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Semileptonic decays of $B_{(s)}$-mesons at Belle

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

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1. Introduction

In the Standard Model (SM) of elementary particle physics, flavor changing weak coupling constants are proportional to elements of the so-called CKM (Cabibbo-Kobayashi-Maskawa) matrix, which must be unitary. Precise measurements of the values of the CKM matrix elements is important to test the unitarity and thus to probe phenomena beyond the SM which can potentially violate it.

In the most common 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 value of $|V_{ub}|$ is to extract it from charmless 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.

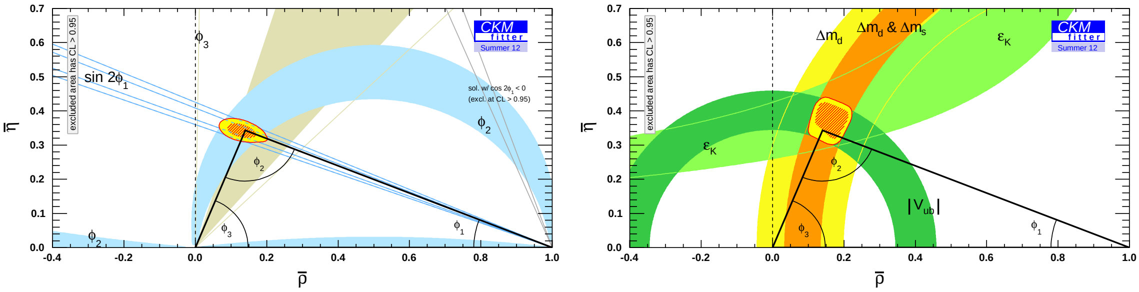

Figure 1: The Unitarity Triangle constraints: left plot – the angle measurements only, right plot – the angle measurements are excluded from the global fit [1].

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

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

The inclusive branching fraction measurement of $\bar{B}_s^0 \to X^+\ell^-\bar{\nu}_\ell$ decay, described in more detail elsewhere [2], is based on 121 fb^{-1} of data collected at $\Upsilon(5S)$ resonance ($\sqrt{s} = 10.87$ GeV) which contains $(7.1 \pm 1.3) \times 10^6$ $B_s^{0(*)}\bar{B}_s^{0(*)}$ pairs. Since most decays of B_s^0 mesons contain a D_s^+ meson ($\mathscr{B}(B_s^0 \to D_s^+X) = (93 \pm 25)\%$), a D_s^+ meson is required, reconstructed in the mode $D_s^+ \to \phi(K^+K^-)\pi^+$ in order to enhance the signal sample. To suppress D_s^+ mesons from continuum events, the D_s^+ meson is required to be low momentum, $x(D_s^+) = p_{D_s^+}/p_{D_s^+}^{\max} < 0.5$. The number of D_s^+ mesons in data is determined from a fit to the $KK\pi$ invariant mass distribution. The total number of selected D_s^+ mesons is $N(D_s^+) = (12.42 \pm 0.08) \times 10^4$ and among them $N_{\text{cont}}(D_s^+) = (2.7 \pm 0.1) \times 10^4$ mesons are expected from prompt production. The charge of the lepton from the signal $\bar{B}_s^0 \to X^+\ell^-\bar{\nu}_\ell$ decay and the reconstructed D_s^+ meson from the tagging B_s^0 meson is required to be the same, to ensure that they originate from different B_s^0 mesons. The numbers of selected same-charge lepton-meson pairs are $N(D_s^+e^+) = (4.26 \pm 0.19) \times 10^3$ and

