Beyond-SM searches in $B \rightarrow D(\ast)\tau\nu$ and rare decays at $BABAR$

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Introduction and overview

Purely leptonic tree decay
(helicity suppressed)
$B^+ \rightarrow \tau^+ \nu$

Semi-leptonic tree decay
$B \rightarrow D^{(*)} \tau \nu$

B$^+ \rightarrow \tau^+ \nu$

Confront standard model (SM) predictions
Constrain the parameter space of new physics (NP) models

$b \rightarrow s$ FCNC process

All these modes have $\nu$ in the final state
NP could significantly alter BF and kinematic observables
Challenge: theoretically & experimentally clean observables for powerful comparison

$BF_{SM} \sim 10^{-4}$

$BF_{SM} \sim 10^{-2}$

$BF_{SM} \sim 10^{-6}$
More specifically: charged Higgs searches

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

Purely leptonic decay (helicity suppressed)

$B^+ \to \tau^+ \nu$

Semi-leptonic decay

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

- $H^\pm -$ fermion coupling $\propto m_{\text{fermion}}$
- $H^\pm$ enters these two modes at tree levels

Constraints on MSSM parameters from $B$ factories before the analyses presented here

$H^\pm$ predicted by several new physics scenarios e.g. Type-II Two-Higgs Doublet Model (2HDM) of MSSM

UTfit (2009)
arXiv:0908:3470

These modes are a good place to look for it
The BaBar detector and dataset

**PEP-II:** asymmetric beams at Y(4S) threshold

BaBar in operation: 1999–2008

All analyses presented use the full BaBar Y(4S) dataset:
- ~430 fb\(^{-1}\) at the Y(4S)
- ~470M B\(\bar{B}\) pairs

BaBar is well suited for the measurements of our modes of interest: hermetic detector and clean environment allow to extract missing momentum-energy
Common reconstruction methodology

1. Fully reconstruct $B_{\text{tag}}$ in hadronic modes (hundreds of decay chains) ⇒ momentum known

Kinematic variables:

$\Delta E = \frac{\sqrt{s}}{2} - E_{B}^*; \quad m_{ES} = \sqrt{\frac{s}{4} - p_{B}^*}$

Selection according to purity

2. Look for specific signal signature (here $B \rightarrow \tau \nu$, single lepton) ⇒ Extract missing 4-momentum ($p_{\text{miss}}$), other discriminating variables

- $B_{\text{tag}}$ hadronic reconstruction (all analyses here):
  - High purity $B$–sample but low efficiency ($\varepsilon \sim 0.1\%$)
  - New BaBar analyses $\sim 3 \times$ more efficient than before
- Alternative tag method uses semileptonic $B$ decays
  - Higher efficiency but lower purity
  - In general similar sensitivity

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EPS HEP, July 19th 2013
Evidence for an Excess of $B \to D^{(*)}_{\tau\nu}$ Decays


Measurement of an Excess of $B \to D^{(*)}_{\tau\nu}$ Decays and Implications for Charged Higgs Bosons

Method

- Measure the ratio:
  \[ R(D^{(*)}) = \frac{\Gamma(B \rightarrow D^{(*)} \tau \nu_\tau)}{\Gamma(B \rightarrow D^{(*)} \ell \nu_\ell)_{\ell=e,\mu}} \]

(Assume normalization mode unaffected by H^±)

- Several uncertainties mostly cancel out in the ratio:
  - Theoretical: form factors (up to ~ 4%), V_{cb}
  - Experimental: e.g. some efficiencies

- Use \( \tau \rightarrow \ell \nu \nu \) (same topology as normalization)

- Signature: \( D^{(*)} \) and exactly one lepton track

- Suppress background with Boosted Decision Tree

- ML fit with two variables to extract yields:
  - \( m_{\text{miss}}^2 = (p_{e^+e^-} - p_{B_{\text{tag}}} - p_{D^{(*)}} - p_{\ell})^2 \)
    (peaks near 0 for normalization, broad for signal)
  - \( p^*_\ell \) in \( B_{\text{sig}} \) rest frame
    (softer in signal)
**Fit results**

- **D**** contribution estimated from simultaneous fit to \( B \rightarrow D(*)\pi^0 \ell \nu 

- **Efficiencies from MC simulation**
  
  \[ R(D^{(*)}) = \frac{N_{\text{sig}}}{N_{\text{norm}}} \times \frac{\epsilon_{\text{norm}}}{\epsilon_{\text{sig}}} \]

- **Results obtained with isospin constraint:**

<table>
<thead>
<tr>
<th>Decay</th>
<th>( N_{\text{sig}} )</th>
<th>( R(D^{(*)}) )</th>
<th>( B(B \rightarrow D^{(*)}\tau\nu) ) (%)</th>
<th>( \Sigma_{\text{stat}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bar{B} \rightarrow D\tau^-\bar{\nu}_\tau )</td>
<td>489 ± 63</td>
<td>( 0.440 \pm 0.058 \pm 0.042 )</td>
<td>1.02 ± 0.13 ± 0.10 ± 0.04</td>
<td>8.4</td>
</tr>
<tr>
<td>( \bar{B} \rightarrow D^*\tau^-\bar{\nu}_\tau )</td>
<td>888 ± 63</td>
<td>( 0.332 \pm 0.024 \pm 0.018 )</td>
<td>1.76 ± 0.13 ± 0.10 ± 0.06</td>
<td>16.4</td>
</tr>
</tbody>
</table>

For \( m_{\text{miss}}^2 > 1 \text{GeV}^2 \)

- First observation

Efficiencies from MC simulation

Results obtained with isospin constraint:

stat. (dominates) syst. (largest: backgrounds)
Results vs. SM

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

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

Combined result (with -27% correlation):
3.4 \sigma deviation from SM

Naïve combination with older Belle results
(see e.g. A.Bozek at FPCP)
4.8 \sigma deviation from SM
Results vs. Type-II 2HDM

