Rare $B$ Decays with Missing Energy at Belle

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$B \to \tau \nu$
$B \to K^* \nu \bar{\nu}$

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$B^+ \rightarrow \tau^+ \nu_{\tau}$

hep-ex/0604018v2
$B \rightarrow \tau \nu$ is sensitive to a charged Higgs boson (if the $B$ decay constant $f_B$ is known)

\[
\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau) = \frac{G_F^2 m_B}{8\pi} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B
\]

\[
\mathcal{B}(B \rightarrow \tau \nu) < 2.6 \times 10^{-4} \text{ (90\% C.L.)}
\]

B. Aubert et al., PRD 73, 057101 (2006)
$B \to \tau \nu$ is hard to measure because the $B$ meson decays (usually) to one charged track + missing energy
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~180 hadronic decay modes reconstructed on tag side; signal region is $-0.08 < \Delta E < 0.06$ GeV & $M_{bc} > 5.27$ GeV/$c^2$. 

Electron (8 GeV) and positron (3.5 GeV) are shown.
$B \rightarrow \tau \nu$ is hard to measure because the $B$ meson decays (usually) to one charged track + missing energy.
\[ B \rightarrow \tau \nu \] candidate event

\[ B^+ \rightarrow \bar{D}^0 \pi^+ \]

\[ K^+ \pi^- \pi^+ \pi^- \]

\[ \tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau \]
Reconstruct $1.1 \times 10^6$ charged and neutral $B$ tags in $449 \times 10^6 B\bar{B}$ events ($\int L \, dt = 414 \, fb^{-1}$)

where

$D^{*0} \rightarrow \{ D^0 \pi^0 \mid D^0 \gamma \}$

$D^{*-} \rightarrow \{ \bar{D}^0 \pi^- \mid D^- \pi^0 \}$

$D_s^{*-} \rightarrow D_s^- \gamma$

and

$D^0 \rightarrow 7$ modes, $D^- \rightarrow 6$ modes, $D_s \rightarrow 2$ modes

$\sim 180$ hadronic decay modes reconstructed
Reconstruct $B_{\text{tag}}$ in purely hadronic mode and $B \rightarrow \tau \nu$
from the remaining detected particles

- Signal side has 1 or 3 charged tracks, with charge opposite that of $B_{\text{tag}}$
- Reject event with $\pi^0$ on signal side (except for $\tau \rightarrow \pi^- \pi^0 \nu$ mode)
- In CM frame,
  - apply mode-dependent threshold on $p_{\text{miss}}$: 0.2 GeV/c for $\ell \nu \bar{\nu}$
    - 1.0 GeV/c for $\pi \nu$
    - 1.2 GeV/c for $\pi \pi^0 \nu$
    - 1.8 GeV/c for $\pi \pi \pi \nu$
  - require $-0.86 < \cos \theta_{\text{miss}} < 0.95$
- Ignore low energy calorimeter clusters (contaminated by beam background):
  - $E < 0.05$ GeV (barrel)
  - $E < 0.10$ GeV (forward endcap)
  - $E < 0.15$ GeV (backward endcap)
- Fit extra calorimeter energy $E_{\text{ECL}}$

All selection criteria were optimized in MC before examining the data (“blind analysis”)
Validate the $E_{ECL}$ simulation using double-tagged events (with $B \rightarrow D^* \ell \nu$ on the “signal” side)

**Extra Calorimeter Energy**

**“Signal” reconstruction (purity $\sim 90\%$):**

$B^- \rightarrow D^0 \ell^- \nu$

$D^0 \pi^0$

$K^- \pi^+$

$K^- \pi^+ \pi^- \pi^+$

**MC:**

- $B^+ B^-$: $494 \pm 18$
- $B^0 \bar{B}^0$: $8 \pm 2$
- Combined: $502 \pm 18$

**Data:** $458$

- B: $458$
- B: $458$
- B: $458$
- B: $458$
We find evidence for $B^+ \rightarrow \tau^+ \nu$ by examining the distribution of extra calorimeter energy $E_{ECL}$.

449 x $10^6$ $B\bar{B}$ pairs
680 x $10^3$ $B^\pm$ tags (55% purity)
54 $\tau\nu$ candidates in signal region:
• $E_{ECL} < 0.2$ GeV [$\ell\nu\nu$, $\pi\nu$]
• $E_{ECL} < 0.3$ GeV [$\pi\pi(\pi)\nu$]

17.2 $\pm 5.3 \over 4.7$ events in signal region
We find evidence for $B^+ \rightarrow \tau^+ \nu$ by examining the distribution of extra calorimeter energy $E_{ECL}$