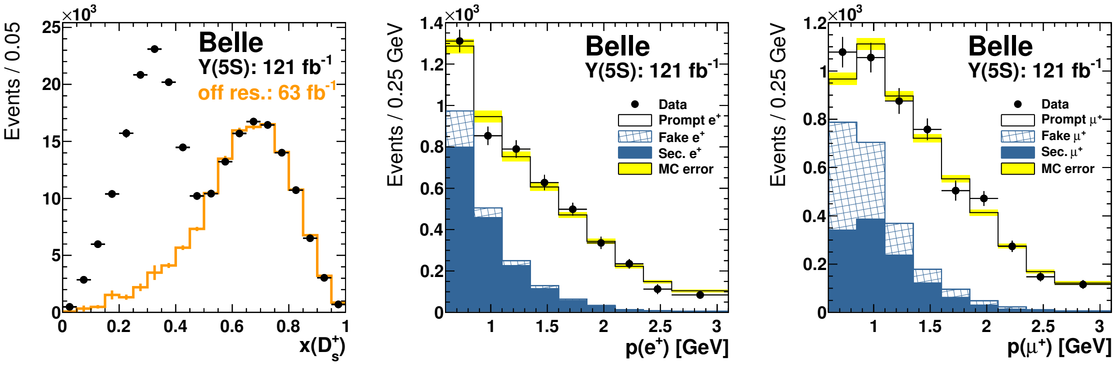

Figure 2: Momentum spectra obtained from $KK\pi$ mass fits: In bins of $x(D_s^+)$ (left) (D_s^+ sample); In bins of $p(e^+)$ (middle) and $p(\mu^+)$ (right), where continuum backgrounds have been subtracted using off-resonance data ($D_s^+\ell^+$ sample). The MC uncertainty (yellow) includes both statistical and systematic uncertainties.

$N(D_s^+\mu^+) = (4.76 \pm 0.23) \times 10^3$. The results of the $KK\pi$ invariant mass fits in bins of D_s^+ and lepton momenta are shown in Fig. 2.

The branching fraction is extracted from the ratio $\mathscr{R} = N(D_s^+\ell^+)/N(D_s^+)$, where the uncertainties related to the D_s^+ reconstruction partially cancel out. The extracted branching fractions separated by lepton flavor are $\mathscr{B}(\bar{B}_s^0 \to X^+e^-\bar{\nu}_e) = (10.1 \pm 0.6_{\rm stat} \pm 0.4_{\rm syst} \pm 0.6_{\rm ext})\%$ and $\mathscr{B}(\bar{B}_s^0 \to X^+\mu^-\bar{\nu}_\mu) = (11.3 \pm 0.7_{\rm stat} \pm 0.5_{\rm syst} \pm 0.7_{\rm ext})\%$. The combined branching fraction is $\mathscr{B}(\bar{B}_s^0 \to X^+\ell^-\bar{\nu}_\ell) = (10.6 \pm 0.5_{\rm stat} \pm 0.4_{\rm syst} \pm 0.6_{\rm ext})\%$ which matches the theoretical expectations [3, 4] and agrees, and is more precise than, the previous BABAR measurement $\mathscr{B}(\bar{B}_s^0 \to X^+\ell^-\bar{\nu}_\ell) = (9.5^{+2.5}_{-2.0}({\rm stat})^{+1.1}_{-1.9}({\rm syst}))\%$ [5].

3. Charmless 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]. The new 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. The hadronic tagging has been calibrated using relatively well-measured high-statistics charmed semileptonic decays with a precision of 4.2 % for B^+ and 4.5 % for B^0 decays.

Using this new tagging method Belle has studied the exclusive charmless semileptonic decays $B^- \to p\bar{p}\ell^-\bar{\nu}_\ell$ [7], $B \to \pi\ell\bar{\nu}_\ell$, $B \to \rho\ell\bar{\nu}_\ell$ and $B^+ \to \omega\ell\bar{\nu}_\ell$ [8]. The study is based on the full data set of 711 fb^{-1} at the $\Upsilon(4S)$ resonance.

3.1 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 [9] which predicts an unexpectedly large branching fraction, $\mathscr{B}(B^- \to p\bar{p}\ell^-\bar{\nu}_\ell) = (1.04 \pm 0.38) \times 10^{-4}$. 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 $10^{-5} - 10^{-6}$ [10], which would lead to only a marginal possibility for observing such decays in the data collected by the Belle or BABAR experiments.

