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

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on behalf of the BaBar collaboration

10th of May 2013
Cornell LEPP Journal Club
Ithaca, NY
Questions, questions

- **Standard Model** remarkably successful theory

  \[
  \frac{g_e - 2}{2} = 0.00115965218073(28)
  \]

- **Gravitation** does not fit in the SM framework

- **Dark matter, Dark energy**

- **Hierarchy problem, strong CP problem...**

**Fundamental Interactions**

- **Strong**

- **Electro-Magnetic**

- **Weak**

- **Gravitation??**

\(B \rightarrow D^{(*)} \tau \nu\)
**Motivation**

*Charged Higgs* required in multiple **New Physics** scenarios

**MSSM**

- $A^0$
- $H^+$
- $H^-$

**SM**

- $h^0$

$t \rightarrow bH^\pm$

**B** → $X_s\gamma$

$B^- \rightarrow \tau^-\bar{\nu}_\tau$

$\overline{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau$

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**BABAR**

**BELLE**
Searches for a charged Higgs at BaBar

\[ B \rightarrow X_s \gamma \]

- Small \( \sigma_{SM} \sim 7\% \)
- H⁻ enters in a loop
- BF \sim 0.03\%
- Inclusive measurement difficult

\[ B^- \rightarrow \tau^- \bar{\nu}_\tau \]

- Large \( \sigma_{SM} \sim 25\% \)
- H⁻ enters at tree level
- BF \sim 0.01\%
- Helicity suppressed

\[ \bar{B} \rightarrow D^{(*)} \tau^- \bar{\nu}_\tau \]

- Small \( \sigma_{SM} \sim 2\text{-}5\% \)
- H⁻ enters at tree level
- BF \sim 1\text{-}2\%
- \( D^{(*)} \) provides constraint

\[ B \rightarrow D^{(*)} \tau \nu \]
We measure ratios

\[ R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \rightarrow D^{(*)} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \rightarrow D^{(*)} \ell^- \bar{\nu}_\ell)} \]

Normalization
\((\ell^- = e^- \text{ or } \mu^-)\)

Various uncertainties cancel in ratio

- **Theoretical**: \(V_{cb}, \text{FFs}\)
- **Experimental**: same final state particles

\[ \tau^- \rightarrow \ell^- \bar{\nu}_\ell \nu_\tau \]
We measure ratios

\[ R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \rightarrow D^{(*)} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \rightarrow D^{(*)} \ell^- \bar{\nu}_\ell)} = \frac{N_{\text{sig}}}{N_{\text{norm}}} \times \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \]

Previous measurements exceed SM by 1-2 \( \sigma \)

We update BaBar 2008 with 2x data and 3x efficiency
PEP-II storage rings

- Operation 1999-2008

- Linear accelerator injects in PEP-II ($\beta\gamma = 0.56$)
  - 9.0 GeV electrons $e^-$
  - 3.1 GeV positrons $e^+$

$B \to D^{(*)}\tau\nu$

CM energy

$m(\Upsilon(4S)) = 10.58$ GeV
The BaBar detector

- Good lepton ID
- Good hadron ID ($\pi/K$ sep.)
- 91% solid angle coverage

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^+B^-$$

$$B^- \rightarrow \rho^0 \mu^-\bar{\nu}_\mu$$

$$\rho^0 \rightarrow \pi^+\pi^-$$

Similar to normalization

$$B^- \rightarrow D^0 (\rightarrow K^-\pi^+)\mu^-\bar{\nu}_\mu$$

Muon detector outside the plot

$B \rightarrow D^{(*)}\tau\nu$
~ Fully reconstructed tag \( B \)
- Efficiency 2x previous analysis

Old \( B_{\text{tag}}: X_c = D, D^* \)

- 630 decay chains

\[ \text{Eff.: 0.21\%} \]
\[ \text{Purity: 91\%} \]

New \( B_{\text{tag}}: X_c = D, D^*, D_s^+, D_s^{*+}, J/\Psi \)

- 1,768 decay chains

\[ \text{Eff.: 0.40\%} \]
\[ \text{Purity: 75\%} \]
Event reconstruction

- **Fully reconstructed tag $B$**
  - Efficiency 2x previous analysis
  - $D(\ast)$: $D^0$, $D^{\ast0}$, $D^+$, $D^{\ast+}$
  - $\ell = e, \mu$ (improved PID)