<table>
<thead>
<tr>
<th></th>
<th>$N_{obs}$</th>
<th>$N_{sig}$</th>
<th>$\mathcal{B} \left( 10^{-4} \right)$</th>
<th>$\Sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^- \bar{\nu}<em>\mu \nu</em>\tau$</td>
<td>13</td>
<td>5.6 ± 3.1</td>
<td>2.57 ± 1.38</td>
<td>2.2σ</td>
</tr>
<tr>
<td>$e^- \bar{\nu}<em>e \nu</em>\tau$</td>
<td>12</td>
<td>4.1 ± 3.3</td>
<td>1.50 ± 1.20</td>
<td>1.4σ</td>
</tr>
<tr>
<td>$\pi^- \nu_\tau$</td>
<td>9</td>
<td>3.8 ± 2.7</td>
<td>1.30 ± 0.89</td>
<td>2.0σ</td>
</tr>
<tr>
<td>$\pi^- \pi^0 \nu_\tau$</td>
<td>11</td>
<td>5.4 ± 3.9</td>
<td>4.54 ± 3.26</td>
<td>1.5σ</td>
</tr>
<tr>
<td>$\pi^- \pi^+ \pi^- \nu_\tau$</td>
<td>9</td>
<td>3.0 ± 3.5</td>
<td>6.42 ± 7.58</td>
<td>1.0σ</td>
</tr>
</tbody>
</table>

$\mathcal{B}(B^+ \rightarrow \tau^+ \nu) = (1.79 \pm 0.56 \pm 0.46) \times 10^{-4}$

Significance: $\Sigma = 3.5\sigma$ (statistical & systematic)
We extract the $B$ decay constant from our branching fraction measurement

\[
\mathcal{B}(B^+ \to \tau^+ \nu) = (1.79 \pm 0.56 \pm 0.46) \times 10^{-4}
\]

\[
\Rightarrow f_B \cdot |V_{ub}| = (10.1 \pm 1.6 \pm 1.3) \text{ GeV}
\]

\[
\Rightarrow f_B = (229 \pm 36 \pm 34) \text{ MeV}
\]

using $|V_{ub}| = (4.39 \pm 0.33) \times 10^{-3}$ from HFAG

Compare with $f_B = 216 \pm 22$ MeV from HPQCD unquenched lattice calculation in PRL 95, 212001 (2005)
We determine constraints on the charged Higgs boson assuming $f_B$ and $|V_{ub}|$ are known

$$\mathcal{B}(B^+ \rightarrow \tau^+ \nu) = (1.79 \pm 0.56 \pm 0.46) \times 10^{-4}$$

$$r_H = \frac{\mathcal{B}_{\text{meas}}}{\mathcal{B}_{\text{SM}}} = \left(1 - \frac{m_B^2}{m_H^2} \tan^2 \beta\right)^2$$

$$= 1.13 \pm 0.51$$
$B \rightarrow K^* \nu \bar{\nu}$

hep-ex/0608047
$B \to K^* \nu \bar{\nu}$ is sensitive to new heavy particles in the penguin loop or box (e.g., supersymmetric)

\[
\text{SM : } \mathcal{B}(B \to K^* \nu \bar{\nu}) \simeq 1.3 \times 10^{-5}
\]

$B \rightarrow K^* + \text{nothing}$ can pair-produce scalar WIMPs with mass below 10 GeV

Unexplored in direct searches

Bird et al., PRL 93, 201803 (2004)
Dedes et al., PRD 65, 015001 (2002)
Adams et al., PRL 87, 041801 (2001)
$B \rightarrow K^* \nu \bar{\nu}$ is reconstructed in a manner similar to $B \rightarrow \tau \nu$ (but with $K^{*0} \rightarrow K^+ \pi^-$ signal)
$B \rightarrow K^*\nu\bar{\nu}$ candidate event (actually, $B \rightarrow K^*\gamma$)

Undetected photon in ECL barrel-endcap gap

$\bar{B}^0 \rightarrow D^+ a_1^-$

$K^*0 \rightarrow K^-\pi^+$

$K \rightarrow \pi^+\pi^-$

$\rho^0\pi^-$
We find no evidence for $B \rightarrow K^* \nu \bar{\nu}$ by examining the distribution of extra calorimeter energy $E_{ECL}$

535 x $10^6$ $B \bar{B}$ pairs
13 $K^* \nu \nu$ candidates in signal region ($E_{ECL} < 0.3$ GeV)
$4.7 \pm 3.1 \pm 2.6$ signal events from fit

$\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu}) < 3.4 \times 10^{-4}$ at 90% C.L.

cf. SM expectation of $1.3 \times 10^{-5}$ by Buchalla, Hiller & Isidori

Preliminary
Conclusions

- Belle has found evidence for $B \rightarrow \tau \nu$ and has used this to determine the $B$ decay constant $f_B$:
  
  \[ B(B^+ \rightarrow \tau^+ \nu) = (1.79 \pm 0.56 \pm 0.46) \times 10^{-4} \]
  
  \[ f_B = (229 \pm 36 \pm 34) \text{ MeV} \]

  using $|V_{ub}| = (4.39 \pm 0.33) \times 10^{-3}$ from HFAG

- Belle has searched for $B \rightarrow K^* \nu \bar{\nu}$:
  
  \[ B(B^0 \rightarrow K^{*0} \nu \bar{\nu}) < 3.4 \times 10^{-4} \text{ @ 90\% C.L.} \]

  ...still 10x above SM expectation

- Further progress will require **Super B Factory** luminosity