Rare B Decays with Leptons at Belle

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New Belle Result on $B \rightarrow \tau \nu$
**B^+ \rightarrow \tau^+ \nu**  

Introduction

- Leptonic decays proceed through W boson annihilation in the Standard Model

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

- Decay rate simply related to B meson decay constant \( f_B \) and \( |V_{ub}| \)

- Charged Higgs contribution enhance/reduce the Br

\[ \mathcal{B}(B \rightarrow \tau \nu) = \mathcal{B}(B \rightarrow \tau \nu)_{SM} \times r_H \]

\[ r_H = \left(1 - \frac{m_B^2}{m_H^2} \tan^2 \beta\right)^2 \]

[Wei-Shu Hou, Phys. Rev. D48, 2342 (1993)]

- CP Violation may be sensitive to “unparticle” physics

More than 2 neutrinos appear in \(B \rightarrow \tau \nu\) decay

Most powerful discriminant variable: \(E\text{ECL}\)

Require **no** particle remain after removing products of tagging \(B\) and the particle(s) from \(B \rightarrow \tau \nu\) decay

Tagging side:
- Semileptonic or Hadronic \(B\) Decay

Signal side:
- Detect \(\tau\) daughter particle(s)

\[\begin{align*}
B^- & \rightarrow X \\
\Upsilon(4S) & \rightarrow B^+ + B^- \\
B^+ & \rightarrow \tau^+ \nu_\tau, \quad \tau^+ \rightarrow e^+ \nu_e \nu_\tau
\end{align*}\]
Previous $B^+ \rightarrow \tau^+ \nu$ Measurements

- **Belle** Hadronic B tag (449x10^6 BB pairs)
  
  [PRL 97, 251802 (2006)]
  
  - 3.5σ evidence
  
  $B(B \rightarrow \tau \nu) = [1.79^{+0.56}_{-0.49} \text{ (stat)}^{+0.46}_{-0.51} \text{ (syst)}] \times 10^{-4}$

- **BaBar** (383 x 10^6 BB pairs)
  
  [PRD 77, 011107(R) (2008)], [PRD 76, 052002 (2007)]
  
  - Hadronic B Tag
  
  - Semileptonic ($B \rightarrow D \nu \ X$) Tag
    
    X: $\gamma$, $\pi^0$,
    
    not reconstructed explicitly
  
  - 2.6σ excess

  $B(B \rightarrow \tau \nu) = [1.2 \pm 0.4 \text{ (stat)} \pm 0.3 \text{ (bkg)} \pm 0.2 \text{ (syst)}] \times 10^{-4}$

→ Need more statistics to establish $B^+ \rightarrow \tau^+ \nu$ Decay

New Belle Result with $D^{(*)}\nu$ tag using 657M BB pairs
Reconstructed B Decay Modes

Though $\text{Br}(B \rightarrow D^{(*)} l \nu)$ is large (~17%), S/N is expected to be worse than with hadronic B tags.

→ We only use clean decay modes with high $\text{Br} \times \varepsilon$.

- **Tagging Side**
  - $B^- \rightarrow D^{*0} l^+ \nu$, $D^0 l \nu$
  - $D^{*0} \rightarrow D^0 \pi^0$, $D^0 \gamma$
  - $D^0 \rightarrow K^- \pi^+, K^- \pi^+ \pi^- \pi^+, K^- \pi^+ \pi^0$
  - Reconstruct $D^{*0} l \nu$ explicitly
  → *prevent additional* $\pi^0 (\gamma)$ *from contaminating* $E_{ECL}$

- **Signal Side**
  1 prong decay
  - $B^+ \rightarrow \tau^+ \nu$
    - $\tau \rightarrow e \nu \nu$, $\mu \nu \nu$, $\pi \nu$

- Require No additional charged tracks or $\pi^0$
Selection Criteria

- Optimized to maximize FoM = \( \frac{N_{\text{sig}}}{\sqrt{N_{\text{sig}} + N_{\text{BG}}}} \) in \( E_{\text{ECL}} < 0.2 \) GeV
  - separately for \( \tau \to \ell \nu \nu \) and \( \pi \nu \) modes

- **Blind analysis**: \( E_{\text{ECL}} < 0.4 \) GeV is masked until selection criteria are finalized