<table>
<thead>
<tr>
<th>Events/(150 MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000</td>
</tr>
<tr>
<td>2000</td>
</tr>
<tr>
<td>1000</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

- $q^2 > 4 \text{ GeV}^2$
- $p_{\text{miss}} > 200 \text{ MeV}$

**Backgrounds**

- **Boosted decision tree** to reject bkg.
- **BB/continuum** from control samples
  - $e^+ e^- \rightarrow u\bar{u}, d\bar{d}, c\bar{c}, s\bar{s}$
- **Simultaneous fit** estimates $B \rightarrow D^{\ast\ast}(\ell/\tau)\nu$
  - 4 $D^{(\ast)}\pi^0$ control samples
Missing mass

Key variable to separate signal and normalization

\[ m_{\text{miss}}^2 = (p_{e^+e^-} - p_{B_{\text{tag}}} - p_{D(*)} - p_\ell)^2 \]

**D^0 \tau\nu**

Signal

**D^0 l\nu**

Normaliz.

**D^{*0} l\nu**

Normalization feed-down

\( D^{*0} \rightarrow D^0 (\pi/\gamma) \)

**D^{**}l\nu**

Background

**Other \( B\bar{B} \)**

Background

\[ B \rightarrow D^{(*)}\tau\nu \]
Fit structure

- Unbinned ML fit
  - 2D: \( m^2_{\text{miss}} - p^*_\ell \)
  - 4 Signal channels
    - \( D^0, D^{*0}, D^+, D^{*+} \)
    - 4 \( D^{(*)}\pi^0 \) channels
- Fitted yields
  - 4 \( D^{(*)}\tau\nu \)
  - 4 \( D^{(*)}\ell\nu \)
  - 4 \( D^{*\star}\ell\nu \)
- Fixed yields (yellow)
  - Charge crossfeed
  - B combinatorial
  - Continuum

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MC Simulation

\( B \to D^{(*)}\tau\nu \)
Fit PDFs: 2D

- Fit uses 56 fully two-dimensional Probability Density Functions

- Irregular
- 2D correlations

Difficult to describe analytically
We use **non-parametric** Kernel estimators (KEYS)

\[
\hat{p}(X ; x_i) = \frac{1}{nw} \sum_{i=1}^{n} K \left( \frac{X - x_i}{w} \right)
\]

_With non-parametric, easy to trade Bias for Variance_
Fit PDFs: Uncertainty

- Uncertainties estimated with Bootstrap algorithm
- For same statistics \(\Rightarrow\) larger uncertainty than analytical (parametric) PDF

Cross-validation algorithm

\[
CV = \frac{1}{n} \sum_{i=1}^{n} \left( \hat{p}^{-2}(X) dX - \frac{2}{n} \sum_{i=1}^{n} \hat{p}^{-i}(x_i) \right)
\]

---

Fit PDFs: Uncertainty

![Graphs showing the fit PDFs with different values of \(\rho_m\)]
Simulation does not reproduce $p^*_{1}$ and yields of $e^+e^- \rightarrow u\bar{u}, d\bar{d}, c\bar{c}, s\bar{s}$.

$1.2 < E_{\text{Extra}} < 2.4$ GeV

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**BB Background**

- **BB background** estimated from control samples

  - $5.20 < m_{ES} < 5.26$ GeV
  - $E_{Extra} = \sum_{\text{unused } \gamma} E_{\gamma} > 0.5$ GeV

<table>
<thead>
<tr>
<th>$m_{ES}$ (GeV)</th>
<th>$A_1 + A_2$</th>
<th>B</th>
<th>C</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.26</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.27</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.29</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Signal region

$E_{Extra}$ (GeV)

BB bkg. 4.3% overestimation corrected

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All channels: MC/data = 1.013 ± 0.005

- data (55352)
- $D^*l\nu$ (632)
- $Dl\nu$ (213)
- $D^{**}l\nu$ (891)
- Bkg (18644)
- Cont (35717)

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$B \rightarrow D^{(*)}\tau\nu$

