Evidence for an excess of $B \to D^{(*)}\tau\nu$ decays

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Abstract. The full data sample from the BaBar experiment is used to measure the ratios of branching fractions \( \mathcal{R}(D) = \frac{B(\bar{B} \to D\tau\nu)\Delta \ell}{B(\bar{B} \to D\ell\nu)} \) and \( \mathcal{R}(D^*) = \frac{B(\bar{B} \to D^*\tau\nu)\Delta \ell}{B(\bar{B} \to D^*\ell\nu)} \), where \( \ell \) refers to an electron or muon. These ratios are sensitive to the presence of new physics in charged current decays and are sensitive probes for charged Higgs bosons. These ratios are predicted in the standard model with small theoretical uncertainties, and many experimental uncertainties cancel in the ratio. The measured values, \( \mathcal{R}(D) = 0.440 \pm 0.058 \pm 0.042 \) and \( \mathcal{R}(D^*) = 0.332 \pm 0.024 \pm 0.018 \), exceed standard model expectations by 2.0\( \sigma \) and 2.7\( \sigma \), respectively. Accounting for correlations, the combined departure from the standard model is 3.4\( \sigma \). The measured values are not compatible with a charged Higgs boson in type-II two-Higgs-doublet models, but can be accommodated in more general models involving charged mediators.

1. Introduction
This talk reports on a recent BaBar measurement published in Ref. [1]. This study is a search for lepton flavour violation in charged current decays of $B$ mesons. Semileptonic decays form a large part of the total $B$ decay width in the standard model (SM). The equality of coupling strengths for semileptonic $B$ decays proceeding through electrons and muons has been tested at the few percent level in $b \to c\ell\nu$ transitions\(^1\), and these decays are expected to be essentially free from new physics effects. However, semileptonic decays proceeding through $\tau$ leptons are less well constrained. There also exist well-motivated scenarios in which the coupling to third-generation leptons is modified; in particular, models involving charged Higgs bosons [2, 3, 4, 5, 6] provide a tree-level contribution to these decays that can lead to an $O(1)$ change in the decay rate.

The purely leptonic decay $\bar{B} \to \tau\nu$ is also sensitive to new charged mediators. While that decay is interesting in its own right, the $\bar{B} \to D^{(*)}\tau\nu$ decay provides several advantages: it’s far less rare ($b \to c$ versus $b \to u$ transition), has a smaller theoretical uncertainty on the SM expectation, and, as a three-body decay, allows for the measurement of decay distributions that are sensitive to the structure of the current.

The $\bar{B} \to D^{(*)}\tau\nu$ decay rate in the SM can be written in terms of helicity amplitudes as follows [7]

\[
\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{tb}|^2 |P_{D^{(*)}}| q^2}{96\pi^3 m_B^3} \frac{1}{q^2} \left( 1 - \frac{m_\tau^2}{q^2} \right)^2 \left[ |H_+|^2 + |H_-|^2 + |H_0|^2 \right] \left( 1 + \frac{m_\tau^2}{2q^2} + \frac{3m_\tau^2}{2q^2} |H_s|^2 \right)
\]

\(^1\) Throughout this paper, $\ell$ refers to an electron or a muon, and charge-conjugate decays are implied.

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where $|\mathbf{p}_{D^*(s)}|$ is the magnitude of the 3-momentum of the $D^{(*)}$ in the $B$ rest frame. The helicity amplitudes $H_{\pm}$ do not contribute to $B \to D(\ell/\tau)\nu$ decays, and the $H_s$ amplitude does not contribute to $B \to D^{(*)}\ell\nu$ decays since the coefficient of this term is proportional to the square of the charged lepton mass. The helicity amplitudes are constrained experimentally except for $H_s$, which is taken from an HQET-based prediction [6]. Many of the factors in Eq. 1 are common for $\ell$, $\mu$ and $\tau$ and associated uncertainties (e.g. on helicity amplitudes) partially cancel in the ratios $R(D^{(*)})$. Experimental uncertainties on efficiencies and acceptances are also reduced in these ratios. The SM predictions for the ratios $R(D^{(*)}) \equiv \mathcal{B}(B \to D^{(*)}\tau\bar{\nu}_\tau)/\mathcal{B}(B \to D^{(*)}\ell\bar{\nu}_\ell)$, using the latest input on measured form factors, are

\begin{align}
R_{SM}(D) & = 0.297 \pm 0.017 \\
R_{SM}(D^*) & = 0.252 \pm 0.003
\end{align}

The uncertainty due to the unmeasured helicity amplitude $H_s$ has a smaller impact on $R_{SM}(D^*)$ than on $R_{SM}(D)$ due to the presence of additional helicity states in the $B \to D^*$ transition. The uncertainties on the measured value are large compared to the uncertainty in the SM predictions.