To extract the number of $B^- \to p\bar{p}\ell^-\bar{\nu}_\ell$ decays an unbinned maximum likelihood fit to the missing mass squared variable, M^2_{miss}, was performed (Fig. 3). The measured branching fractions obtained, separated by lepton flavor are $\mathscr{B}(B^- \to p\bar{p}e^-\bar{\nu}_e) = (8.2^{+3.7}_{-3.2}(\mathrm{stat}) \pm 0.6(\mathrm{syst})) \times 10^{-6}$ and $\mathscr{B}(B^- \to p\bar{p}\mu^-\bar{\nu}_\mu) = (3.1^{+3.1}_{-2.4}(\mathrm{stat}) \pm 0.7(\mathrm{syst})) \times 10^{-6}$. The combined branching fraction, assuming lepton universality is $\mathscr{B}(B^- \to p\bar{p}\ell^-\bar{\nu}_\ell) = (5.8^{+2.4}_{-2.1}(\mathrm{stat}) \pm 0.9(\mathrm{syst})) \times 10^{-6}$ and has 3.2σ significance. Upper limits at the 90% confidence level are also evaluated: $\mathscr{B}(B^- \to p\bar{p}e^-\bar{\nu}_e) < 14 \times 10^{-6}$, $\mathscr{B}(B^- \to p\bar{p}\mu^-\bar{\nu}_\mu) < 8.5 \times 10^{-6}$ and for the combined mode $\mathscr{B}(B^- \to p\bar{p}\ell^-\bar{\nu}_\ell) < 9.6 \times 10^{-6}$. This result clearly contradicts the prediction from [9] and contributes to a deeper understanding of the baryonic transition form factors in B-meson decays.

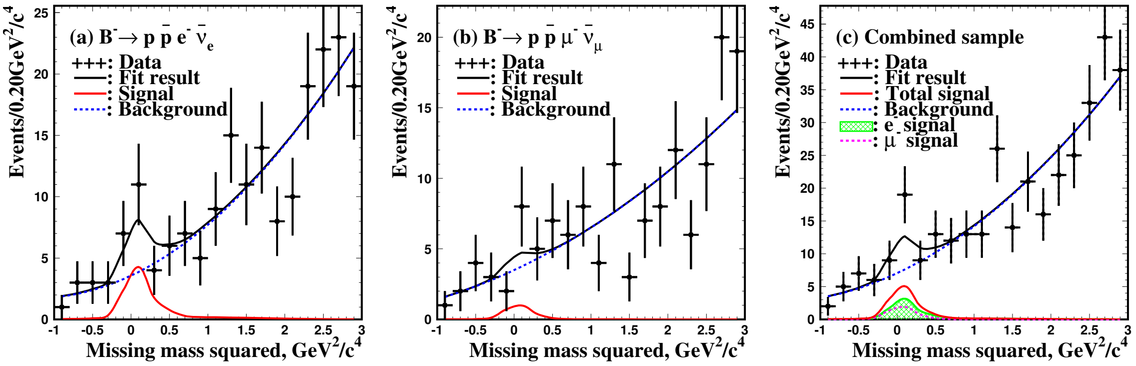

Figure 3: Fitted M^2_{miss} distributions for (a) $B^- \to p\bar{p}e^-\bar{\nu}_e$, (b) $B^- \to p\bar{p}\mu^-\bar{\nu}_\mu$ and (c) the combined fit. Points with error bars represent data, while the curves denote various components of the fit: signal (solid red), total background (dashed blue), and the sum of all components (solid black). The hatched green area denotes the signal fit component from $B^- \to p\bar{p}e^-\bar{\nu}_e$ and the dashed purple curve that from $B^- \to p\bar{p}\mu^-\bar{\nu}_\mu$.