Slide 17
Background very well described for large $E_{\text{Extra}}$

- $m_{\text{miss}}$ shapes
- Yields

BB Background

$B \rightarrow D^{(*)} \tau \nu$
**Background**

- Background very well described for large $E_{\text{Extra}}$
- 5-10% diff. for $E_{\text{Extra}} < 0.5$ GeV
- Corrected with $m_{ES}$ sideband
- Significant uncertainty

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### MC/data for $m_{miss}^2 > 1.5$ GeV$^2$

- $A_1 + A_2$
  - $m_{ES}$ SB correction
  - $1.000 \pm 0.003$
- $B$
  - $1.011 \pm 0.003$
- $C$
  - $1.000 \pm 0.003$
- $E_{\text{Extra}}$
  - $0.998 \pm 0.006$
- $D$
  - BB bkg. 4.3% overestimation corrected

---

**MC/data flat in $m_{ES}$ ⇒ Extrapolation of the correction OK**
D* channels: 1/2 data

- Efficiency 3x
- Good agreement with previous analysis

<table>
<thead>
<tr>
<th></th>
<th>2008</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D*0τν</td>
<td>D*+τν</td>
</tr>
<tr>
<td>N_{sig}</td>
<td>92 ± 20</td>
<td>16 ± 7</td>
</tr>
<tr>
<td>Signif.</td>
<td>5.8 σ</td>
<td>2.7 σ</td>
</tr>
<tr>
<td>R(D*)</td>
<td>0.35 ± 0.07</td>
<td>0.21 ± 0.10</td>
</tr>
</tbody>
</table>

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\[ B \rightarrow D^{(*)} \tau \nu \]
**Fit results: D*τν**

- **Good fit** agreement
- **Uncertainties** statistical

<table>
<thead>
<tr>
<th></th>
<th>D*0τν</th>
<th>D*+τν</th>
<th>D*τν</th>
</tr>
</thead>
<tbody>
<tr>
<td>N_{sig}</td>
<td>639 ± 62</td>
<td>245 ± 27</td>
<td>888 ± 63</td>
</tr>
<tr>
<td>Signif.</td>
<td>11.3 σ</td>
<td>11.6 σ</td>
<td>16.4 σ</td>
</tr>
<tr>
<td>R(D*)</td>
<td>0.322 ± 0.032</td>
<td>0.355 ± 0.039</td>
<td>0.332 ± 0.024</td>
</tr>
</tbody>
</table>

- Isospin constrained
- D*0 and D*+ channels combined. Background subtracted
Fit results: $D\tau\nu$

First 5σ observation

Uncertainties statistical

<table>
<thead>
<tr>
<th></th>
<th>$D^0\tau\nu$</th>
<th>$D^+\tau\nu$</th>
<th>$D\tau\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{sig}}$</td>
<td>$314 \pm 60$</td>
<td>$177 \pm 31$</td>
<td>$489 \pm 63$</td>
</tr>
<tr>
<td>Signif.</td>
<td>$5.5 \sigma$</td>
<td>$6.1 \sigma$</td>
<td>$8.4 \sigma$</td>
</tr>
<tr>
<td>$R(D)$</td>
<td>$0.429 \pm 0.082$</td>
<td>$0.469 \pm 0.084$</td>
<td>$0.440 \pm 0.058$</td>
</tr>
</tbody>
</table>

-45% correlation $D$-$D^*$

Isospin constrained

Fixed

Free in the fit

- First 5σ observation
- Uncertainties statistical

D$^0$ and D$^+$ channels combined. Background subtracted

B → $D^{(*)}\tau\nu$
Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
<th>$R(D)$</th>
<th>$R(D^*)$</th>
<th>$\rho$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^{**}\ell\nu$ background</td>
<td>5.8</td>
<td>3.7</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td>MC statistics</td>
<td>5.0</td>
<td>2.5</td>
<td>-0.48</td>
<td></td>
</tr>
<tr>
<td>Cont. and $B\bar{B}$ bkg.</td>
<td>4.9</td>
<td>2.7</td>
<td>-0.30</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_{\text{sig}}/\varepsilon_{\text{norm}}$</td>
<td>2.6</td>
<td>1.6</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>Systematic uncertainty</td>
<td>9.5</td>
<td>5.3</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>13.1</td>
<td>7.1</td>
<td>-0.45</td>
<td></td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>16.2</td>
<td>9.0</td>
<td>-0.27</td>
<td></td>
</tr>
</tbody>
</table>

