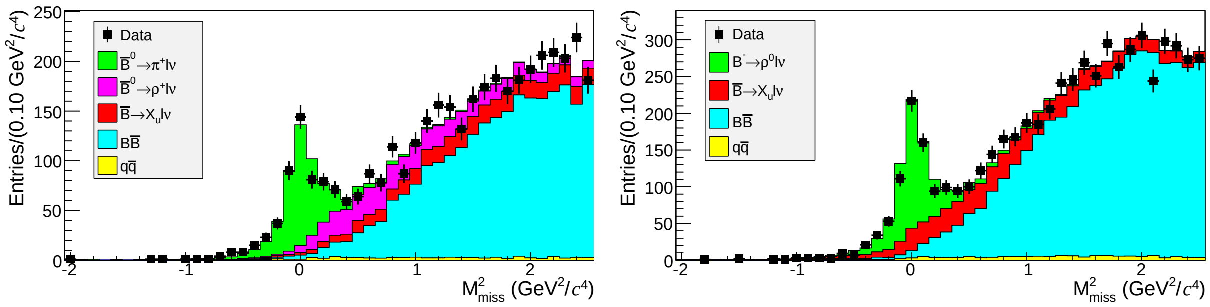

Figure 2. The fit to the $M^2_{\rm miss}$ distribution for $B^0 \to \pi^+\ell\bar{\nu}_\ell$ (left) and $B^+ \to \rho^0\ell\bar{\nu}_\ell$ (right) decays.

To extract $|V_{ub}|$, Belle also extracted the differential branching fraction as a function of q^2. The combined fit to the extracted $B \to \pi\ell\bar{\nu}_\ell$ differential branching fraction, the recent LCSR calculation [12] and lattice QCD results [13] using a model-independent parametrization of the hadronic form factor [14], yields a value of the CKM matrix element $|V_{ub}| = (3.52 \pm 0.29) \times 10^{-3}$. Adding the untagged measurement from Belle [15] and *BABAR* [16] to the fit gives $|V_{ub}| = (3.41 \pm 0.22) \times 10^{-3}$. The tension between the inclusive determination of $|V_{ub}| = (4.41^{+0.21}_{-0.23}) \times 10^{-3}$ quoted by PDG [17] remains significant at the $\sim 3\sigma$ level.

3.4. Results for $B \to \rho\ell\bar{\nu}_\ell$ decays

The maximum likelihood fit result for $B^+ \to \rho^0\ell\bar{\nu}_\ell$ decays is also shown in Fig. 2, where again the signal peak is clearly visible and the signal-to-background ratio is excellent. The extracted branching fractions are $\mathcal{B}(B^0 \to \rho^+\ell\bar{\nu}_\ell) = (3.22 \pm 0.27_{\rm stat} \pm 0.24_{\rm syst}) \times 10^{-4}$ and $\mathcal{B}(B^+ \to \rho^0\ell\bar{\nu}_\ell) = (1.83 \pm 0.10_{\rm stat} \pm 0.10_{\rm syst}) \times 10^{-4}$. The isospin average of measured branching fractions is 43% (2.7σ) higher than the previous PDG [17] value and its precision is almost a factor of two better.

The projection onto the $M_{\pi\pi}$ axis in the region $|M^2_{\rm miss}| < 0.25$ GeV/c^2 of the two-dimensional binned likelihood fit in the $M^2_{\rm miss}$-$M_{\pi\pi}$ plane is shown in Fig. 3. The extracted number of $B^- \to f_2\ell^-\bar{\nu}_\ell$ decays from the fit is $N(B^- \to f_2\ell^-\bar{\nu}_\ell) = 154 \pm 22$ which is more than 5σ away from zero and almost 3 times larger than the ISGW2 model prediction, whereas the main anticipated background from the HQE model and the PYTHIA package, the non-resonant process $\bar{B} \to X_u(\pi\pi)\ell^-\bar{\nu}_\ell$, is compatible with zero. This study can help to better estimate the uncertainty in inclusive determinations of $|V_{ub}|$ which comes from modeling of charmless semileptonic decays, and might decrease the tension with the exclusive measurements.

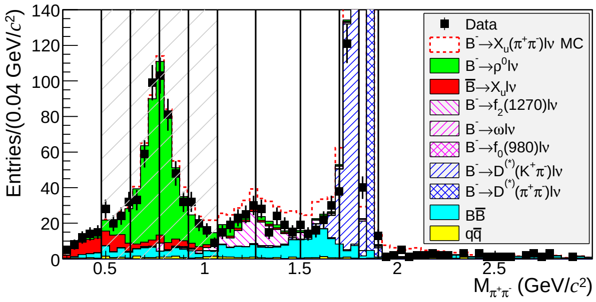

Figure 3. Projection of the fitted distribution to data for the $B^+ \to \rho^0\ell\bar{\nu}_\ell$ decay onto the $M_{\pi\pi}$ axis.

4. Conclusions

The Belle detector was decommissioned in 2010 but analysis of the collected data is not finished and is still producing outstanding scientific results. The clean environment of e^+e^- colliders is especially useful for studying semileptonic decays of B mesons in order to derive fundamental parameters of the SM such as the elements $|V_{cb}|$ and $|V_{ub}|$ of the CKM matrix.

Belle has significant progress in the (semi-)inclusive semileptonic branching fractions measurements of the B^0_s meson.

Belle has also recently developed a new procedure for B-meson full reconstruction in hadronic decay modes. This allows a number of semileptonic modes: $B \to D\ell\bar{\nu}_\ell$, $B^- \to p\bar{p}\ell^-\bar{\nu}_\ell$, $B \to \pi\ell\bar{\nu}_\ell$, $B \to \rho\ell\bar{\nu}_\ell$ and $B^+ \to \omega\ell\bar{\nu}_\ell$ to be studied.

There is much progress in the determination of $|V_{cb}|$ and $|V_{ub}|$ from B-meson semileptonic decays, where recent high-statistic measurements allow the form factor shapes to be constrained from the experimental data. Together with theory calculations this allows $|V_{cb}|$ and $|V_{ub}|$ values to be determined with high precision.

Despite all of this progress, there are still tensions at the 3σ level between exclusive and inclusive measurements of $|V_{cb}|$ and $|V_{ub}|$. This might yet be solved by improved theoretical calculations of hadronic form factors, better description of charmless semileptonic decays, and more sophisticated analysis of the existing data.

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