$B \rightarrow \bar{D}^{(*)}\tau\nu$ and Constraints on Charged Higgs Models

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OUTLINE

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The $B \rightarrow \bar{D}^{(*)}\tau\nu_{\tau}$ decay is sensitive to New Physics at tree level in the form of a charged Higgs boson.

Using the large sample of $B$ mesons collected at $BABAR$, we measure the quantity:

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow \bar{D}^{(*)}\tau\nu_{\tau})}{\mathcal{B}(B \rightarrow \bar{D}^{(*)}\ell\nu_{\ell})}$$

Theoretical uncertainties on $\mathcal{R}(D^{(*)})$ are reasonably small and well understood in the Standard Model (SM).

Systematic uncertainties of the experiment cancel in this ratio.
For each event, we reconstruct all possible $B_{tag}D^{(*)}\ell$ candidates.

We then choose the lowest $E_{extra}$ candidate to represent the event, where $E_{extra}$ is defined to be the energy sum of all photons that are not part of the reconstructed candidate.

The signal efficiency is 3 times larger than the previous BABAR analysis, *Phys. Rev. Lett. 100, 021801 (2008).*

- More modes are reconstructed for the seed meson $S$.
- Improved lepton PID for $\ell$. 

$S = D, D^*, D_s, \text{ or } D_s^*$

$X^{\pm} = \text{ up to } 5 \pi, K, \pi^0, \text{ or } K^0_S$
Event Selection

- At this point, each event belongs to one of four samples: $D^0\ell$, $D^{*0}\ell$, $D^+\ell$, and $D^{*+}\ell$. This group is referred to as the $D^{(*)}\ell$ samples.

- In order to constrain the large $D^{**}$ background, we also reconstruct $D^0\pi^0\ell$, $D^{*0}\pi^0\ell$, $D^+\pi^0\ell$, and $D^{*+}\pi^0\ell$ control samples. They are referred to as the $D^{(*)}\pi^0\ell$ samples.
  - For each sample in $D^{(*)}\ell$, we separate out a subset of events that can be combined with a well reconstructed $\pi^0$. 
EVENT SELECTION

Each event belongs to one of the following categories:

- $D^{(*)}_{\tau}$: Signal
- $D^{(*)}_{\ell}$: Normalization
- $D^{**}(\ell/\tau)$: $D^{**}$ background.
- $B\bar{B}$ and continuum backgrounds.

For each of the $D^{(*)}_{\ell}$ samples, we train a boosted decision tree to separate out signal and normalization events and to reject background events.

For each of the $D^{(*)}_{\pi^{0}\ell}$ samples, we train a boosted decision tree to separate out $D^{**}$ events and to reject others.
To extract the signal and normalization yields, we perform an unbinned extended maximum likelihood fit to the 2D distribution in $m_{miss}^2$ vs $|p_\ell^*|$. Each sample has contribution from all event types. For each such contribution, we estimate its distribution in $m_{miss}^2$ vs $|p_\ell^*|$ using non-parametric kernel estimators.
YIELD EXTRACTION

- The fit is performed on all $D^{(*)}\ell$ and $D^{(*)}\pi^0\ell$ samples simultaneously.
- The fit gives us the number of signal and normalization events selected. We then compute the desired quantity:

$$R(D^{(*)}) = \frac{N_{\text{sig}}}{N_{\text{norm}}} \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}}$$

$\varepsilon_{\text{norm}}/\varepsilon_{\text{sig}}$ is the ratio of efficiencies taken from Monte Carlo.
To assess the impact of systematic uncertainties, we vary each source following a certain distribution and repeat the fit for each such variation. The uncertainty is assigned to be the standard deviation of the resulting $\mathcal{R}(D^{(*)})$ values.

There are two types of systematic uncertainties:

- **Additive**: These affect the yield of the fits, which influence the significance.
  - Monte Carlo (MC) statistics to estimate PDF shapes.
  - Fit constraints for fixing backgrounds and cross-feed contributions. The dominant source comes from $D^{**}$ cross-feed constraints.

- **Multiplicative**: These affect the $\varepsilon_{\text{norm}}/\varepsilon_{\text{sig}}$ ratio and do not affect the significance.
  - MC statistics is the dominant source of uncertainty.
The impact on the uncertainty of $R(D^{(*)})$ due to correlations between any pair of systematic sources is small.

However, the correlation between the uncertainties of $R(D)$ and $R(D^{*})$ is large.