- **Largest syst. due to backgrounds**

- **Small uncertainty on efficiency ratio $\varepsilon_{\text{sig}}/\varepsilon_{\text{norm}}$**

- **Statistical uncertainty dominates**
Gaussian uncertainties

- Statistical uncertainty

- Largest systematic uncertainties

Likelihood scan

Variations of the $D^{**}\ell\nu$ rate from the $D\pi^0$ into the signal samples

Variations of the PDFs due to MC statistics

$B \rightarrow D^{(*)}\tau\nu$
Stability checks

Results are consistent for different run periods

\[ \chi^2: \frac{5.1}{7} = 0.73 \]
\[ \text{Prob.} = 64.73\% \]

Results are consistent for e Vs \( \mu \), within the large uncertainties

\[ \chi^2: \frac{4.3}{3} = 1.42 \]
\[ \text{Prob.} = 23.40\% \]
$E_{\text{Extra}}$ after the fit

- **Key variable in the BDT**

$$E_{\text{Extra}} = \sum_{\text{unused } \gamma} E_\gamma$$

- **Signal peaks in $E_{\text{Extra}}$**
  - Re-scaled to the results of the fit
  - $m^2_{\text{miss}} > 1.5 \text{ GeV}^2$

$D^{(*)0}$ and $D^{(*)+}$ channels combined
Background subtracted
Results

<table>
<thead>
<tr>
<th>Decay</th>
<th>$N_{\text{sig}}$</th>
<th>$N_{\text{norm}}$</th>
<th>$R(D^{(*)})$</th>
<th>$\mathcal{B}(B \to D^{(*)}\tau\nu), (%)$</th>
<th>$\Sigma_{\text{tot}}(\sigma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^\tau\bar{\nu}_\tau$</td>
<td>489 ± 63</td>
<td>2981 ± 65</td>
<td>0.440 ± 0.058 ± 0.042</td>
<td>1.02 ± 0.13 ± 0.11</td>
<td>6.8</td>
</tr>
<tr>
<td>$D^{*\tau}\bar{\nu}_\tau$</td>
<td>888 ± 63</td>
<td>11953 ± 122</td>
<td>0.332 ± 0.024 ± 0.018</td>
<td>1.76 ± 0.13 ± 0.12</td>
<td>13.2</td>
</tr>
</tbody>
</table>

- First 5$\sigma$ observation of $B\to D\tau\nu$
- Agreement with previous measurements

Average does not include this analysis

$B \to D^{(*)}\tau\nu$

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Disagreement with SM

\[ R(D) = \begin{cases} 
0.440 \pm 0.072 & \text{BABAR} \\
0.297 \pm 0.017 & \text{SM} 
\end{cases} \]

\[ R(D^*) = \begin{cases} 
0.332 \pm 0.030 & \text{BABAR} \\
0.252 \pm 0.003 & \text{SM} 
\end{cases} \]

- 3.4\sigma

- 2.7\sigma

- 2.0\sigma

3.2\sigma \text{ with largest } R(D)_{\text{SM}}

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-27\% correlation

R(D) and R(D^*) not independent
**Type II 2HDM Calculation**

- **SM matrix element**
  \[ M_{\lambda M}^{\lambda_\ell} (q^2, \theta_\ell) \big|_W = \frac{G_F V_{cb}}{\sqrt{2}} \sum_{\lambda_W} L_{\lambda_W}^{\lambda_\ell} H_{\lambda_W}^{\lambda_M} \]

- **\( L_{\lambda_W}^{\lambda_\ell} \)** are the **leptonic currents**
  - Simple functions of \( q^2 \) and \( \theta_1 \)

- **\( H_{\lambda_W}^{\lambda_H} \)** are the **hadronic currents**
  - Parameterized by Form Factors