3.2 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. There has not been much progress recently on the theory side for other light hadron states. The differential decay rate for $B \to \pi\ell\bar{\nu}_\ell$ decay with light leptons $\ell = e, \mu$ can be expressed in terms of the 4-momentum transfer squared $q^2 = (p_B - p_\pi)^2 = (p_\ell + p_\nu)^2$:

$$\frac{\mathrm{d}\Gamma(B \to \pi\ell\bar{\nu}_\ell)}{\mathrm{d}q^2} = \frac{G_F^2 p_\pi^3}{24\pi^3}|V_{ub}|^2|f_+(q^2)|^2, \tag{3.1}$$

where all QCD uncertainties are hidden in the $f_+(q^2)$ vector form factor. The $f_+(q^2)$ values calculated within the LCSR framework are valid within a limited q^2 range close to $q^2 = 0$, whereas

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lattice QCD calculations can only be done when the recoil hadron system is produced at rest, which corresponds to maximum momentum transfer. With a well chosen form factor parametrization, and using experimental data, it is possible to fix the form factor shape in q^2 regions where theory calculations are absent, and thus extract a value of the $|V_{ub}|$ element with well-motivated theoretical uncertainty for this decay.

To extract the number of signal events an extended binned maximum likelihood fit to the $M^2_{\rm miss}$ distribution is performed. The fit results are shown in Fig. 4 where signal peaks are clearly visible and the signal-to-background ratio is much better in comparison with untagged measurements. The extracted yields are $N(B^0 \to \pi^+\ell\bar{\nu}_\ell) = 463 \pm 28$ and $N(B^+ \to \pi^0\ell\bar{\nu}_\ell) = 232 \pm 23$, which translate to $\mathscr{B}(B^0 \to \pi^+\ell\bar{\nu}_\ell) = (1.49 \pm 0.09(\text{stat}) \pm 0.07(\text{syst})) \times 10^{-4}$ and $\mathscr{B}(B^+ \to \pi^0\ell\bar{\nu}_\ell) = (0.80 \pm 0.08(\text{stat}) \pm 0.04(\text{syst})) \times 10^{-4}$. With these branching fractions a test of isospin symmetry can be performed using the expression $\mathscr{R}_\pi = 2 \times \mathscr{B}(B^+ \to \pi^0\ell\bar{\nu}_\ell)/\mathscr{B}(B^0 \to \pi^+\ell\bar{\nu}_\ell) \times \tau_{B^0}/\tau_{B^+} = 1.00 \pm 0.13$ which in case of exact isospin symmetry should be $\mathscr{R}_\pi = 1$.

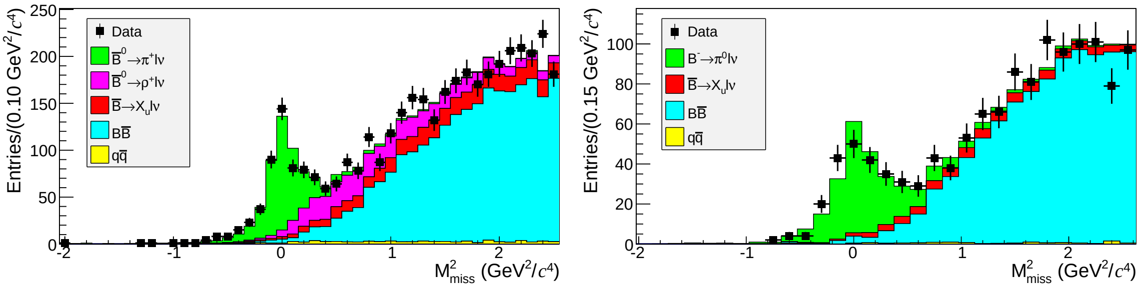

Figure 4: The fit to the $M^2_{\rm miss}$ distribution for $B^0 \to \pi^+\ell\bar{\nu}_\ell$ (left) and $B^+ \to \pi^0\ell\bar{\nu}_\ell$ (right) decays.

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 [11], lattice QCD results [12] using a model-independent parametrization of the hadronic form factor [13], yields a value of the CKM matrix element $|V_{ub}| = (3.52 \pm 0.29) \times 10^{-3}$. Adding the untagged measurement from Belle [14] and *BABAR* [15] 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 [16] remains significant at the $\sim 3\sigma$ level.

