SEMILEPTONIC B DECAYS AND IMPLICATIONS FOR HIGGS SEARCHES*

Roberto Sacco

Queen Mary, University of London, Mile End Road, London E1 4NS, UK

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We present recent results on semileptonic B decays from the BaBar experiment, with emphasis on $\overline{B} \to D^{(*)}\tau\bar{\nu}$ and the implications that these decays have on our understanding of the Standard Model and New Physics effects.

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1. Introduction

Semileptonic decays of heavy-flavored hadrons serve as a powerful probe of the electroweak and strong interactions and are essential to determinations of Cabibbo–Kobayashi–Maskawa (CKM) matrix elements. In the Standard Model (SM), CP-violating effects result from an irreducible phase in the CKM matrix [1, 2]. Precise determinations of the magnitude of the matrix element $|V_{ub}|$ and $|V_{cb}|$ are fundamental in testing the CKM sector of the Standard Model, and complement the measurements of CP asymmetries in B decays.

The inclusive semileptonic branching fractions of the B_d and B_u mesons are measured to high precision by experiments operating at the $\Upsilon(4S)$ resonance, which decays almost exclusively to $B\overline{B}$ pairs ($B_d\overline{B}_d$ and $B_u\overline{B}_u$). However, lacking an analogous production mechanism, information on branching fractions of the B_s meson remains scarce nearly two decades after its first observation.

In addition, semileptonic decays of B mesons to the τ lepton provide a new source of information on SM processes [3, 4, 5], as well as a new window on physics beyond the SM [6, 7, 8, 9, 10, 11]. In the SM, semileptonic decays occur at tree level and are mediated by the W boson, but the large mass

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of the τ lepton provides sensitivity to additional amplitudes, such as those mediated by a charged Higgs boson. Experimentally, $b \to c\tau^- \nu_\tau$ decays are challenging to study because the final state contains not just one, but two or three neutrinos as a result of the τ decay.

We report recent results on these semileptonic B decays using data collected with the *BABAR* detector at the PEP-II asymmetric-energy electron-positron collider [12], located at the SLAC National Accelerator Laboratory.

2. Determination of $|V_{ub}|$ and $|V_{cb}|$

The determination of $|V_{ub}|$ and $|V_{cb}|$ is done through the study of the semileptonic transitions $b \to u\ell\bar{\nu}$ and $b \to c\ell\bar{\nu}$ ($\ell = e, \mu$) respectively, to exclusive or inclusive final states. The theory describing these transitions use the fact that the mass m_b of the b quark is large compared to the scale $\Lambda_{\rm QCD}$ that determines low-energy hadronic physics. Precise calculations are done via a systematic expansion in powers of Λ/m_b (where $\Lambda \sim \Lambda_{\rm QCD}$), using effective field theory methods to separate non-perturbative from perturbative contributions.

The wealth of data collected by the B factories have opened up new possibilities experimentally. It is now possible to fully reconstruct a B meson from an $\Upsilon(4S)$ decay, such that the recoiling semileptonic B decay can be studied with higher purity than was previously possible. Improved knowledge of $\overline{B} \to X_c\ell\bar{\nu}$ decays allows partial rates for $\overline{B} \to X_u\ell\bar{\nu}$ transitions to be measured in regions previously considered inaccessible, increasing the acceptance for $\overline{B} \to X_u\ell\bar{\nu}$ transitions and reducing theoretical uncertainties. Experimental measurements of the exclusive $B \to \pi\ell\nu$ decay are quite precise. Further improvement in the theoretical calculation of the form factor normalization is needed to fully exploit these measurements.

Substantial progress has been made in the calculation of the total semileptonic rate via Operator Product Expansion (OPE), which yields the Heavy Quark Expansion (HQE), a systematic expansion in inverse powers of the b-quark mass [13, 14]. Fits to moments of $\overline{B} \to X_c\ell\bar{\nu}$ and $B \to X_s\gamma$ decays provide precise values for $|V_{cb}|$ and m_b. Exploiting such a technique, *BABAR* has recently measured $|V_{cb}| = (42.1 \pm 0.6 \pm 0.8) \times 10^{-3}$ [15].