- **\( H \)** enters through the **scalar current** \( H_{s}^{2\text{HDM}} \)
  - We re-weight the simulation to account for it

\[ H_{s}^{2\text{HDM}} \approx H_{s}^{\text{SM}} \times \left( 1 - \frac{\tan^2 \beta}{m_{H^+}^2} \frac{q^2}{1 \mp m_c/m_b} \right) \]

**Type II Two-Higgs-Doublet Model**
Recent papers, like Nierste, Trine, Westho... I made the simple calculations right, the e... But I am not sure if it would be worth it, as it would imply that we have to p... The original Tanaka (1995) paper has the full Type II 2HDM matrix e... Due to the spin of the Higgs and the fact that it couples to the mass,... Going forward (for the PRD for instance), it would be easy to implem... $\approx H_s^{SM} \times \left(1 - \frac{\tan^2 \beta}{m_{H^+}^2} \frac{q^2}{1 + m_c/m_b}\right)$

**Type II 2HDM: $q^2$**

- $q^2$ spectrum impacted by $H_s^{2HDM} \approx H_s^{SM} \times \left(1 - \frac{\tan^2 \beta}{m_{H^+}^2} \frac{q^2}{1 + m_c/m_b}\right)$

**Spin 0**

- P-waves pick up a factor of $p_{D(*)}$

**Spin 1**

- $B \to D^{(*)}\tau\nu$
PDFs re-calculated in the 2HDM context

Higgs impact on $m_{\text{miss}}^2$ similar to $q^2$

$$m_{\text{miss}}^2 = (p_{e^+e^-} - p_{B_{\text{tag}}} - p_{D(\ast)} - p_{\ell})^2 = (q - p_{\ell})^2$$

$B \rightarrow D^{(*)}\tau\nu$
Type II 2HDM: PDFs

- $\tau^-$ polarization in $B \to D^{(*)}\tau^-\bar{\nu}_\tau$
  - **SM**: Left-handed 30-80%, Right-handed 70-20%
  - $\tau$ spin points back (partially) to B meson
  
  $\bar{\nu}_\tau \leftrightarrow H^- \to \tau^-$
  
  $\lambda_{\bar{\nu}_\tau} = + \quad \lambda_\tau = +$

- **2HDM**: Left-handed 0%, Right-handed 100%
  - $\tau$ spin away from B meson

$p^*_\ell$ is the momentum of the secondary lepton from $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$ decays in B frame

\[
\begin{align*}
\ell^- & \leftrightarrow \tau^- \quad \lambda_{\ell^-} = - \\
\lambda_{\nu_\tau} = - \\
\lambda_{\bar{\nu}_\ell} = + \\
\lambda_\tau & \quad \text{Favored}
\end{align*}
\]

\[
\begin{align*}
\bar{\nu}_\ell & \leftrightarrow \tau^- \quad \lambda_{\bar{\nu}_\ell} = + \\
\lambda_\nu & \quad \text{Suppressed}
\end{align*}
\]
Type II 2HDM scan

PDFs re-calculated in the 2HDM context

Fitted yields

Efficiency

$B \rightarrow D\tau\nu_{\tau}$

$B \rightarrow D^{*}\tau\nu_{\tau}$

$B \rightarrow D^{(*)}\tau\nu$

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Type II 2HDM scan

\[ R(D^*) = \frac{\mathcal{B}(\bar{B} \to D^*(\tau^- \bar{\nu}_\tau))}{\mathcal{B}(\bar{B} \to D^*(\ell^- \bar{\nu}_\ell))} = \frac{N_{\text{sig}}}{N_{\text{norm}}} \times \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \]

in the full 2HDM parameter space

\[ \tan \beta/m_{H^+} = \]

0.44 ± 0.02 GeV\(^{-1}\)

\[ \tan \beta/m_{H^+} = \]

0.75 ± 0.04 GeV\(^{-1}\)
Compatibility of $\Delta(D^{(*)}) = R(D^{(*)})_{\text{exp}} - R(D^{(*)})_{\text{2HDM}}$ given by a $\chi^2$ for each 2HDM point

$$\chi^2(\tan\beta/m_{H^+}) = (\Delta(D), \Delta(D^*)) \begin{pmatrix} \sigma^2_{\text{exp}} + \sigma^2_{\text{th}} & \rho \sigma_{\text{exp}} \sigma^*_{\text{exp}} \\ \rho \sigma_{\text{exp}} \sigma^*_{\text{exp}} & \sigma^2_{\text{exp}} + \sigma^2_{\text{th}} \end{pmatrix}^{-1} \begin{pmatrix} \Delta(D) \\ \Delta(D^*) \end{pmatrix}$$

