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# Measurements of $\bar{B} \to D^{(*)}\tau^-\overline{\nu}_\tau$ and $|V_{ub}|$ at BABAR

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We report the first observation of the exclusive semileptonic decay $B \to D\tau^-\overline{\nu}_\tau$ with $6.9\,\sigma$ significance and improved measurements on the ratios $\mathscr{R}(D^{(*)}) = \mathscr{B}(B \to D^{(*)}\tau^-\overline{\nu}_\tau)/\mathscr{B}(B \to D^{(*)}\ell^-\overline{\nu}_\ell)$, where $D^{(*)}$ refers to a $D$ or $D^*$ meson. The analysis is performed on a sample of 471 million $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the BABAR detector. The preliminary results, $R(D) = 0.456 \pm 0.053 \pm 0.056$ and $R(D^*) = 0.325 \pm 0.023 \pm 0.027$ , exceed the standard model predictions of $R(D) = 0.31 \pm 0.02$ and $R(D^*) = 0.25 \pm 0.02$ by $1.8\,\sigma$.

We also report the final measurements of $|V_{ub}|$, the magnitude of the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $V_{ub}$, using the full BABAR dataset. An inclusive analysis studying $B \to X_u\ell\nu$ decays (where $X_u$ refers to a charmless hadronic state) determines a value of $|V_{ub}| = (4.31 \pm 0.25 \pm 0.26) \times 10^{-3}$, and the combination of two results based on the $q^2$ dependent decay rate of the exclusive $B \to \pi\ell\nu$ decay yields $|V_{ub}| = (3.13 \pm 0.14 \pm 0.27) \times 10^{-3}$.

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# 1. Measurement of $\bar{B} \to D^{(*)}\tau^-\overline{\nu}_\tau$

## 1.1 Motivation

Several of the most popular extensions of the Standard Model (SM) include charged Higgs bosons $H^\pm$. Searches are usually carried out in the context of one of the two Higgs-doublet models (2HDM). Of special importance is Type II, which coincides with the Higgs sector of the Minimal Supersymmetric Standard Model at tree level. This sector is fully determined by the mass of $H^\pm$ and $\tan\beta$, the ratio of the two Higgs-doublet vacuum expectation values, which are not predicted by theory. Hadron machines have been performing direct and indirect searches for $H^\pm$ in the last decade [1]. The large data samples and high precision of the $B$ factories, Belle and BABAR, have recently allowed measurements of $B$ decays such as $B \to X_s\gamma$, $B \to \tau^-\overline{\nu}_\tau$ and $B \to D^{(*)}\tau^-\overline{\nu}_\tau$, which provide complementary and expanded constraints on the parameter space of $H^\pm$ models. Of these decays, $B \to \tau^-\overline{\nu}_\tau$ has the most direct dependence on $H^\pm$, but $B \to D^{(*)}\tau^-\overline{\nu}_\tau$ may provide the highest experimental sensitivity, due to the larger branching fraction and smaller theoretical uncertainty [2].

In this note, we report the measurement of $\mathscr{R}(D^{(*)}) = \mathscr{B}(B \to D^{(*)}\tau^-\overline{\nu}_\tau)/\mathscr{B}(B \to D^{(*)}\ell^-\overline{\nu}_\ell)$, where $\ell^-$ is a light lepton (electron or muon). Using $B \to D^{(*)}\ell^-\overline{\nu}_\ell$ decays as normalization eliminates the dependence on the CKM matrix element $V_{cb}$ and other theoretical uncertainties. We only reconstruct the leptonic decays of the $\tau$ meson, $\tau^- \to \ell^-\overline{\nu}_\ell\nu_\tau$, which further reduces the uncertainty on the reconstruction efficiency by ensuring that the signal and normalization components have the same topology in the final state.

## 1.2 Event selection

We select $B\bar{B}$ events with a tag $B$ meson ($B_{\rm tag}$), a charmed meson $D^{(*)}$ and a charged lepton $\ell^-$. The $B_{\rm tag}$ is reconstructed in a hadronic decay using a recently improved algorithm that triples the efficiency of the $B_{\rm tag}$ reconstruction with respect to previous BABAR analyses [3]. We divide the events into four samples corresponding to the decays to four charm mesons, $D^0, D^{*0}, D^+, D^{*+}$.