- $H^\pm$ couples through different helicity amplitudes to $D$ (- sign) and $D^*$ (+)

$$H_s^{2\text{HDM}} \approx H_s^{\text{SM}} \times \left(1 - \frac{\tan^2 \beta}{m_H^2 + \frac{q^2}{(m_c/m_b)^2}}\right)$$

- 2HDM affects fit-variables distributions and hence the efficiency $\Rightarrow$ different PDF for each $\tan \beta/m_H$

- 2HDM-II predictions match $R(D^{(*)})$ at

  $R(D) \implies \tan \beta/m_H = 0.44 \pm 0.02 \text{ GeV}^{-1}$

  $R(D^*) \implies \tan \beta/m_H = 0.75 \pm 0.04 \text{ GeV}^{-1}$

- Combination of $R(D)$ and $R(D^*)$:

  Type-II 2HDM excluded in full $\tan \beta$-$m_H$ parameter space with probability of $> 99.8%$

More in arXiv:1303.0571 e.g:
- limits on Type-III 2HDM
- Information from $q^2$ distributions

Calculation valid for $m_H > 15 \text{ GeV}/c^2$, but $m_H < 300 \text{ GeV}/c^2$ was already excluded from $B \to X_s\gamma$
Evidence of $B^+ \rightarrow \tau^+ \nu$ decays with hadronic $B$ tags

Formalism and method

- Pure leptonic tree decay: **theoretically clean**
  - No QCD uncertainties from final state hadrons
  - Dominant SM uncertainties: $V_{ub}$ (global CKM fit), $B$ decay constant $f_B$ (lattice QCD)

- In the SM:
  $$B(B \to \ell \nu) = \frac{G_F^2 m_B}{8\pi} m_l^2 \left(1 - \frac{m_l^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

- $H^\pm$ can alter this rate:
  $$B(B \to \tau \nu)_{2HDM} = B_{SM} \times \left(1 - \tan^2 \beta \frac{m_B^2}{m_H^2}\right)^2$$

- **Reconstruct 1-prong $\tau$ decay modes:**
  - $e\nu_\tau$, $\mu\nu_\tau$, $\pi\nu_\tau$, and $\rho(\pi^0\pi^0)\nu_\tau$
  (>70% of all $\tau$ decays)

- **Cut on specific likelihood ratios for $\pi \nu$ and $\rho \nu$**

- **Unbinned ML fit to $E_{extra}$**
  - Signal and peaking background PDFs from MC; data/MC ratio corrected (double tagged events); systematic uncertainty is assigned.
  - Combinatorial background from $m_{ES}$ sideband.

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# Results vs. SM

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Tag</th>
<th>Branching Fraction ($\times 10^{-4}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>hadronic</td>
<td>$1.83^{+0.53}_{-0.49} \pm 0.24$</td>
</tr>
<tr>
<td>BaBar</td>
<td>semileptonic</td>
<td>$1.7 \pm 0.8 \pm 0.2$</td>
</tr>
<tr>
<td>Belle</td>
<td>hadronic</td>
<td>$0.72^{+0.27}_{-0.25} \pm 0.11$</td>
</tr>
<tr>
<td>Belle</td>
<td>semileptonic</td>
<td>$1.54^{+0.38}<em>{-0.37}^{+0.29}</em>{-0.31}$</td>
</tr>
</tbody>
</table>

New average (HFAG): $1.14 \pm 0.22$

Present result (preliminary): exclusion of null hypothesis at $3.8\sigma$

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BaBar SL: PRD 81, 051101 (2010)
Belle SL: PRD 82, 071101 (2010)
Search for $B \rightarrow K^{(*)}\nu\nu$ and invisible quarkonium decays

In SM:

(Also via $J/\psi \rightarrow \nu\nu$ and $\psi(2S) \rightarrow \nu\nu$ that we also search in the present analysis)
Rates can have comparable contributions to SM in, e.g.
- Non standard $Z/Z'$ couplings
- NP with invisible signatures
Analysis and results

- **Signature:** reconstructed $K^{(*)} 0/+$ with no additional tracks, requiring low $E_{\text{extra}}$
- **Results:**
  - **Branching fraction UL** at 90% CL with $s_B = m(\nu\nu)^2/m_B^2 < 0.3$
    
    |          | $K^+\nu\nu$ | $K^0\nu\nu$ | $K^{*+}\nu\nu$ | $K^{*0}\nu\nu$ |
    |----------|-------------|-------------|----------------|----------------|
    | (>0.4, < 3.7) | < 8.1       | < 11.6      | < 9.3          |
    | (>0.2, < 3.2) | < 7.9       |             |                |

- Several best limits using hadronic $B_{\text{tag}}$
- First lower limits at 90% CL on $B \to K\nu\nu$ (excess less than 2σ)

**We also obtain:**
- $J/\psi \to \nu\bar{\nu} < 3.9 \times 10^{-3}$
- $\psi(2S) \to \nu\bar{\nu} < 15.5 \times 10^{-3}$ ← first ever

All limits are consistent with SM expectations.
Summary and Conclusions

- BaBar provides access to missing energy decays and to high-energy regions that are not accessible to hadron machines

- $B \to D^{(*)}\tau\nu$ has excluded MSSM Type-II 2HDM at 99.8% CL

- Agreement with standard model prediction has improved for the average $BF(B \to \tau\nu)$. More data is needed to clarify the issue (Belle-II…)

- Some new and improved limits obtained for $B \to K^{(*)}\nu\nu$ processes. They are all consistent with SM and provide tighter constraints on NP scenarios.