**Type II 2HDM excluded at 99.8%, or equivalently, 3.1$\sigma$.**

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Type III 2HDM

General spin-0 interactions

\[ \mathcal{H}_{\text{eff}} = \frac{4G_F V_{cb}}{\sqrt{2}} \left[ (\overline{c} \gamma_\mu P_L b) (\overline{\tau} \gamma^\mu P_L \nu_\tau) + S_R (\overline{c} P_R b) (\overline{\tau} P_L \nu_\tau) + S_L (\overline{c} P_L b) (\overline{\tau} P_L \nu_\tau) \right] \]

Type II 2HDM

No solutions

\( \tan \beta/m_{H^+} = \sqrt{-\frac{S_R}{m_b m_\tau}} \) (GeV\(^{-1}\)) \( [S_L = 0] \)

R(D) - R(D\(^*\)) depend on independent NP parameters

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

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

General spin-0 interactions

\[ \mathcal{H}_{\text{eff}} = \frac{4G_F V_{cb}}{\sqrt{2}} \left[ (\bar{c} \gamma_\mu P_L b) (\bar{\tau} \gamma_\mu P_L \nu_\tau) + S_R (\bar{c} P_R b) (\bar{\tau} P_L \nu_\tau) + S_L (\bar{c} P_L b) (\bar{\tau} P_L \nu_\tau) \right] \]

Type III 2HDM

Favored at

1σ  2σ  3σ

4 solutions for real \( S_R - S_L \)

and more for complex values

\( \mathcal{R}(D) - \mathcal{R}(D^*) \) depend on independent NP parameters

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

\[ \mathcal{R}(D^*) = \mathcal{R}(D^*)_{\text{SM}} + A_{D^*}' \text{Re}(S_R - S_L) + B_{D^*}' |S_R - S_L|^2 \]
Recent papers, like Nierste, Trine, Westho
I made the simple calculations right, the e
agree at the 2% level.
But I am not sure if it would be worth it, as it would imply that we have to p

For which includes some approximations. This is the expression we use. Th
Due to the spin of the Higgs and the fact that it couples to the mass,
The average
Going forward (for the PRD for instance), it would be easy to impleme

\[ \Gamma \approx H_{2\text{HDM}} \approx H_{\text{SM}} \times \left( 1 - \frac{\tan^2 \beta}{m_{H^+}^2} \frac{q^2}{1 \mp m_c/m_b} \right) \]

\[ B \rightarrow D\tau\nu \]

\[ B \rightarrow D^*\tau\nu \]

- **P-waves** have lower \( q^2 \) spectra, due to \( p^2_D \)
- \( B \rightarrow D\tau\nu \) more affected
  by NP than \( B \rightarrow D^*\tau\nu \)
$m_{\text{miss}}^2 > 1.5 \text{ GeV}^2$

SM shape

Yields from fit

(40% over SM)

Corrected for relative efficiency
Background sub.

$\tan \beta/m_{H^+} = 0.30 \text{ GeV}^{-1}$

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

$B \rightarrow D^{(*)} \tau\nu$
q² spectra

\[ \chi^2: 15.1/14, \ p = 36.9\% \quad D\ell \]

\[ \chi^2: 6.6/12, \ p = 88.4\% \quad D^+\ell \]

\[ \chi^2: 11.0/14, \ p = 68.6\% \quad D\ell \]

\[ \chi^2: 6.7/12, \ p = 87.6\% \quad D^+\ell \]

\[ \chi^2: 44.5/14, \ p = 0.0049\% \quad D\ell \]

\[ \chi^2: 8.1/12, \ p = 77.4\% \quad D^+\ell \]

p-values including conservative systematics

<table>
<thead>
<tr>
<th>( \frac{\tan \beta}{m_{H^+}} = 0.30 \text{ GeV}^{-1} )</th>
<th>( \frac{\tan \beta}{m_{H^+}} = 0.45 \text{ GeV}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B \to D\tau^- \bar{\nu}_\tau )</td>
<td>83.1%</td>
</tr>
<tr>
<td>( B \to D^+\tau^- \bar{\nu}_\tau )</td>
<td>98.8%</td>
</tr>
</tbody>
</table>

\[ S_R = -m_b m_\tau \tan^2 \beta/m^2_{H^+} = -1.51 \]

\[ S_L = 0 \]

\[ S_R \pm S_L = -1.51 \]