The poorly understood $\bar{B} \to D^{**}\ell^-\overline{\nu}_\ell$ background enters the selection when the soft pion of $D^{**} \to D^{(*)}\pi$ decays is missed or assigned to the $B_{\rm tag}$. We build four $D^{**}$-enriched samples adding a $\pi^0$ to the signal selection. We further improve the significance of these 8 samples by applying multivariate methods (BDT) that make use of variables describing the quality of the reconstruction like the mass of the reconstructed $D^{(*)}$ or $\Delta E = E_{\rm tag} - \sqrt{s}/2$.

## 1.3 Fit procedure

We extract the signal and normalization yields with an extended, unbinned maximum-likelihood fit to the two-dimensional $m^2_{\rm miss}$ and $|p^*_\ell|$ distributions. The missing mass, $m^2_{\rm miss} = (p_{e^+e^-} - p_{\rm tag} - p_{D^{(*)}} - p_\ell)^2$, separates the normalization with $m^2_{\rm miss} \sim 0$ (only one unreconstructed neutrino), from signal with much larger $m^2_{\rm miss}$ (three unreconstructed neutrinos). The leptons in normalization events have higher momentum than the secondary leptons in signal events coming from $\tau^- \to \ell^-\overline{\nu}_\tau\nu_\ell$ decays. We estimate the 56 2D Probability Distribution Functions (PDFs) from a 3.8 ab$^{-1}$ Monte Carlo sample using Gaussian Kernel Estimators (KEYS). The fit is performed simultaneously in the 4 signal and 4 $D^{**}$-samples, with cross-channel constraints taken from simulations. The fit results for $D^0$ and $D^{*0}$ are shown in Fig. 1.

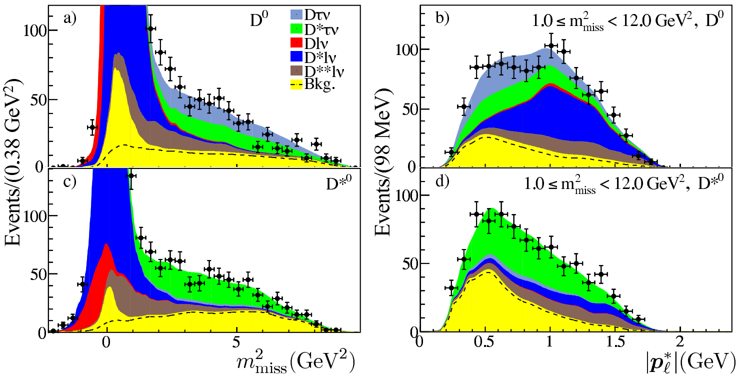

**Figure 1:** $m^2_{\text{miss}}$ and $|p^*_\ell|$ projections of the fit to the $D^0$ and $D^{*0}$ channels.

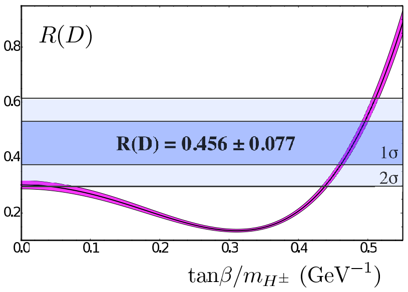

**Figure 2:** Impact of charged Higgs mediation on $\mathscr{R}(D)$ [4].

### 1.4 Results

The fits to the two $D^*$ channels agree very well with the data, but the agreement in the $D$ channels is less satisfactory. We studied the effect of different proportions of background repeating the analysis with tighter and looser BDT cuts. The fits agree well in both cases, suggesting that the nominal sample might be affected by a statistical fluctuation. However, the resulting $\mathscr{R}(D)$ changed significantly, so we assign half of the maximum variation as a systematic uncertainty in these preliminary results. The other major sources of systematic uncertainty are the PDFs and the $\bar{B} \to D^{**}\ell^-\overline{\nu}_\ell$ background.

We measure $\mathscr{R}(D) = 0.456 \pm 0.053 \pm 0.056$ and $\mathscr{R}(D^*) = 0.325 \pm 0.023 \pm 0.027$, where the isospin relations $\mathscr{R}(D^+) = \mathscr{R}(D^0)$ and $\mathscr{R}(D^{*+}) = \mathscr{R}(D^{*0})$ are imposed. We report a significance of $5\sigma$ in all four channels, the first such result in the $D$ channels. The measured $\mathscr{R}(D)$ and $\mathscr{R}(D^*)$ are $1.8\sigma$ above the SM, which favors values of $\tan\beta/m_H^\pm \sim 0.5\,\text{GeV}^{-1}$ as shown in Fig. 2.

