

Measurements of the Partial Branching Fraction for $\bar{B} \rightarrow X_u \ell \bar{\nu}$ and the Determination of $|V_{ub}|$

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We measure partial branching fractions for the inclusive charmless semileptonic decay of $\bar{B} \rightarrow X_u \ell \bar{\nu}$, and present determinations of the CKM matrix element $|V_{ub}|$. This analysis is based on a sample of 467 million $\Upsilon(4S)$ decays into $B\bar{B}$ pairs, collected with the *BABAR* detector at the PEP-II e^+e^- storage rings. We select events where one of the B mesons is fully reconstructed in a hadronic decay mode and the other B decays semileptonically into an electron or a muon. We then use the invariant mass, M_X , of the hadronic system, the invariant mass squared, q^2 , of the lepton and neutrino pair, the lepton momentum in the in the B meson rest frame p_ℓ^* , the kinematic variable P_+ or one of their combinations as discriminating variables to isolate $\bar{B} \rightarrow X_u \ell \bar{\nu}$ decays from the background. We then measure the following partial branching fractions in various regions of phase space: $\Delta\mathcal{B} = (1.08 \pm 0.08_{\text{stat.}} \pm 0.06_{\text{sys.}} \pm 0.01_{\text{theo.}}) \times 10^{-3}$ ($M_X < 1.55 \text{ GeV}/c^2, p_\ell^* > 1.0 \text{ GeV}/c$), $\Delta\mathcal{B} = (1.15 \pm 0.10_{\text{stat.}} \pm 0.08_{\text{sys.}} \pm 0.01_{\text{theo.}}) \times 10^{-3}$ ($M_X < 1.70 \text{ GeV}/c^2, p_\ell^* > 1.0 \text{ GeV}/c$), $\Delta\mathcal{B} = (0.98 \pm 0.09_{\text{stat.}} \pm 0.08_{\text{sys.}} \pm 0.01_{\text{theo.}}) \times 10^{-3}$ ($P_+ < 0.66 \text{ GeV}, p_\ell^* > 1.0 \text{ GeV}/c$), $\Delta\mathcal{B} = (0.68 \pm 0.06_{\text{stat.}} \pm 0.04_{\text{sys.}} \pm 0.02_{\text{theo.}}) \times 10^{-3}$ ($M_X < 1.7 \text{ GeV}/c^2, q^2 > 8 \text{ GeV}^2/c^4, p_\ell^* > 1.0 \text{ GeV}/c$), $\Delta\mathcal{B} = (1.50 \pm 0.13_{\text{stat.}} \pm 0.14_{\text{sys.}} \pm 0.02_{\text{theo.}}) \times 10^{-3}$ ($p_\ell^* > 1.3 \text{ GeV}/c$). These partial branching fractions are translated into values of $|V_{ub}|$ using several theoretical calculations. An estimate based on the most inclusive analysis gives $|V_{ub}| = (4.31 \pm 0.35) \times 10^{-3}$. Furthermore, we place a limit on isospin breaking in $B \rightarrow X_u \ell \nu$ decays of 9% at 90% C.L. using separate measurements of partial branching ratios for B^0 and B^+ .

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1. Introduction

In the Standard Model of electroweak interactions, the coupling strength of the b to the u quark in the weak interaction is described by the Cabibbo-Kobayashi-Maskawa (CKM) [1] matrix element $|V_{ub}|$. A precise determination of $|V_{ub}|$ is therefore crucial for probing the CKM mechanism for quark mixing. Experimentally, $|V_{ub}|$ is obtained using branching fraction measurements of charmless $\bar{B} \rightarrow X_u \ell \bar{\nu}$ decays. However, separating $\bar{B} \rightarrow X_u \ell \bar{\nu}$ from the $\bar{B} \rightarrow X_c \ell \bar{\nu}$ background, whose rate is some fifty times larger is very difficult due to the fact that it shares a very similar event topology as the signal. Therefore, for inclusive measurements we are forced to restrict the experimental phase space to regions where this background is highly suppressed and measure partial branching fractions (PBFs). We extrapolate back to the full phase space using QCD -based theoretical calculations that are themselves affected by uncertainties which increase if the phase space is reduced. We then try to find a balance between the theoretical and experimental uncertainties in selecting regions which minimise the total uncertainty on $|V_{ub}|$.

2. Analysis technique

We begin by selecting events whereby one of the B mesons from the $\Upsilon(4S)$ decay is fully reconstructed in a hadronic decay mode (B_{reco}). We then identify a semileptonic decay by requiring an electron or muon from the opposite B meson (B_{recoil}) in the event. This technique leaves a clean B_{recoil} sample with both the flavour and four-momentum of the event well determined. The remaining particles are associated to the hadronic system X , and the detection of missing energy is associated to the neutrino. We use an un-binned maximum likelihood fit to the m_{ES} ¹ distribution in order to suppress the combinatorial background (badly reconstructed B mesons), and the continuum background ($e^+e^- \rightarrow q\bar{q}$). We use an ARGUS [2] function to describe the sum of both the combinatorial and continuum background, and a modified Crystal-Ball function [3] to describe the signal peak. The results are shown in Fig. 1.