On the exclusive side, semileptonic B decays into charmed mesons D and D^* can provide measurements of $|V_{cb}|$ through knowledge of the form factors that describe $B \to D$ and $B \to D^*$ transitions. The ignorance of these form factors dominate the uncertainty on $|V_{cb}|$. Several approaches, like Heavy Quark Symmetry (HQS) [16, 17] or lattice QCD simulations [18] have been used. Recent *BABAR* measurement on $\bar{B}^0 \to D^{*+}e^-\bar{\nu}_e$ [19] and $B^0 \to D^{*-}\ell^+\nu_\ell$ [20] can be averaged to give $(37.4 \pm 1.2 \pm 1.4) \times 10^{-3}$ [1]. The

[1] Charge-conjugate modes are implied throughout this letter, unless explicitly stated.

2.2σ tension between the inclusive and exclusive $|V_{cb}|$ values highlights the need for further work. The most recent result from the Belle Collaboration on $B^0 \to D^{*-}\ell^+\nu_\ell$ [21], $|V_{cb}| = (34.6 \pm 0.2 \pm 1.0) \times 10^{-3}$, also shows this discrepancy.

The theory behind the description of inclusive $\overline{B} \to X_u \ell \bar{\nu}$ decays relies, as for $\overline{B} \to X_c \ell \bar{\nu}$, on HQE. The total $\overline{B} \to X_u \ell \bar{\nu}$ decay rate is difficult to measure due to the overwhelming background from semileptonic decays to charm. Calculating the partial decay rate in regions of phase space, where $\overline{B} \to X_c \ell \bar{\nu}$ decays are suppressed is more challenging, as the HQE convergence in these regions is spoiled, requiring the introduction of a non-perturbative distribution function. Several approaches have been used recently to calculate reliably the charmless partial decay rate [22, 23, 24, 25, 26, 27, 28]. Inclusive determinations of partial charmless branching fractions in several regions of phase space have been done recently by *BABAR* [29]. The $|V_{ub}|$ value corresponding to the most inclusive measurement, with no phase space restrictions, except for a requirement on the lepton momentum in the B rest frame $p^*_\ell > 1.0$ GeV, is $|V_{ub}| = (4.31 \pm 0.25 \pm 0.16) \times 10^{-3}$.

Exclusive charmless semileptonic decays offer a complementary means of determining $|V_{ub}|$. For the experiments, the specification of the final state provides better background rejection, but the lower branching fraction gives lower yields compared with inclusive decays. The theory describing exclusive decays relies on non-perturbative methods for the calculation of the form factors, such as lattice QCD and light-cone sum rules [30, 31]. *BABAR* has measured the differential $B \to \pi \ell \nu$ rate *versus* the momentum transfer q^2 with good accuracy [32, 33]. These results have been used in simultaneous fits to the experimental partial rate and lattice points *versus* q^2; the determination of $|V_{ub}|$ from a combination of these two results yields $|V_{ub}| = (3.13 \pm 0.14 \pm 0.27) \times 10^{-3}$. This is in good agreement with the most recent result from Belle on $B^0 \to \pi^- \ell^+ \nu$, $|V_{ub}| = (3.34 \pm 0.33) \times 10^{-3}$ [34].

Again, there is a sizeable tension (2.8σ) between inclusive and exclusive determinations of $|V_{ub}|$ that warrants further studies. Indeed, further progress is possible, but will require higher order radiative corrections from the theory and improved experimental knowledge of the $\overline{B} \to X_c \ell \bar{\nu}$ background, and independent confirmations of the input used for m_b. Progress in the past few years has been impressive, but it is going to be extremely difficult to achieve an uncertainty of 5% on $|V_{ub}|$ from inclusive decays.

Progress in both $b \to u$ and $b \to c$ exclusive decays depends on progress in lattice calculations. Here the prospects are good, since unquenched lattice simulations are now possible, although the ultimate attainable precision is hard to estimate.

2.1. The semileptonic branching fraction of the B_s meson

The data on which we base this measurement were collected by BABAR in a scan of center-of-mass (CM) energies above the $\Upsilon(4S)$ resonance, including the region near the $B_s\overline{B}_s$ threshold. As ϕ mesons are particularly abundant in B_s decays due to the CKM-favored $B_s \to D_s$ transition, the inclusive production rate of ϕ mesons and the rate of ϕ mesons produced in association with a high momentum electron or muon can be used to simultaneously determine the B_s semileptonic branching fraction and the B_s production fraction as a function of the CM energy $E_{\rm CM}$ [35]. The energy scan data correspond to an integrated luminosity of 4.25 fb^{-1} collected in 2008 in 5 MeV steps in the range 10.54 GeV $\leq E_{\rm CM} \leq$ 11.2 GeV.