- For each source of uncertainty, its contribution to the total correlation is estimated from the 2D $R(D)$ vs $R(D^{*})$ distribution that results from the fit variations.
- Since each source of uncertainty is uncorrelated, we add their covariance matrices to estimate the total covariance.
**RESULTS: FIT YIELDS AND MARGINAL DISTRIBUTIONS FOR THE $D^{(*)}\pi^0\ell$ SAMPLE**

*Phys. Rev. Lett. 109, 101802 (2013)*

+ follow up submission to PRD
RESULTS: FIT YIELDS AND MARGINAL DISTRIBUTIONS FOR THE $D^{(*)}\ell$ SAMPLE

<table>
<thead>
<tr>
<th>Decay</th>
<th>$\mathcal{R}(D^{(*)})$</th>
<th>$N_{\text{sig}}$</th>
<th>$N_{\text{norm}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \to D\tau^-\bar{\nu}_\tau$</td>
<td>0.440 ± 0.058 ± 0.042</td>
<td>489 ± 63</td>
<td>2981 ± 65</td>
</tr>
<tr>
<td>$\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$</td>
<td>0.332 ± 0.024 ± 0.018</td>
<td>888 ± 63</td>
<td>11953 ± 122</td>
</tr>
</tbody>
</table>

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We compare our results to those predicted in the Standard Model (SM), and find that $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ are in excess over the SM predictions at the level of $2.0\sigma$ and $2.7\sigma$ respectively.

- We perform a $\chi^2$ test between the theory and experimental result using the covariance matrices determined previously and find that the possibility of both measurements agreeing with the SM is excluded at the $3.4\sigma$ level.
Comparison with Type-II 2HDM

- In the type-II 2HDM, $\mathcal{R}(D)$ is affected as a function of $\tan \beta / m_{H^+}$ as follows:

$$\mathcal{R}(D^{(*)})_{2\text{HDM}} = \mathcal{R}(D^{(*)})_{\text{SM}} + A_{D^{(*)}} \frac{\tan^2 \beta}{m_{H^+}^2} + B_{D^{(*)}} \frac{\tan^4 \beta}{m_{H^+}^4}$$

- The presence of a charged Higgs can affect the $m_{miss}^2$ and $|p_\ell^*|$ signal distributions significantly. We assess and account for its impact as a function of $\tan \beta / m_{H^+}$ in order to examine whether the observed excess is consistent with the type-II 2HDM.
We exclude the type-II 2HDM at 99.8% confidence level in the full \( \tan \beta - m_{H^+} \) parameter space.
In the type-III 2HDM, a right handed current is included in the effective Hamiltonian. The relative contributions between left and right handed current are parameterized with $S_L$ and $S_R$.

In this model, $\mathcal{R}(D^{(*)})$ take the form:

\[
\mathcal{R}(D) = \mathcal{R}(D)_{SM} + A_D' \text{Re}(S_R + S_L) + B_D'|S_R + S_L|^2,
\]

\[
\mathcal{R}(D^*) = \mathcal{R}(D^*)_{SM} + A_{D^*}' \text{Re}(S_R - S_L) + B_{D^*}'|S_R - S_L|^2.
\]

We extrapolate the measured results obtained for $\mathcal{R}(D^{(*)})$ from the type-II 2HDM to the type-III 2HDM. For real values of $S_L$ and $S_R$, we find 4 favored solutions.
We compare the $q^2$ distribution of background subtracted data for three values of $\tan \beta/m_{H^+}$.

- $\tan \beta/m_{H^+} = 0.35 \text{ GeV}^{-1}$ corresponds to the value of $S_L + S_R \sim 1.5$. We exclude the bottom 2 solutions at $2.9\sigma$.

$\tan \beta/m_{H^+} = 0.45 \text{ GeV}^{-1}$
**CONCLUSION**

- We have measured the ratios $\mathcal{R}(D^{(*)})$ based on the full *BABAR* data sample:

  $$\mathcal{R}(D) = 0.440 \pm 0.058 \pm 0.042$$

  $$\mathcal{R}(D^{*}) = 0.332 \pm 0.024 \pm 0.018$$

- $\mathcal{R}(D)$ and $\mathcal{R}(D^{*})$ exceed the SM predictions by $2.0\sigma$ and $2.7\sigma$ respectively. Taken together, they disagree with the SM at the $3.4\sigma$ level.

- We exclude the entire type-II 2HDM parameter space at the 99.8% confidence level.

- More general charged Higgs models are compatible with our results. For instance, the type-III 2HDM is compatible with these results in regions where $|S_L + S_R| < 1.4$.

- Updated results from Belle are expected soon.

- For more details on this analysis, please refer to *Phys. Rev. Lett. 109, 101802 (2012)* or arxiv: 1303.0571 (submitted to PRD).