In our resulting B_{recoil} sample we are left with various physics processes including signal $\bar{B} \rightarrow X_u \ell \bar{\nu}$ and $\bar{B} \rightarrow X_c \ell \bar{\nu}$ semileptonic decays. All other processes are referred to as ‘‘other’’. The backgrounds include leptons found in secondary cascade $B \rightarrow D \rightarrow \ell$ or $B \rightarrow D_s \rightarrow \tau$ decays, leptons from τ decays, leptons from $J/\psi \rightarrow \ell\ell$, or hadrons mis-identified as leptons (mainly affects the muon sample). In order to suppress these backgrounds we perform various selection cuts on the B_{recoil} . Firstly, we require one lepton with momentum in the B_{recoil} rest-frame of $p_\ell^* > 1 \text{ GeV}/c$. This reduces the charm background since secondary leptons are frequent in $\bar{B} \rightarrow X_c \ell \bar{\nu}$ due to cascade decays of the X_c . Whereas, secondary leptons are very rare in $\bar{B} \rightarrow X_u \ell \bar{\nu}$ decays. Also, we require $Q_{B_{recoil}} Q_\ell < 0$, where $Q_{B_{recoil}}$ is the charge of the B_{recoil} and Q_ℓ is the charge of the primary lepton. Furthermore, we set $Q_{tot} = Q_{B_{reco}} + Q_X + Q_\ell = 0$, where $Q_{B_{reco}}$ is the charge of the B_{reco} and Q_X is the charge of the hadronic system. Also, we reduce $B \rightarrow D^* \ell \nu$ decays by exploiting the properties of the soft pion produced in the $D^* \rightarrow D\pi$ decay in order to infer and place cuts on the missing mass. The only undetected particle should be a neutrino, so we require the missing mass squared to be less than $0.5 \text{ GeV}^2/c^4$. Lastly, we veto charged kaons and K_S^0 found in the B_{recoil} .

¹ $m_{ES} = \sqrt{s/4 - \vec{p}_B^2}$, where \sqrt{s} is the total energy of the $\Upsilon(4S)$ and p_B is the momentum of the B_{reco} .

After these selection cuts we use various kinematic variables in differing phase space regions to select the final signal sample. This includes the lepton momentum (p_ℓ^*), the hadronic invariant mass (M_X), the di-lepton invariant mass squared (q^2) and $P_+ = E_X - |\vec{P}_X|^2$. We determine the number of $\bar{B} \rightarrow X_u \ell \bar{\nu}$ signal events and subsequently the PBF ($\Delta\mathcal{B}$) in the following optimised regions of phase space: $M_X < 1.55 \text{ GeV}/c^2$ and $M_X < 1.70 \text{ GeV}/c^2$, $P_+ < 0.66 \text{ GeV}/c$, $p_\ell^* > 1.3 \text{ GeV}$, $M_X < 1.70 \text{ GeV}/c^2$ and $q^2 > 8.0 \text{ GeV}^2/c^4$, and $M_X - q^2$ full phase space using a χ^2 minimisation fit of MC to data (for the last two cases a 2-dimensional fit is performed). It is worth mentioning that we normalize the PBF to the total semileptonic branching fraction, which reduces certain systematic uncertainties. We find that the quality of the fit in regions dominated by the charm background (the high M_X region for example) is poor. So we rescale the contribution in MC from semileptonic decays into P-wave D mesons, which improves the quality of the fit in these regions without affecting the final signal yield greatly. The results are shown in Fig. 2.

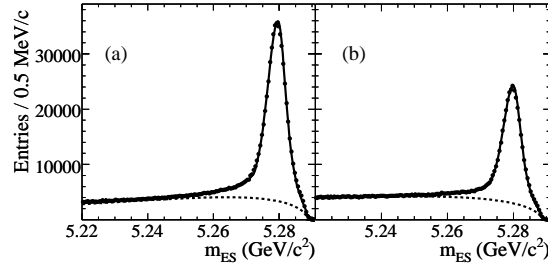


Figure 1: Fit of m_{ES} distributions of $\bar{B} \rightarrow X_u \ell \bar{\nu}$ candidates passing the semileptonic selection criteria in MC events where a B^\pm (a) or a B^0 (b) has been fully reconstructed in a hadronic decay mode.