For this measurement, we present the scan data as a function of $E_{\rm CM}$ in bins of 15 MeV. In each bin we measure the number of $B\overline{B}$-like events, the number of such events containing a ϕ meson, and the number of events in which the ϕ meson is accompanied by a charged lepton candidate. The results are normalized to the number of $e^+e^- \to \mu^+\mu^-$ events in the same energy bin so that the luminosity dependence in each bin is removed. These three measurements are used to extract the fractional number of $B_s\overline{B}_s$ events and the semileptonic branching fraction $\mathcal{B}(B_s \to \ell\nu X)$.

To suppress QED background, events are preselected with a multi-hadronic event filter optimized to select $B\overline{B}$ and $B_s\overline{B}_s$ events. Candidate ϕ mesons are reconstructed in the $\phi \to K^+K^-$ decay mode, by forming pairs of oppositely charged tracks that are consistent with the kaon hypothesis. The invariant mass distribution of these candidates is used to determine the ϕ yield in a given $E_{\rm CM}$ bin using a maximum likelihood fit. Events containing ϕ candidates and an electron or muon candidate with a CM momentum exceeding 900 MeV are used to determine the yield of events with both a ϕ and a lepton (ϕ-lepton events). The requirement on the lepton momentum suppresses background from semileptonic charm decays.

To determine the ϕ and ϕ-lepton yields from B decays in each $E_{\rm CM}$ bin, the contribution of continuum events is subtracted. This is achieved by using the data collected below the $\Upsilon(4S)$. The event, ϕ, and ϕ-lepton yields are measured in this dataset and corrected for the energy dependence of the reconstruction efficiencies and are then subtracted from the scan yields in each $E_{\rm CM}$ bin.

The normalized event, ϕ, and ϕ-lepton yields after the continuum subtraction are presented in Fig. 1. We determine the ϕ and ϕ-lepton yields in the $\Upsilon(4S)$ data. These can be expressed in terms of contributions from events containing $B_{u,d}^{(*)}$ and $B_s^{(*)}$ events, the cross section ratio

$$R_B \equiv \sum_{q=\{u,d,s\}} \sigma\left(e^+e^- \to B_q\overline{B}_q\right)/\sigma_{\mu^+\mu^-} \, ,$$

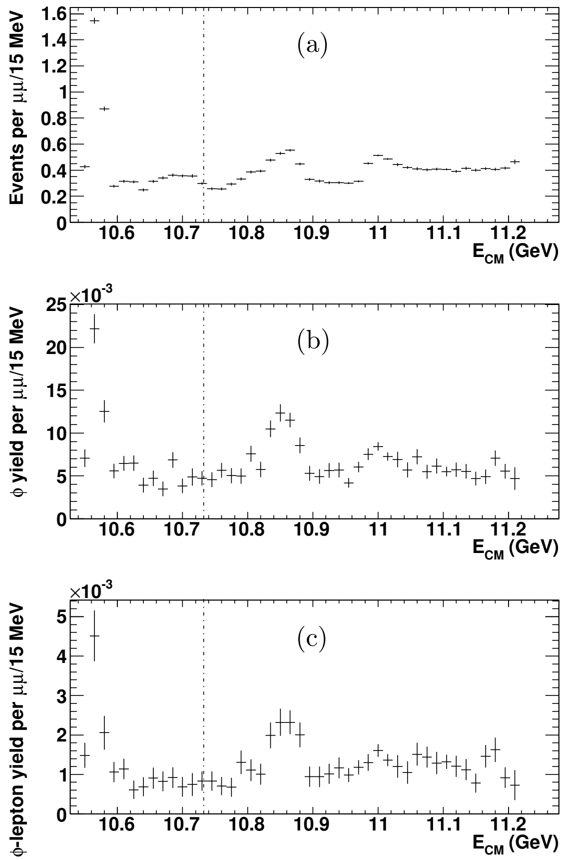

Fig. 1. Relative (a) event, (b) ϕ, and (c) ϕ-lepton yields, normalized to the $\mu^+\mu^-$ yields. Corrections for detector efficiency have not been applied. The dotted vertical line indicates the B_s production threshold.

the related reconstruction efficiencies, and

$$f_s \equiv \frac{N_{B_s}}{N_{B_u} + N_{B_d} + N_{B_s}} \,. \quad (1)$$

The ratio f_s can be determined as a function of $E_{\rm CM}$ from its expression in terms of ϕ, and ϕ-lepton yields and known branching fractions. The result is presented in Fig. 2.