- Tagging side
  - Identified using a kinematic relation

\[
\cos \theta_{B-D^*l} = \frac{2E_B E_{D^*l} - M_B^2 - M_{D^*l}^2}{2P_B P_{D^*l}}
\]

- **Signal side**
  - \( N_{\text{sig}} \) extracted from \( E_{\text{ECL}} \)
  - Clear Signal and BG separation expected

- BLIND analysis: \( E_{\text{ECL}} < 0.4 \) GeV is masked until selection criteria are finalized
Validation of the Analysis Method

Check analysis procedure and $E_{ECL}$ distribution

- Reconstruct $D^{*0}\ell\nu$ as the Signal

Obtained $\text{Br}(B^-\rightarrow D^{*0}\ell\nu) = 6.0\pm 0.2\%$ (stat error only)

$\rightarrow$ consistent with the world average

$6.5\pm 0.5\%$ (PDG2007)

Confirmed our analysis procedure and $E_{ECL}$ description are correct
Observe a Clear Signal

$$N_{\text{sig}} = 154^{+36}_{-35} (\text{stat})^{+21}_{-22} (\text{syst})$$

$$\mathcal{B}(B \to \tau\nu) = [1.65^{+0.38}_{-0.37} (\text{stat})^{+0.35}_{-0.37} (\text{syst})] \times 10^{-4}$$

Dominant systematic error for $\mathcal{B}(B \to \tau\nu)$:
BG MC Statistics (12%), Tagging Efficiency (12%)
Peaking BG Uncertainty (8%)

Consistent with previous Belle result with hadronic tags using $449 \times 10^6$ BB pairs

$$\mathcal{B}(B \to \tau\nu) = [1.79^{+0.56}_{-0.49} (\text{stat})^{+0.46}_{-0.51} (\text{syst})] \times 10^{-4}$$

1.4 $\sigma$ from SM expectation from other experimental constraints

$$\mathcal{B}(B \to \tau\nu)_{\text{SM}} = [0.93^{+0.11}_{-0.12}] \times 10^{-4}$$

[CKMfitter http://ckmfitter.in2p3.fr/]
Statistical Significance of Signal Yield

- Significance incl. systematic error
  
  \[ = 3.8 \sigma \]

(without syst. 4.7 \( \sigma \))
Result for each $\tau$ decay mode

- Each is consistent with the combined fit result

![Graphs showing event distribution for $\tau \rightarrow e\nu\nu$, $\tau \rightarrow \mu\nu\nu$, and $\tau \rightarrow \pi\nu$ decay modes.]

- $N_{\text{sig}} = 78^{+23}_{-22}$ for $\tau \rightarrow e\nu\nu$
- $N_{\text{sig}} = 15^{+18}_{-17}$ for $\tau \rightarrow \mu\nu\nu$
- $N_{\text{sig}} = 58^{+21}_{-20}$ for $\tau \rightarrow \pi\nu$

![Bar graph showing branching ratios (BR) for $B \rightarrow \tau\nu$ decay modes.]

- $\text{BR}(B \rightarrow \tau\nu) \times 10^{-4}$
- $2.02^{+0.59}_{-0.56}$
- $0.62^{+0.76}_{-0.71}$
- $1.88^{+0.70}_{-0.66}$
- $1.65^{+0.38}_{-0.37}$

(statistical error only)
Determination of $f_B$

- Product of B meson decay constant $f_B$ and CKM matrix element $|V_{ub}|$

$$f_B |V_{ub}| = (9.7 \pm 1.1^{+1.0}_{-1.1}) \times 10^{-4} \text{ GeV}$$

- Using $|V_{ub}| = (3.99^{+0.35}_{-0.30}) \times 10^{-3}$ from HFAG

$$f_B = 242^{+28}_{-27} \pm 33 \text{ MeV}$$

$f_B = 216 \pm 22 \text{ MeV}$ (an unquenched lattice calc.)