3. $|V_{ub}|$ results

To translate the measured PBFs into $|V_{ub}|$ we use calculations from Neubert and collaborators (BLNP) [4], Andersen and Gardi (DGE) [5], Aglietti and collaborators (ADFR) [6], and Gambino and collaborators (GGOU) [7]. Generally, we relate $|V_{ub}|$ to $\Delta\mathcal{B}(\bar{B} \rightarrow X_u \ell \bar{\nu})$ with

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(\bar{B} \rightarrow X_u \ell \bar{\nu})}{\tau_B \cdot \Delta\Gamma_{theory}}}, \quad (3.1)$$

where $\tau_B = 1.573 \times 10^{-12}$ s is the lifetime of the B meson [8], and $\Delta\Gamma_{theory}$ is the theoretical $\bar{B} \rightarrow X_u \ell \bar{\nu}$ width according to the applied cuts. $\Delta\Gamma_{theory}$ varies from the calculation used, and the experimental region. For this measurement we adopt and propagate the uncertainty on this quantity as assessed by the authors. We quote an estimate for $|V_{ub}|$ using the most inclusive measurement. Namely, the two-dimensional fit to the $M_X - q^2$ plane with no cuts other than $p_\ell^* > 1.0 \text{ GeV}$. So, using $\Delta\mathcal{B} = (1.80 \pm 0.13_{\text{stat.}} \pm 0.15_{\text{sys.}}) \times 10^{-3}$ and calculating the arithmetic mean average of the four theoretical calculations we find that $|V_{ub}| = (4.31 \pm 0.35) \times 10^{-3}$.

4. Conclusion

In summary, we present measurements of PBFs for the inclusive charmless semileptonic decay of $\bar{B} \rightarrow X_u \ell \bar{\nu}$, in various regions of phase space. We require one of the of the B mesons in the event

²where E_X and \vec{P}_X are the energy and momentum of the hadronic X system in the B meson rest frame.

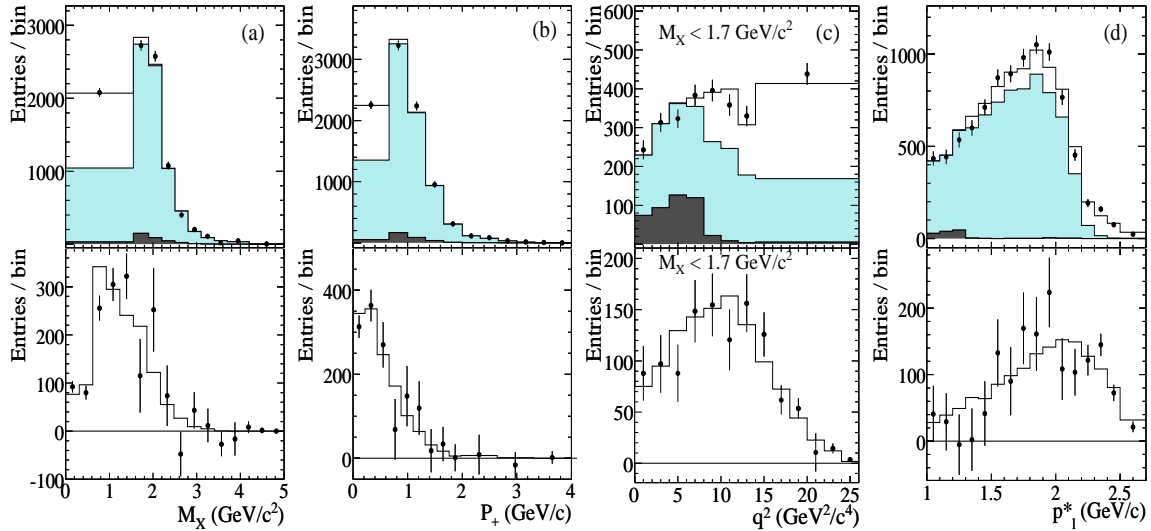


Figure 2: Upper row: The result of the MC fit to data (points) using the M_X (a), P_+ (b), q^2 with $M_X < 1.7 \text{ GeV}/c^2$ (c) and p_ℓ^* (d) spectra. The MC contributions correspond to $\bar{B} \rightarrow X_u \ell \bar{\nu}$ decays generated inside signal region (no shading), outside the signal region (dark shading), and the sum of $\bar{B} \rightarrow X_c \ell \bar{\nu}$ and “other” backgrounds (light shading). Lower row: The same spectra after background subtraction using finer binning.

to be fully reconstructed in a hadronic decay mode, and the other B to decay semileptonically into either an electron or a muon. Using the analysis based on the two-dimensional fit on $M_X - q^2$ with no cut other than $p_\ell^* > 1.0 \text{ GeV}$, we obtain $|V_{ub}| = (4.31 \pm 0.35) \times 10^{-3}$ as the most precise result. The total uncertainty is around 8%, which is comparable to a similar study performed by Belle [9], which uses a multivariate discriminant to reduce the background. Furthermore, we place a limit on the potential contribution from the Weak Annihilation of 9% at 90% C.L.

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