The ratio f_s peaks around the $\Upsilon(5S)$ mass. The total excess below the $B_s\overline{B}_s$ threshold and deficit above 11 GeV are consistent with zero within 1.5 and 1.3 standard deviations, respectively.

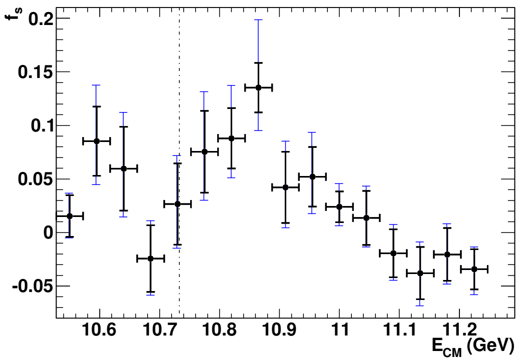

Fig. 2. Results for the fraction f_s as a function of E_{CM}. The inner error bars show the statistical uncertainties and the outer error bars the statistical and systematic uncertainties added in quadrature. The dotted line denotes the B_s threshold.

Finally, a χ^2 is constructed from the measured and expected values of $P(B_s\overline{B}_s \to \phi\ell X)$ across the entire scan. The χ^2 is minimized with respect to $\mathcal{B}(B_s \to \ell\nu X)$. After assessing systematic uncertainties, dominated by the inclusive D_s yield per B_s, we calculate the inclusive semileptonic branching fraction as $\mathcal{B}(B_s \to \ell\nu X) = 9.5^{+2.5+1.1}_{-2.0-1.9}\%$, which is the average of the branching fractions to e and μ.

2.2. Study of the decay $\overline{B} \to D^{(*)}\tau\bar{\nu}$

Experimentally, $b \to c\tau^-\nu_\tau$ decays are distinguishable from other semileptonic decays because they result in one or two additional neutrinos from the τ decay. The branching fractions are smaller than those to lower mass leptons, $\ell = e^\pm$ or $\mu^\pm$. SM predictions for the relative rates are $\mathcal{R}(D) = \mathcal{B}(\overline{B} \to D\tau\nu_\tau)/\mathcal{B}(\overline{B} \to D\ell\nu_\ell) = 0.302 \pm 0.15$ [40] and $\mathcal{R}(D^*) = \mathcal{B}(\overline{B} \to D^*\tau\nu_\tau)/\mathcal{B}(\overline{B} \to D^*\ell\nu_\ell) = 0.252 \pm 0.013$ [10]. These two decay modes account for most of the predicted inclusive rate, $\mathcal{B}(\overline{B} \to X_c\tau\overline{\nu}_\tau) = (2.30 \pm 0.25)\%$ [4] (here X_c refers to all charm hadronic states). Calculations [6, 7, 8, 9, 10] based on multi-Higgs doublet models predict a substantial impact, either positive or negative, on the ratio $\mathcal{R}(D)$, and a much smaller effect on $\mathcal{R}(D^*)$.

This analysis is based on the full data sample recorded by the *BABAR* detector. It places constraints on the unobserved particles in the event by reconstructing both B mesons and can be summarized as follows: the hadronic decay of one B meson is fully reconstructed (hadronic tag) and the remaining charged particles and photons are required to be consistent with a semileptonic decay of the other, specifically a charm meson (charged or neutral D or D^*) and a charged lepton (either $e^\pm$ or $\mu^\pm$). We divide the events into four samples, corresponding to four decay channels to charm mesons, D^0, D^{*0}, D^+, D^{*+}. Signal decays have a secondary charged lepton from a $\tau^- \to \ell^- \overline{\nu}_\ell \nu_\tau$ decay, whereas the normalization decays have a primary lepton from a $\overline{B} \to D^{(*)} \ell \overline{\nu}_\ell$ decay. Primary leptons typically have higher momenta than secondary leptons. The missing four momentum is used to distinguish between decays with a single neutrino and three neutrinos in the final state, $p_{\rm miss} = (p_{e^+e^-} - p_{\rm tag} - p_{D^{(*)}} - p_\ell)$, where $p_{e^+e^-}$ is the energy of the colliding beams, $p_{\rm tag}$ the energy of the fully reconstructed B, and p_ℓ the lepton energy.

