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Recent results on semileptonic B meson decays from Belle and Babar

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Recent results from the Belle and Babar experiments on semileptonic B meson decays are presented. The topics discussed are an updated measurement of the CKM matrix element $|V_{cb}|$ from Belle based on analysis of $B \to D\ell\nu$ events; the first observation, from Babar, of $B \to D\pi^+\pi^-\ell\nu$ decays; the first evidence, from Belle, of $B_s \to D_s^* X\ell\nu$ decays; and a new method, from Babar, to extract a value of the CKM matrix element $|V_{ub}|$ using $D^0 \to \pi^- e^+\nu$ decays.

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1. Introduction

The Belle and Babar Collaborations have each collected large samples of B mesons. Belle, which operated at KEK from 1999-2010, collected a sample of 772×10^6 $B\overline{B}$ pairs and a sample of 14×10^6 B_s mesons. Babar, which operated from 1999-2008 at SLAC, collected a sample of 471×10^6 $B\overline{B}$ pairs. In both cases, the analysis of data is still very active. Recent results on semileptonic B meson decays based upon these samples are presented below. All results discussed are preliminary.

2. $B \to D\ell\nu$ decays and $|V_{cb}|$ from Belle

Belle has presented new results on $B \to D\ell\nu$ decays and the measurement of the CKM matrix element $|V_{cb}|$. The results, based on the full Belle $B\overline{B}$ data sample, update previous results [1] that used 70 times less data. The new analysis relies on the so-called hadronic tag method, in which there is full reconstruction of the hadronic decay of one of the B mesons in the $B\overline{B}$ events. This fully reconstructed meson is denoted B_{tag}. The other B meson is required to decay through the $B \to D^0\ell\nu$ or $B \to D^+\ell\nu$ channels, with ℓ an electron or muon, and where the D mesons are reconstructed in an extensive number of decay channels. The full reconstruction of the B_{tag} meson allows the reconstruction of the 4-momentum of the other B meson, including the 4-momentum of the neutrino, greatly constraining the kinematics of signal events and providing a stringent means to reduce background.

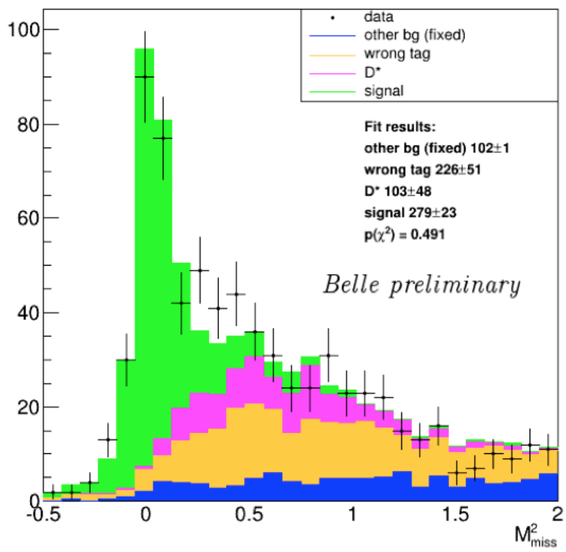

Figure 1: Distribution from Belle of the missing-mass-squared in $B \to D\ell\nu$ decays.

The missing-mass-squared distribution of selected events is shown in Fig. 1. Signal events, with one genuine missing neutrino, show a peak at zero in the missing-mass-squared variable. Events with unreconstructed particles yield larger values of this variable. A maximum likelihood fit is used to extract the signal and background yields, with the shapes of signal and background distributions described with simulation. The results are interpreted using the form factor parametrization of Ref. [2] to describe the hadronic transition of the B meson to the D meson. The results are quoted in terms of the product of variables $\eta_{EW}\mathscr{G}(1)|V_{cb}|$, where η_{EW} is a small electroweak correction and where $\mathscr{G}(1)$ is the form factor value in the "zero recoil" limit, i.e., the limit in which the D meson is produced at rest. The result, $\eta_{EW}\mathscr{G}(1)|V_{cb}| = 42.63 \pm 0.96(stat) \pm 1.39(syst) \times 10^{-3}$, improves the precision of the previous Belle result by a factor of 4 and is the most precise single measurement of this quantity.