2. Measurement strategy

The data were collected from $e^+e^-$ collisions at a centre-of-mass (CM) energy of 10.58 GeV, where the $\Upsilon(4S)$ resonance decays to $B\bar{B}$ pairs with a cross-section of about 1 nb and the underlying $q\bar{q}$ continuum has a cross-section of about 3.3 nb. The beam energies are unequal but known, allowing measured quantities to be boosted into the CM frame of the colliding beams. BaBar collected a sample of 471 M $B\bar{B}$ events; in these events the two $B$ mesons are produced near threshold, and there is insufficient energy to produce any additional particles. The energies of the $B$ mesons therefore sum to the precisely-known beam energy, and the decay products of the $B$ mesons overlap in the detector. The BaBar detector has silicon and gas chamber tracking for charged particles, a ring-imaging Cherenkov detector, and a CsI(Tl) calorimeter inside a 1.5T solenoid, and muon chambers interspersed in the return yoke; it is described in detail in Ref. [8].

The measurement involves the reconstruction of two related decay modes: the signal decay, $B \to D^{(*)}\tau\bar{\nu}_\tau$ with $\tau \to E\bar{\nu}_\tau\bar{\nu}_\ell$, and the normalization decay, $B \to D^{(*)}\ell\bar{\nu}_\ell$. The detected particles in each case are the same. The signal decay involves three neutrinos; as a result, the proper assignment of particles to the $B$ and $B$ mesons requires one of them to be fully reconstructed in a hadronic decay mode. This reconstruction sums over approximately 1700 distinct decay chains and selects hadronic $B_{\text{tag}}$ candidates based on the quantities $\Delta E \equiv E_{\text{tag}} - E_{\text{beam}}$ and $m_{\text{ES}} \equiv \sqrt{E_{\text{beam}}^2 - |\mathbf{p}_{\text{tag}}|^2}$, where $E_{\text{tag}}$ and $|\mathbf{p}_{\text{tag}}|$ are the energy and the magnitude of the 3-momentum of the $B_{\text{tag}}$ candidate; these quantities are calculated in the CM frame. Given a $B_{\text{tag}}$ candidate, a reconstructed $D^{(*)}$ meson and an identified electron or muon, two quantities are used to discriminate between signal and background. The missing mass squared is given by $M_{\text{miss}}^2 = (p_{\ell^+\ell^-} - p_{\text{tag}} - p_{D^{(*)}} - p_\ell)^2$, where each $p$ represents the corresponding 4-vector. This quantity peaks sharply at zero for the normalization decays, where there is only one missing neutrino, and is spread over the range 0 to $\sim 9$ GeV$^2$ for signal decays. The second quantity used is the momentum of the lepton candidate $|\mathbf{p}_\ell^\prime|$ in the $B$ rest frame; the leptons from the signal decay have a softer distribution than those from the normalization mode. Electron (muon) candidates with laboratory momenta above 300 (200) MeV can be identified as leptons; low-momentum muons are distinguished from pions based on $dE/dx$ and energy deposition in the calorimeter.

Further requirements are imposed to suppress backgrounds. The signal $B$ and the $B_{\text{tag}}$ are required to have the expected charge correlation for coming from an $\Upsilon(4S)$ decay. Events with unassigned charged tracks are vetoed. A boosted decision tree (BDT) classifier is used to further
3. Backgrounds and control samples

The normalization decays, $\bar{B} \rightarrow D^{(*)} \ell \nu$, are much more numerous than the signal decays; normalization decays that are mis-reconstructed are a source of background and need to be well understood. On the other hand, normalization decays in the region $q^2 < 4 \text{GeV}^2$ are essentially free of any signal contribution and serve as an excellent control sample for understanding the modelling of detector response. Other control samples are also available. The region $5.20 < m_{E\text{T}} < 5.26 \text{GeV}$ allows the simulation of the combinatorial $B_{tag}$ background to be corrected. A sample collected at $e^+e^-$ collision energies just below $BB$ threshold allows the simulation of $q\bar{q}$ continuum events to be corrected. Sidebands in $E_{\text{extra}}$ allow further tests of the simulation.