The missing mass squared, $m^2_{\rm miss} = p^2_{\rm miss}$, peaks at zero for decays with a single missing neutrino, whereas for signal events the $m^2_{\rm miss}$ distribution is broad, and extends to about $8\,{\rm GeV}^2$. To determine the yield of the signal and normalization samples for the four decay channels, we perform fits to the two-dimensional distributions of $m^2_{\rm miss}$ *versus* $|\boldsymbol{p}^*_\ell|$, the lepton momentum in the rest frame of the B meson. The selection criteria and the fit configuration were designed using simulations and data control samples. The signal region was not analyzed until the procedure was settled to prevent bias.

The event selection proceeds in two stages: first, we select $B\overline{B}$ events with a hadronic tag and the semileptonic decay candidate, and second, we apply a boosted decision tree (BDT) algorithm to improve the signal-to-background ratio.

For semileptonic decays the minimum momentum transfer is largely determined by the mass of the charged lepton. For decays involving τ leptons, $q^2 = (p_\tau + p_{\nu_\tau})^2 \geq m^2_\tau \simeq 3.16\,{\rm GeV}^2$. Thus the selection $q^2 > 4\,{\rm GeV}^2$ retains 98% of the $\overline{B} \to D^{(*)} \tau \overline{\nu}_\tau$ decays and rejects more than 30% of the $\overline{B} \to D^{(*)} \ell \overline{\nu}_\ell$ decays. The event sample with $q^2 < 4\,{\rm GeV}^2$ is dominated by $\overline{B} \to D^{(*)} \ell \overline{\nu}_\ell$ and serves as very clean data control sample for comparisons with MC simulation.

We extract the signal and normalization yields from an extended, unbinned maximum-likelihood fit to two-dimensional $m^2_{\rm miss}$–$|\boldsymbol{p}^*_\ell|$ distributions. The fit is performed simultaneously for the four signal channels and four $\overline{B} \to D^{(*)} \pi^0 \ell \overline{\nu}$ channels. The channels containing $D^{(*)}\pi^0$ states help modeling background from $\overline{B} \to D^{**} \ell \overline{\nu}$, where D^{**} are the four orbital excitations of the $c\bar{q}$ state, and decay primarily as $D^{**} \to D^{(*)}\pi$. The distribution for each signal channel is described as the sum of eight components: $D\tau\overline{\nu}_\tau$, $D^*\tau\overline{\nu}_\tau$, $D\ell\overline{\nu}_\ell$, $D^*\ell\overline{\nu}_\ell$, $D^{**}\ell\overline{\nu}_\ell$, charge cross feed, B combinatorial, and continuum. In the $D^{(*)}\pi^0$ channels, the $D^{(*)}\tau\overline{\nu}_\tau$ and $D^{(*)}\ell\overline{\nu}_\ell$ components are combined, but otherwise we use the same configuration, resulting in a fit with a total of $8 \times 4 + 6 \times 4 = 56$ probability distribution functions (PDFs). The fit has 22 free parameters; by performing a fit in which we impose isospin relations for all semileptonic decays of charged and neutral B mesons, the number of free parameters is reduced to 13 and results in

$\mathcal{R}(D^0) = \mathcal{R}(D^+) \equiv \mathcal{R}(D)$ and $\mathcal{R}(D^{*0}) = \mathcal{R}(D^{*+}) \equiv \mathcal{R}(D^*)$.