## 2. Measurement of $|V_{ub}|$

The CKM matrix element $V_{ub}$ is measured in charmless $B$ semileptonic decays for which the rate may be expressed as $\Gamma_{B\to X_u\ell\nu} \propto |V_{ub}|^2 \times F^2_{\text{had}}(q^2, M_X, \ldots)$. Here, $F_{\text{had}}$ parameterizes the effects of the hadronic current and depends on the kinematic variables of the event. The measurement may be done reconstructing all the particles in the final state (*exclusive*), or just the lepton (*inclusive*). The two approaches are complementary but, so far, yield significantly different $|V_{ub}|$ values [5].

### 2.1 Exclusive measurement: $B \to \pi\ell\nu$ decay

The two recently published $B \to \pi\ell\nu$ analyses [6] follow similar strategies: they select events with a pion and a light lepton, and reconstruct the neutrino based on the missing energy and momentum of the whole event. The signal yields are extracted in fits to the $\Delta E$ and $m_{\text{ES}} = \sqrt{E^2_{\text{beam}} - \mathbf{p}^2_B}$ distributions in bins of $q^2 = (p_B - p_\pi)^2$. Since the event overlap between the two analyses is negligible due to different signal optimization techniques (neural networks versus square cuts), the statistical uncertainties are independent. We consider the systematic uncertainties fully correlated.

Figure 3 shows a simultaneous fit to the measured $\Delta\mathscr{B}/\Delta q^2$ distributions and predictions from lattice calculations [7]. This kind of fit takes full advantage of the shape information in these spectra, greatly reducing the uncertainty with respect to the traditional method where only the integrals of data and theory are used. We measure $|V_{ub}| = (3.13\pm0.14\pm0.27)\times10^{-3}$, where the first uncertainty is experimental, and the second comes from theory.

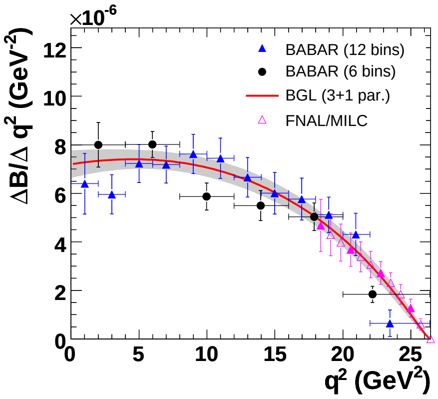

**Figure 3:** Fit to $\Delta\mathscr{B}/\Delta q^2$ for $B\to\pi\ell\nu$. Only 4 of the 12 lattice points are used due to large correlations between them.

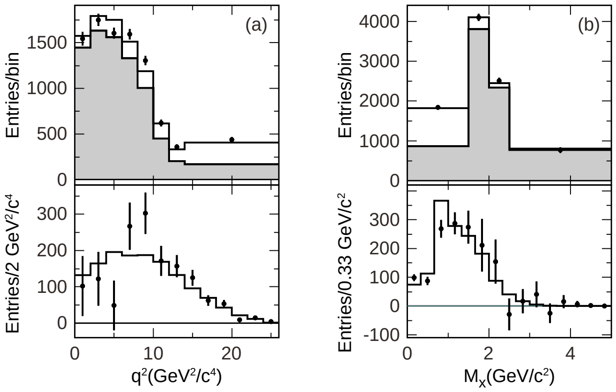

**Figure 4:** $q^2$ and $M_X$ projections for inclusive $B\to X_u\ell\nu$ in white and $B\to X_c\ell\nu$ in gray. In the bottom plots background has been subtracted and bin width made uniform.

### 2.2 Inclusive measurement: $B\to X_u\ell\nu$

We look for $B\bar{B}$ events of the type $\Upsilon(4S)\to B_{\rm tag}(\to \text{hadrons})B_{\rm sig}(\to X_u\ell\nu)$. The combinatorial background is subtracted with a fit to $m_{\rm ES}$, the copious $B\to X_c\ell\nu$ background reduced with kaon and $D^*\ell\nu$ vetoes, and $m^2_{\rm miss}$ required to be consistent with the missing neutrino ($m^2_{\rm miss} < 0.5\,\mathrm{GeV}^2$).

The signal yields are extracted by fits to seven different phase space regions. The most precise results come from the 2D fit to $q^2$ and $M_X$ (the mass of the $X_u$ system) shown in Fig. 4. $|V_{ub}|$ values extracted with four different QCD calculations [8] yield similar results. Thus, we quote the arithmetic average $|V_{ub}| = (4.31\pm0.25\pm0.16)\times10^{-3}$. The discrepancy with the exclusive value persists (our results are even further apart than the world averages), and further research is needed.

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