An intrinsic source of background that overlaps significantly with the signal decays in both $M^2_{\text{miss}}$ and $|p^*_\ell|$ are decays of the type $\bar{B} \rightarrow D^{**} \ell \nu$ where $D^{**}$ is a charmed state that decays to $D^{(*)}\pi$ and the $\pi$ is undetected. The properties of this class of semileptonic decay are not well measured; furthermore, known decays of the type $\bar{B} \rightarrow X_c \ell \nu$ do not saturate the inclusive $b \rightarrow c \ell \nu$ decay rate, leaving room for other potential sources of background. A novel feature of this analysis relative to previous measurements of $\bar{B} \rightarrow D^{(*)}\tau \nu$ is the use of a dedicated control sample sensitive to these contributions, namely a sample where an additional neutral pion is reconstructed: $\bar{B} \rightarrow D^{(*)}\pi^0 \ell$. Decays that proceed through any intermediate charm state (resonant or not) that ends up as $D^{(*)}\pi^0$ will produce a peak at $M^2_{\text{miss}} = 0$ where $M^2_{\text{miss}} = (p_{e^+e^-} - p_{\text{tag}} - p_{D^{(*)}} - p_{\pi^0} - p_{\ell})^2$, providing experimental sensitivity to these decays. A second BDT, trained to select $\bar{B} \rightarrow D^{**}\ell \nu$ decays and reject $\bar{B} \rightarrow D^{(*)}(\ell/\tau)\nu$ decays and $BB$ background, is used to improve the signal-to-noise in these control samples. The yield measured in these $D^{(*)}\pi^0 \ell$ control samples constrains the amount of $D^{**}$ background in the $D^{(*)}\ell$ samples.

4. Fit model and results

The fit takes as input events reconstructed in the four samples sensitive to the signal, $D^0 \ell$, $D^{(*)} \ell$, $D^+ \ell$ and $D^{*+} \ell$, and in the four control samples, $D^0 \pi^0 \ell$, $D^{(*)} \pi^0 \ell$, $D^+ \pi^0 \ell$ and $D^{*+} \pi^0 \ell$. The value of $M^2_{\text{miss}}$ (or $M^2_{\text{miss}}$) and $|p^*_\ell|$ in each sample are input to an unbinned maximum-likelihood fit. In the fit, the continuum and $BB$ combinatorial backgrounds are fixed, as is the background from charge cross-feed (where neutral $B$ mesons are reconstructed as charge $B$ mesons or vice-versa). The fit has 22 free parameters: 4 yields for the signal modes (one per sample), 4 yields for the normalization modes, 2 parameters for the feed-down from $D^*$ to $D$ when a transition particle is missed, and 12 parameters for the $D^{(*)}\pi^0 \ell$ control samples (yield, feed-up from $D^{(*)}$, and $BB$ background). The fit enforces constraints between related parameters, e.g. the $D^{**}$ background in the signal samples and the corresponding yields in the $D^{(*)}\pi^0 \ell$ control samples, and feed-up/feed-down probabilities in the signal and normalization modes.

There are 56 individual probability distribution functions (PDFs) used to describe the components of the fit. They are determined using large Monte Carlo samples with equivalent luminosities of nine times the data for $BB$ events and twice the data for $q\bar{q}$ continuum events. The PDFs are constructed using non-parametric kernel estimation, and the uncertainties on the PDF shapes are obtained by creating 1000 distributions for each based on a bootstrapping technique (sampling with replacement).
Table 1. Fit results. The last two lines show the results of the isospin-constrained fit. The columns give the decay mode, the yields of signal and normalization events, the efficiency ratio for signal decays to normalization decays, the ratios $R(D^{(*)})$, and the significance of the measured signal yield. Where two uncertainties are listed the first is statistical and the second, systematic.

| Decay         | $N_{\text{sig}}$ | $N_{\text{norm}}$ | $\epsilon_{\text{sig}}/\epsilon_{\text{norm}}$ | $R(D^{(*)})$ | $\Sigma_{\text{tot}}$ |
|---------------|------------------|-------------------|-----------------------------------------------|--------------|---------------------|
| $B^- \to D^0 \tau^- \bar{\nu}_\tau$ | 314 ± 60         | 1995 ± 55         | 0.368 ± 0.011                                 | 0.429 ± 0.082 ± 0.052 | 4.7            |
| $B^- \to D^{*0} \tau^- \bar{\nu}_\tau$ | 639 ± 62         | 8766 ± 104        | 0.227 ± 0.004                                 | 0.322 ± 0.032 ± 0.022 | 9.4            |
| $B^0 \to D^+ \tau^- \bar{\nu}_\tau$ | 177 ± 31          | 986 ± 35          | 0.384 ± 0.014                                 | 0.469 ± 0.084 ± 0.053 | 5.2            |
| $B^0 \to D^{*+} \tau^- \bar{\nu}_\tau$ | 245 ± 27          | 3186 ± 61         | 0.217 ± 0.005                                 | 0.355 ± 0.039 ± 0.021 | 10.4           |
| $\bar{B} \to D^- \tau^+ \nu_\tau$ | 489 ± 63          | 2981 ± 65         | 0.372 ± 0.010                                 | 0.440 ± 0.058 ± 0.042 | 6.8            |
| $\bar{B} \to D^{*} \tau^+ \nu_\tau$ | 888 ± 63          | 11953 ± 122       | 0.224 ± 0.004                                 | 0.332 ± 0.024 ± 0.018 | 13.2           |

Figure 1. Projections of the fit for the four $D^{(*)}\ell$ samples in the two fit variables. The large peak from the normalization decays is cut off to emphasize the region populated by the signal decays. The dashed line in the yellow background component separates $q\bar{q}$ continuum from $B \bar{B}$ combinatorial background.