Figure 3 shows the projections of the fit to data in $m^2_{\rm miss}$ for the four signal channels, showing both the low $m^2_{\rm miss}$ region, which is dominated by the normalization modes $\overline{B} \to D^{(*)}\ell\overline{\nu}_\ell$, and the high $m^2_{\rm miss}$ region, which is dominated by the signal modes $\overline{B} \to D^{(*)}\tau\overline{\nu}_\tau$. The fit describes reasonably

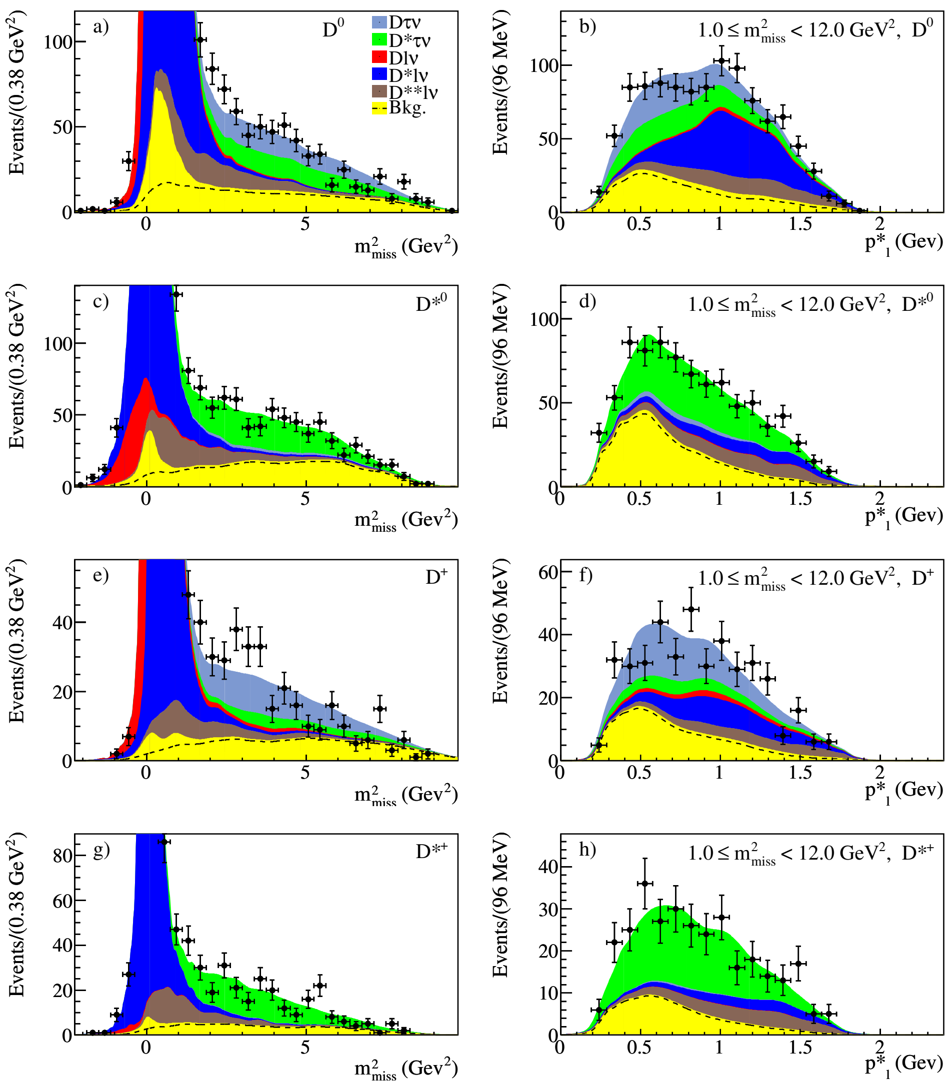

Fig. 3. $m^2_{\rm miss}$ and $|\boldsymbol{p}^*_\ell|$ projections of the unconstrained fit to the signal sample. The $|\boldsymbol{p}^*_\ell|$ projections do not include the region $m^2_{\rm miss} < 1\,{\rm GeV}^2$, where the normalization modes dominate.

well the four $D^{(*)}\pi^0$ channels inside the sizeable statistical uncertainties. It describes very well the large contributions of the reference decay modes. Fit results for D^{*0} and D^{*+} channels are very good. Both channels are observed with a significance higher than 11σ (when only statistical uncertainties are considered). For the D channels, the fit projection onto $m^2_{\rm miss}$ shows an excess of data in the range $1.5 < m^2_{\rm miss} < 3.5$ GeV^2 and an overestimation of events for $m^2_{\rm miss} > 5$ GeV^2. These regions are dominated by continuum and B combinatorial backgrounds which are fixed in the fit to what is expected by simulation. It is not yet clear if these differences are statistical or systematic in nature. Both D^0 and D^+ channels are observed for the first time with a significance greater than 6σ.