3. $B \to D^{(*)}\pi^+\pi^-\ell\nu$ decays from Babar

Measurements of exclusive $b \to c\ell\nu$ branching fractions exist for $B \to D^{(*)}\ell\nu$ and $B \to D^{(*)}\pi\ell\nu$ decays [3, 4]. However, the sum of the measured exclusive rates does not saturate the well-determined inclusive branching fraction of $\mathscr{B}(B \to X_c\ell\nu) = 10.92 \pm 0.17\%$, but instead lies $1.45 \pm 0.29\%$ [5] below the inclusive result. It is of interest to identify the "missing" channels and test the consistency of the observations with predictions from heavy-quark effective theory. Furthermore, a better understanding of higher multiplicity $B \to X_c\ell\nu$ decays can potentially reduce systematic uncertainties for measurements like the $B \to D^{(*)}\tau\ell\nu$ result from Babar [6], where a 3.4 standard deviation discrepancy is observed with respect to the standard model expectation, and where higher multiplicity $B \to X_c\ell\nu$ decays form a significant uncertainty. The analysis is based on the full Babar $B\overline{B}$ sample. As for the Belle analysis discussed above, the hadronic tag method is used, i.e., full reconstruction of one B meson. The other B meson is reconstructed in one of 12 modes: $B \to D^{(*)}\ell\nu$, $D^{(*)}\pi^{\pm}\ell\nu$, and $D^{(*)}\pi^+\pi^-\ell\nu$, with ℓ an electron or muon, where the main interest is on the latter, previously unmeasured modes, i.e., those with a $\pi^+\pi^-$ pair in the final state. The $B \to D^{(*)}\ell\nu$ modes are used for normalization.

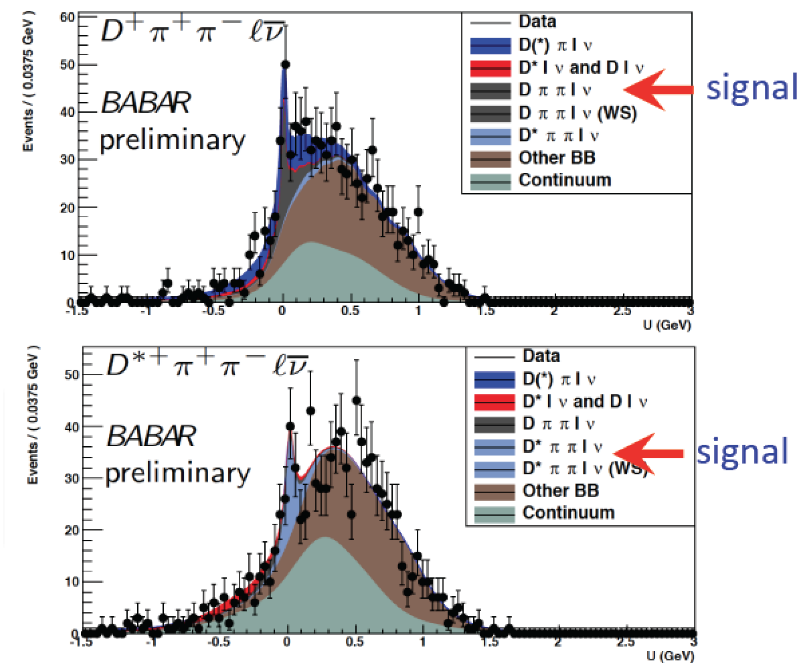

Figure 2: Distribution from Babar of the $U \equiv E_{miss} - |\vec{p}_{miss}|$ variable in the $B^0 \to D^+\pi^+\pi^-\ell\nu$ and $D^{*+}\pi^+\pi^-\ell\nu$ channels.