Non-zero spin contributions favored

\[ m^2_{\text{miss}} > 1.5 \text{ GeV}^2 \]

Corrected for relative efficiency

Background sub.
Improved $B \rightarrow D^{(*)}\tau\nu$ uncertainty more than 2x

New Belle/BaBar results (semileptonic tag, $\tau \rightarrow \pi \nu \tau$) soon: confirmation?
Fit PDFs: Uncertainty

- In PDF estimation, **Mean Squared Error**
  \[
  \text{MSE}[\hat{p}(X; X_i)] = E \left[ (\hat{p}(X; X_i) - p(X))^2 \right]
  \]

- **Variance term** due to **limited** amount of statistics
  \[
  \text{Var}[\hat{p}] = E \left[ (\hat{p}(X) - E[\hat{p}(X)])^2 \right]
  \]

- **Bias term** due to **inadequacies** of your **model**
  \[
  \text{Bias}[\hat{p}] = E [\hat{p}(X)] - p(X)
  \]
  - Difficult to estimate

- With **non-parametric**, easy to trade **Bias** for **Variance**
  - Estimate **Variance** with **Bootstrap algorithm**
Stability checks

Results consistent for large variations of BDT requirements

Fit to 30% sample
R(D^0) = 0.42 ± 0.09
S/B = 1.3

Fit to 100% sample (nominal)
R(D^0) = 0.43 ± 0.08
S/B = 0.8

Fit to 300% sample
R(D^0) = 0.35 ± 0.10
S/B = 0.3
Systematic uncertainties

- Largest uncertainty due to $B \rightarrow D^{**}(\ell/\tau)\nu$ background
- Peaks are well described
  - Some excess at $m_{\text{miss}}^2 \sim 1$-2 GeV$^2$

50% uncert. on $B \rightarrow D^{**}\tau\nu$

8.2 Cross-feed constraints

In this section we estimate the uncertainty on the cross-feed constraints. These are the constraints used in the fit to link different components from the same source reconstructed in different channels, such as $D^0 \tau\nu \Rightarrow D^0$ and $D^0 \tau\nu \Rightarrow D^{*0}$. They are computed as the ratio between the number of expected events in the respective channels.

Figure 8.8: $m_{\text{miss}}^2$ and $p^*_\ell$ distributions of $B \rightarrow D^{**}\ell\nu$ and $B \rightarrow D^{**}\tau\nu$ decays in the $D^{(*)}\pi^0$ samples, all channels combined. The numbers in the legend indicate the expected yields in data. The histograms are normalized to 1000 entries.

The simulated events are re-weighted, the PDFs re-calculated, and the fit repeated for each set of form factors. We estimate the uncertainty as the standard deviation of the $R(D^{(*)}\text{distribution})$.

Figure 8.9: $m_{\text{miss}}^2$ and $p^*_\ell$ distributions of $B \rightarrow D^{**}\ell\nu$, $B \rightarrow D^{**}\tau\nu$ and signal decays in the $D^{(*)}\ell\nu$ samples, all channels combined. The numbers in the legend indicate the expected yields in data. The histograms are normalized to 1000 entries.

Sum 4 $D^{(*)}\pi^0\ell\nu$ samples

- $D^{**}(\rightarrow D^{(*)}\pi)\ell\nu$
- $D^{**}(\rightarrow D^{(*)}\pi\pi)\ell\nu$
- $D^*\ell\nu$
- $D\ell\nu$
- Combinatorial
Systematics on $q^2$

$D\tau\nu$
$D^*\tau\nu$
$D\ell\nu$
$D^*\ell\nu$
$D^{**}(\ell/\tau)\nu$
Bkg.

$B \to D^{(*)}\tau\nu$

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