The main sources of systematic uncertainties are the MC simulation of the background, the statistical uncertainties of the simulated samples, and the $D^{**}\ell\overline{\nu}_\ell$ decay modes. In order to understand the origin of the difference in the comparison between data and fit result, the BDT requirements have been changed in such a way that the number of events with $m^2_{\rm miss} > 1.5$ GeV^2 that pass the event selection correspond to 50%, 80%, 120%, and 200% of the nominal sample. The agreement between fit and data improved using both more and less restrictive BDT requirements. We assign a systematic uncertainty equal to half of the variation on $\mathcal{R}(D^*)$ in the fit when applying tight BDT requirements (50% of the nominal sample) and loose BDT requirements (200% of the nominal sample). This systematic uncertainty (9.5% on $\mathcal{R}(D)$ and 6.5% on $\mathcal{R}(D^*)$) is comparable in size with the statistical uncertainties. It should be eliminated or reduced once the source of the difference is fully understood.

Table I summarizes the results obtained from the two fits: the one in which all four signal yields can vary independently (first four lines), and the one in which isospin relations are imposed. These preliminary results are in agreement with previous *BABAR* [36] and Belle [37, 38, 39] measurements.

The results shown in Table I differ significantly (by about 2σ for each measurement, that can grow to about 3σ considering the large anticorrelation between them) with respect to the SM predictions.

By conservatively combining *BABAR* and Belle results, one can estimate what is the compatibility of these measurements with the Two Higgs Doublet Model (2HDM) [7]. Precise calculations are still in progress, but the lookout is not good, with the model being excluded in a very large fraction of the $\tan\beta - m_H$ phase space.

2.3. Conclusions

We have presented here recent *BABAR* result on the study of semileptonic B and B_s decays. Analyses of charmed and charmless semileptonic B decays

TABLE I

Results for the ratios $\mathcal{R}(D^{(*)})$, the individual signal branching fraction, the signal significance $\Sigma_{\rm tot}$ including systematic uncertainties, and the significance $\Sigma_{\rm stat}$, where only statistical uncertainties are considered.

Mode	$\mathcal{R}(D^{(*)})$	$\mathcal{B}(B \to D^{(*)}\tau\nu)$ (%)	$\Sigma_{\rm tot}$ ($\Sigma_{\rm stat}$)
$D^0\tau^-\overline{\nu}_\tau$	$0.422 \pm 0.074 \pm 0.059$	$0.96 \pm 0.17 \pm 0.14$	5.0 (6.2)
$D^{*0}\tau^-\overline{\nu}_\tau$	$0.314 \pm 0.030 \pm 0.028$	$1.73 \pm 0.17 \pm 0.18$	8.9 (11.9)
$D^+\tau^-\overline{\nu}_\tau$	$0.513 \pm 0.081 \pm 0.067$	$1.08 \pm 0.19 \pm 0.15$	6.0 (7.5)
$D^{*+}\tau^-\overline{\nu}_\tau$	$0.356 \pm 0.038 \pm 0.032$	$1.82 \pm 0.19 \pm 0.17$	9.5 (12.1)
$D\tau^-\overline{\nu}_\tau$	$0.456 \pm 0.053 \pm 0.056$	$1.04 \pm 0.12 \pm 0.14$	6.9 (9.6)
$D^*\tau^-\overline{\nu}_\tau$	$0.325 \pm 0.023 \pm 0.027$	$1.79 \pm 0.13 \pm 0.17$	11.3 (17.1)

has confirmed the marginal agreement between inclusive and exclusive measurements, for both $|V_{cb}|$ and $|V_{ub}|$, that has persisted for many years, despite the progress in theory and experiment made in recent years. On the other hand, determination of the semileptonic branching fraction for B_s decays is consistent with theoretical calculations. Discrepancy with SM predictions emerges once again in the analysis of $\overline{B} \to D^{(*)}\tau\overline{\nu}_\tau$ decays. Measurements of $\mathcal{R}(D^{(*)})$ are consistent between experiments, but seem to disagree with the SM at the level of 2σ. Moreover, these results are incompatible with prediction from 2HDM.

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