The missing 4-momentum is determined in the event, and the quantity $U \equiv E_{miss} - |\vec{p}_{miss}|$ is constructed, with E_{miss} and $\vec{p}_{miss}$ the missing energy and missing 3-momentum, respectively. The U variable has a value of zero for signal events. The U variable is found to be less dependent on model assumptions than more traditional variables such as the missing-mass-squared variable. A maximum likelihood fit is performed, with the distributions of signal and background events described using simulation, in order to extract the signal yields. The distributions of U in $B^0 \to D^+\pi^+\pi^-\ell\nu$ and $D^{*+}\pi^+\pi^-\ell\nu$ decays are shown in Fig. 2. The peaks at $U = 0$ correspond to a signal significance of 2.6 and 2.9 standard deviations, respectively, for these two channels. Adding the results for the corresponding B^+ decay modes, the overall significance for the $D\pi^+\pi^-\ell\nu$ results is 5.1 standard deviations, corresponding to a first observation, and for the $D^*\pi^+\pi^-\ell\nu$ results 3.5 standard deviatons, corresponding to first evidence. With respect to the gap of $1.45 \pm 0.29\%$ [5] between the exclusive and inclusive results, mentioned above, the addition of the $D^{(*)}\pi^+\pi^-\ell\nu$ channels explains around 60% of the missing channels. Thus the gap is reduced by a significant amount but is not fully explained by the $D^{(*)}\pi^+\pi^-\ell\nu$ modes.

In addition to the $D^{(*)}\pi^+\pi^-\ell\nu$ channels, results are obtained for the branching fractions of the $D^{(*)}\pi^\pm\ell\nu$ channels. These latter measurements are about 20% more precise than the current world averages.

4. $B_s \to D_s^{(*)}\ell\nu$ decays from Belle

Belle has made use of their sample of B_s mesons to measure the $B_s \to D_s^{(*)}X\ell\nu$ inclusive semileptonic transitions. The $D_sX\ell\nu$ sample includes feed-down from the D_s^* and D_s^{**} states, while the $D_s^*X\ell\nu$ sample includes feed-down from the D_s^{**} states. In the analysis, the D_s^- is reconstructed in the $\phi\pi^-$ decay mode, with $\phi \to K^+K^-$, while the D_s^{*-} is reconstructed in the $D_s^-\gamma$ decay mode. Events are required to contain a charged lepton ℓ (either an electron or muon) with opposite charge to the $D_s^{-(*)}$. The events are examined using the variable $X_{mis} \equiv (E^*_{beam} - E^*_{vis} - |\vec{p}^{\,*}_{vis}|)/p^*_{beam}$, with E_{vis} and $\vec{p}_{vis}$ the visible energy and visible 3-momentum of the event, excluding the visible decay products of the signal B_s meson, and where the asterisk indicates measurement in the event center-of-mass frame. The variable X_{mis} peaks at zero for signal events.

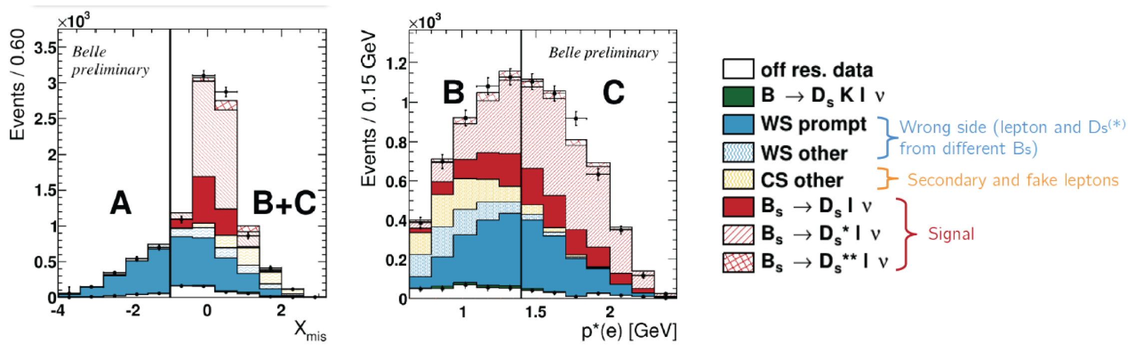

Figure 3: Distributions from Belle of the X_{mis} and p^*_ℓ variables for $D_sX\ell\nu$ events with ℓ an electron.