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

The maximum likelihood fit results for $B \to \rho\ell\bar{\nu}_\ell$ decays are shown in Fig. 5, where again the signal peaks are clearly visible and the signal-to-background ratio is excellent. The extracted yields are $N(B^0 \to \rho^+\ell\bar{\nu}_\ell) = 343 \pm 28$ and $N(B^+ \to \rho^0\ell\bar{\nu}_\ell) = 622 \pm 35$, which translate to $\mathscr{B}(B^0 \to \rho^+\ell\bar{\nu}_\ell) = (3.22 \pm 0.27_{\rm stat} \pm 0.24_{\rm syst}) \times 10^{-4}$ and $\mathscr{B}(B^+ \to \rho^0\ell\bar{\nu}_\ell) = (1.83 \pm 0.10_{\rm stat} \pm 0.10_{\rm syst}) \times 10^{-4}$. Again with these branching fractions a test of isospin symmetry can be performed using the expression $\mathscr{R}_\rho = 2 \times \mathscr{B}(B^+ \to \rho^0\ell\bar{\nu}_\ell)/\mathscr{B}(B^0 \to \rho^+\ell\bar{\nu}_\ell) \times \tau_{B^0}/\tau_{B^+} = 1.06 \pm 0.13$ which is in agreement with the exact isospin symmetry prediction $\mathscr{R}_\rho = 1$. The isospin average of measured branching fractions is 43% (2.7σ) higher than the PDG [16] value and its precision is almost a factor of two better.

Since only a fraction of the total charmless semileptonic decays of B mesons is relatively well measured, a major part of the representation of these decays in simulations used by experiments

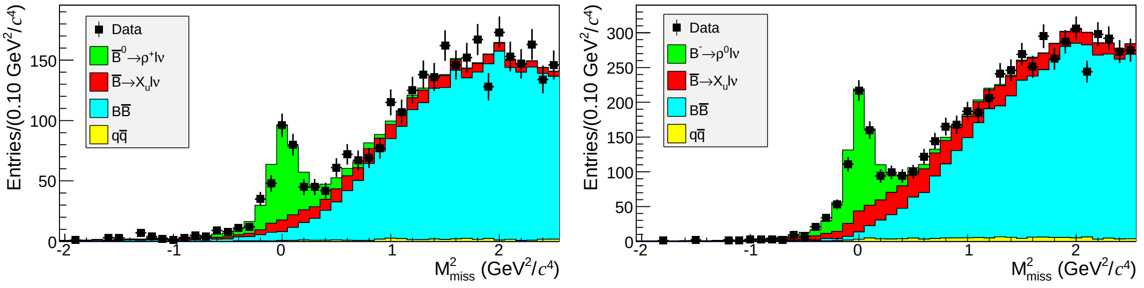

Figure 5: The fit to the M^2_{miss} distribution for $B^0 \to \rho^+ \ell \bar{\nu}_\ell$ (left) and $B^+ \to \rho^0 \ell \bar{\nu}_\ell$ (right) decays.

consists of an "educated guess" based on the ISGW2 model for exclusive light hadron recoils and the HQE model and subsequent hadronization of the initial partons using the PYTHIA package for the inclusive component. Within this scheme the main anticipated background to the $B \to \rho \ell \bar{\nu}_\ell$ decay is the non-resonant process $\bar{B} \to X_u(\pi\pi)\ell^- \bar{\nu}_\ell$ which is indistinguishable from the signal using the M^2_{miss} variable alone. To estimate this kind of background, a two-dimensional binned likelihood fit is used in the M^2_{miss}-$M_{\pi\pi}$ plane. The outcome of the fit is that the MC considerably overestimates the $\bar{B} \to X_u(\pi\pi)\ell^- \bar{\nu}_\ell$ process, and its amount is in fact compatible with zero in the data, which leads to a smaller systematic uncertainty. This fit also suggests that the broad peak in data around 1.3 GeV/c^2 is the $B^- \to f_2 \ell^- \bar{\nu}_\ell$ decay where $f_2 \to \pi^+\pi^-$. The extracted number of $B^- \to f_2 \ell^- \bar{\nu}_\ell$ decays 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. The projection onto the $M_{\pi\pi}$ axis in the region $|M^2_{\text{miss}}| < 0.25$ GeV/c^2 is shown in Fig. 6, where vertical lines show the bins in invariant mass used during the fit procedure and the hatched region shows the actual selection criterion on the invariant mass. 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.