[HPQCD, Phys. Rev. Lett. 95, 212001 (2005)]
Constraint on Charged Higgs

\[ r_H = (1 - \frac{m_B^2}{m_H^2} \tan^2 \beta)^2 \]

\[ \mathcal{B}(B \to \tau \nu) = (1.65^{+0.38+0.35}_{-0.37-0.37}) \times 10^{-4} \]

\[ \mathcal{B}(B \to \tau \nu)_{SM} = (0.93^{+0.12}_{-0.11}) \times 10^{-4} \]

SM expectation from other experimental constraints by CKMfitter

\[ r_H = 1.77 \pm 0.65 \]
Conclusions

- New Belle Measurement of $B \to \tau \nu$ Decays with semileptonic tagging method
  - By optimizing selection criteria for $B \to \tau \nu$ to achieve clear signal separation in $E_{ECL}$,
  - $N_{\text{sig}} = 154^{+36}_{-35}(\text{stat})^{+21}_{-22}(\text{syst})$ with 3.8 $\sigma$
    - Preliminary
  - $\mathcal{B}(B \to \tau \nu) = [1.65^{+0.38}_{-0.37}(\text{stat})^{+0.35}_{-0.37}(\text{syst})] \times 10^{-4}$
  - Confirmed Belle’s hadronic tags result
  - Gave stringent limits on the charged Higgs mass

Update of hadronic tags will be available soon.
- To establish $B \to \tau \nu$ signal $>5\sigma$
- Enable test of CP violation, providing another method to search for new physics
Backup
Selection Criteria and Efficiency

- For $\tau \to \mu \nu \nu$, $e \nu \nu$ modes
  - Dominant BG: true D(*)lnu tagged B-decays $\rightarrow$ looser tagging selection
  - $-2.1 < \cos \theta_{BDL} < 1.3$, $-2.6 < \cos \theta_{BD^*L} < 1.2$, $0.5 < P_{\mid \text{tag}} < 2.5$
  - $P_{\mid \text{sig}} > 0.3$

- For $\tau \to \pi \nu$ mode
  - Suppress continuum and combinatorial BG $\rightarrow$ tighter tagging selection
  - $-1.1 < \cos \theta_{B(*)DL} < 1.1$, $1.0 < P_{\mid \text{tag}} < 2.2$
  - $1.0 < P_{\mid \text{sig}} < 2.4$
  - $|\cos \theta_{\text{thrust}}| < 0.9$

- Reconstruction efficiency
  - Including Br of $\tau$ decay modes and tagging side efficiency
    - $\tau \to e \nu \nu$ mode: $\ 6.0 \times 10^{-4}$
    - $\tau \to \mu \nu \nu$ mode: $\ 3.8 \times 10^{-4}$
    - $\tau \to \pi \nu$ mode: $\ 4.9 \times 10^{-4}$
### Systematic Errors of Yield

<table>
<thead>
<tr>
<th>Category</th>
<th>Error Low</th>
<th>Error High</th>
</tr>
</thead>
<tbody>
<tr>
<td>BG PDF Shape</td>
<td>+18.1</td>
<td>-17.2</td>
</tr>
<tr>
<td>Signal PDF Shape</td>
<td>+3.1</td>
<td>-3.2</td>
</tr>
<tr>
<td>Br of Peaking BG</td>
<td>+6.4</td>
<td>-13.0</td>
</tr>
<tr>
<td>Rare $B, b \rightarrow ul\nu, \tau$ pair BG</td>
<td>+5.9</td>
<td>-5.9</td>
</tr>
<tr>
<td>Efficiency Ratio</td>
<td>+0.5</td>
<td>-0.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>+20.3</td>
<td>-22.3</td>
</tr>
</tbody>
</table>
Br Systematic Error

$$\begin{array}{ccc}
\text{Error for Efficiency} & +(\%) & -(\%)
\hline
\text{MC stat} & 0.9 & 0.9 \\
\text{PID} & 1.3 & 1.3 \\
\text{Br of } \tau & 0.4 & 0.4 \\
\text{Tracking} & 1.0 & 1.0 \\
\text{Tagging Efficiency} & 11.6 & 11.6 \\
\hline
\text{Signal Yield} & 13.2 & 14.7 \\
\hline
\text{N}_{BB} & 1.4 & 1.4 \\
\hline
\text{Total} & 21.2 & 22.2
\end{array}$$
Neutral B Tagged Sample

- $E_{ECL}$ distribution well described by MC