There are two principal background categories: 1) "wrong-side" events, in which the $D_s^{(*)}$ and leptons arise from different B_s mesons, and 2) "fake" events, in which secondary leptons are present, or else in which hadrons are misidentified as leptons. The first background category appears at small values of X_{mis} and the second background category at large values of X_{mis}. The data are divided into three regions, denoted A, B, and C. Region A, defined by $X_{mis} < -1$, is dominated by the wrong-side background. Region B, defined by $X_{mis} > -1$ and lepton momentum $p_\ell^* < 1.4$ GeV, is enhanced in fake-event background. Region C, defined by $X_{mis} > -1$ and $p_\ell^* > 1.4$ GeV, is enhanced in signal events. As an example, Fig. 3 shows the distributions of X_{mis} and p_ℓ^* for the $D_s X \ell \nu$ sample with ℓ an electron.

Templates are defined to describe the shapes of the wrong-side, fake, and signal event samples. The normalizations of the templates are adjusted in a χ^2 fit to the data. The distribution of three-particle invariant mass $m_{KK\pi}$ is fitted in each of the three regions to determine the number of D_s candidates. To determine the number of D_s^* candidates, the distribution of the mass difference $\delta_m = m_{KK\pi\gamma} - m_{KK\pi}$ is fitted. The branching fraction for $B_s \to D_s X \ell \nu$ is found to be $8.2 \pm 0.2(stat) \pm 0.8(syst) \pm 1.5(N_{B_s\overline{B}_s})\%$, where the last uncertainty is due to the uncertainty in the number $N_{B_s\overline{B}_s}$ of produced $B_s\overline{B}_s$ pairs. This result is 30% more precise than the current world average, with improvements expected as the uncertainty in $N_{B_s\overline{B}_s}$ is reduced. The branching fraction for $B_s \to D_s^* X \ell \nu$ is found to be $5.4 \pm 0.4(stat) \pm 0.5(syst) \pm 1.0(N_{B_s\overline{B}_s})\%$, which represents the first evidence for this decay mode (4.5 standard deviations of significance).

5. The $D^0 \to \pi^- e^+ \nu$ form factor and $|V_{ub}|$ from Babar

Babar has presented an analysis that utilizes a novel technique to extract the CKM matrix element $|V_{ub}|$. Instead of B meson decays, D meson decays are used, specifically the $D^0 \to \pi^- e^+ \nu$ process. The form factor $f_{+,D\to\pi}$ relevant for this process is related to the form factor $f_{+,B\to\pi}$ relevant for $B^0 \to \pi^- e^+ \nu$ decays [7]. Exploiting this relation allows $|V_{ub}|$ to be determined from the much more copious $c \to u$ (compared to $b \to u$) quark transition process. Specifically, the decay rate in $D^0 \to \pi^- e^+ \nu$ events is measured as a function of $w_D = v_D \cdot v_\pi$, where v_D and v_π are the 4-velocities of the indicated mesons. The corresponding measurements for $B^0 \to \pi^- e^+ \nu$ events are taken from Ref. [8] as a function of $w_B = v_B \cdot v_\pi$, with v_B the 4-velocity of the B meson. Taking the ratio $f_{+,B\to\pi}(w_B)/f_{+,D\to\pi}(w_D)$ to be constant [9, 10], as suggested by lattice calculations, and using the precisely known values of the CKM matrix element $|V_{cd}|$ and the D and B meson masses leaves $|V_{ub}|$ as the only unknown factor, allowing $|V_{ub}|$ to be determined.

Events are selected using $D^{*+} \to D^0\pi^+$ decays to identify D^0 meson candidates. The events are divided into hemispheres using the thrust axis. An identified π^- meson and an identified e^+ lepton are required to lie within the same hemisphere. The D^0 momentum is determined from the negative of the vector sum over the 3-momenta of all particles in the event except for the π^- and e^+ candidates. A mass-constrained kinematic fit is then performed to the entire $D^{*+} \to D^0(\to \pi^- e^+ \nu)\pi^+$ decay chain, with a requirement that the χ^2 probability of the fit exceed 0.01. Background is reduced using Fisher discriminants and by using sideband data in the distribution of the $\delta_m = m_{D^0\pi^+} - m_{D^0}$ mass difference. The extracted $D^0 \to \pi^- e^+ \nu$ signal yield and corresponding form factor are shown in Fig. 4.