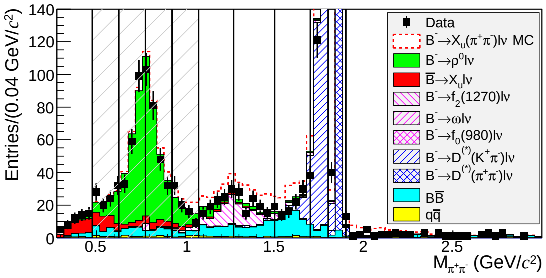

Figure 6: Projection of the fitted distribution to data for the $B^+ \to \rho^0 \ell \bar{\nu}_\ell$ decay onto the $M_{\pi\pi}$ axis.

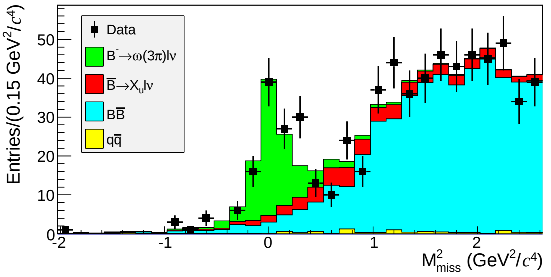

Figure 7: The fit to the M^2_{miss} distribution for $B^- \to \omega(3\pi)\ell^- \bar{\nu}_\ell$ decays.

3.4 Results for $B^+ \to \omega \ell \bar{\nu}_\ell$ decays

The M^2_{miss} fit of the $B^+ \to \omega \ell \bar{\nu}_\ell$ decay where $\omega \to \pi^+\pi^-\pi^0$ is shown in Fig. 7. The extracted yield $N(B^- \to \omega(3\pi)\ell^- \bar{\nu}_\ell) = 97 \pm 15$ corresponds to $\mathscr{B}(B^+ \to \omega \ell \bar{\nu}_\ell) = (1.07 \pm 0.16_{\text{stat}} \pm 0.07_{\text{syst}}) \times 10^{-4}$, which is in good agreement with the combined *BABAR* result $\mathscr{B}(B^+ \to \omega \ell \bar{\nu}_\ell) = (1.20 \pm 0.11_{\text{stat}} \pm 0.09_{\text{syst}}) \times 10^{-4}$ [15].

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 element $|V_{ub}|$ of the CKM matrix.

Belle has measured with the world best precision the inclusive semileptonic branching fraction of the B_s^0 meson, which is a valuable test of theoretical predictions.

Belle has recently introduced a new procedure for B-meson full reconstruction in hadronic decay modes, which offers a factor of two efficiency gain compared to the previously employed cut based algorithm. With this new method Belle has studied a number of charmless semileptonic modes: $B^- \to p\bar{p}\ell^-\bar{\nu}_\ell$, $B \to \pi\ell\bar{\nu}_\ell$, $B \to \rho\ell\bar{\nu}_\ell$ and $B^+ \to \omega\ell\bar{\nu}_\ell$.

There is much progress in the determination of $|V_{ub}|$ from $B \to \pi\ell\bar{\nu}_\ell$ decay, where recent high-statistic measurements allow the form factor shape to be extracted. Together with theory calculations this allows $|V_{ub}|$ to be determined in a model independent way.

Despite all of this progress, there is still a continued tension at the 3σ level between exclusive and inclusive measurements of $|V_{ub}|$. 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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