The fit results are shown in table 1 and the corresponding projections onto the fit variables are shown in figure 1 for the signal samples and in figure 2 for the $D^{(*)}\pi^0\ell$ control samples.
The results of an isospin-constrained fit are also given. The significance of the results, including systematic uncertainties, is well above 5σ for both $\bar{B} \rightarrow D\tau\nu$ and $\bar{B} \rightarrow D^*\tau\nu$. The measured values for $R(D)$ and $R(D^*)$ are consistent with previous measurements [9, 10, 11] but are significantly more precise.

![Graphs of fit projections for $D(s)\pi^0\ell$ and $D(s)\ell\nu$](image)

**Figure 2.** Projections of the fit for the four $D(s)\pi^0\ell$ samples in the two fit variables. The components labelled $(\ell/\tau)$ include contributions from all charged lepton flavours, but are dominated by contributions from $e$ and $\mu$.

The results for the $e$ and $\mu$ channels are consistent with each other, and the results from the 4-channel fit are consistent with isospin symmetry. The results are stable across a wide range of BDT cuts, over which the number of events in the signal region range from 30% to 300% of the nominal sample, and the signal to background varies by a factor of 5.

An extensive set of systematic uncertainties were evaluated. They arise from imprecise knowledge of branching fractions, form factors, detector response and the statistics of the simulation samples and data control samples. These uncertainties were recorded for each channel as were their correlations between channels. The most significant uncertainties come from the modelling of the $D^{**}$ background, which affects the constraints between the $D(s)\ell$ and $D(s)\pi^0\ell$ samples, the limited statistics of the MC samples, and the uncertainties on the fixed $q\bar{q}$ and $BB$ samples; these are listed in table 2 along with the total uncertainties. The large negative correlation in the statistical uncertainty comes from the feed-down of the $D^*$ decays into the $D\ell$ samples.
Table 2. Leading sources of systematic uncertainty, total uncertainties and their linear correlation coefficient ($\rho$).

| Source                | Uncertainty (%) | $\mathcal{R}(D)$ | $\mathcal{R}(D^*)$ | $\rho$ |
|-----------------------|-----------------|------------------|-------------------|--------|
| $D^{**}\ell\nu$ background | 5.8             | 3.7              | 0.62              |        |
| MC statistics         | 5.0             | 2.5              | -0.48             |        |
| $q\bar{q}$ and $BB$ bkg. | 4.9             | 2.7              | -0.30             |        |
| $\epsilon_{\text{sig}}/\epsilon_{\text{norm}}$ | 2.6             | 1.6              | 0.22              |        |
| Systematic uncertainty | 9.5             | 5.3              | 0.05              |        |
| Statistical uncertainty | 13.1            | 7.1              | -0.45             |        |
| Total uncertainty     | 16.2            | 9.0              | -0.27             |        |

5. Discussion

The measured values for $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ exceed standard model predictions by 2.0$\sigma$ and 2.7$\sigma$, respectively. Taking these measurements together and accounting for the correlation between them, their joint departure from the SM expectations is 3.4$\sigma$. The comparison of these results with the Type-II two-Higgs-doublet model (2HDM) requires a re-evaluation of the signal PDFs and efficiency, since the presence of a spin-0 mediator changes the signal shape in $M_{\text{miss}}^2$ and $|p_T^{\tau}|$ as a function of $\tan\beta/m_H$. Figure 3 shows that, while each measurement can be accommodated individually, no value of $\tan\beta/m_H$ provides a good description of both $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$, and the Type-II 2HDM is excluded over the full parameter space at 99.8% confidence level. More general models with charged mediators are compatible with these measurements.

Figure 3. Comparisons of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ as a function of $\tan\beta/m_H$ in the type-II 2HDM. The blue band shows the measured value, which varies as the signal kinematics change, and the red band shows the expected value in the 2HDM; the standard model corresponds to $\tan\beta/m_H = 0$.

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2 Using alternative calculations of the SM expectation the smallest departure is 3.2$\sigma$.

3 The exclusion from this measurement is valid for $m_H > 15$ GeV, but lighter $m_H$ values have already been excluded by $b \rightarrow s\gamma$. 

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