The value of $|V_{ub}|$ is then adjusted so that the results determined for the $B^0 \to \pi^- e^+ \nu$ decay rate from the $D^0 \to \pi^- e^+ \nu$ events agree with the directly measured [8] $B^0 \to \pi^- e^+ \nu$ results. The comparison between the extracted and directly measured results is shown in Fig. 5, after the adjust-

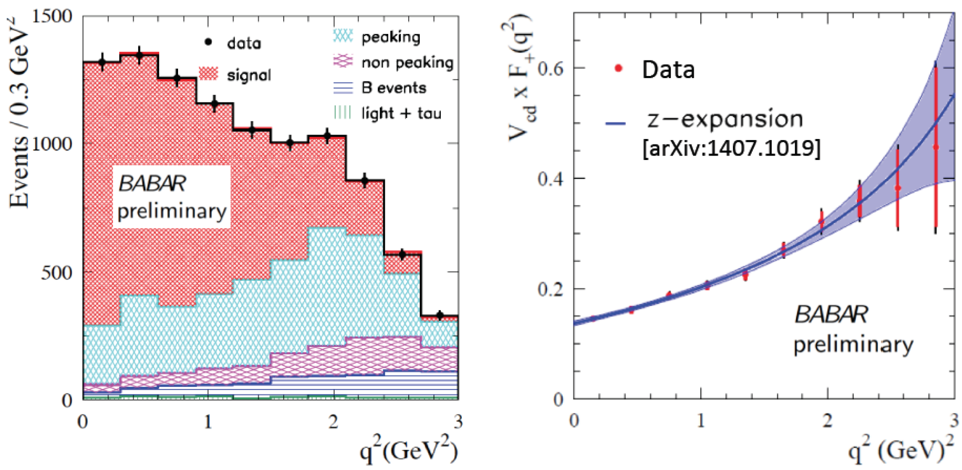

Figure 4: (right) Extracted $D^0 \to \pi^- e^+ \nu$ signal yield, and (left) resulting $f_{+,D\to\pi}$ form factor measurement from Babar.

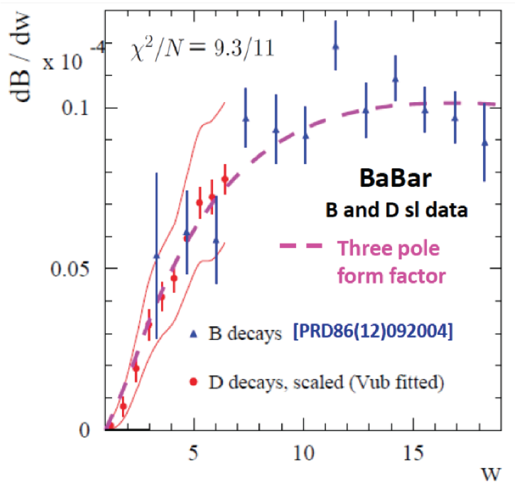

Figure 5: Distribution from Babar of the B meson decay rate in $B^0 \to \pi^- e^+ \nu$ events measured directly (triangular blue symbols) or from $D^0 \to \pi^- e^+ \nu$ events (circular red symbols) as a function of the w_B kinematic variable. The band indicated by the solid curves shows the uncertainty associated with the ratio of the $f_{+,B\to\pi}$ and $f_{+,D\to\pi}$ form factors.

ment of $|V_{ub}|$ has been made. The resulting value is $|V_{ub}| = 3.65 \pm 0.18(exp) \pm 0.40(R_{B/D}) \times 10^{-3}$, where the first uncertainty accounts for uncertainties in the experimental analysis, including experimental statistical uncertainties, while the second uncertainty accounts for the uncertainty in the ratio of the $f_{+,B\to\pi}$ and $f_{+,D\to\pi}$ form factors. This result for $|V_{ub}|$ lies between those found for exclusive and inclusive B meson decays [11].

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