Leptonic and semileptonic B decays with tau at B factories

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Contents

- $B \rightarrow D^{(*)} \tau V$ from Belle.
  (Result of BaBar reported by C. Bozzi.)

- $B \rightarrow \tau V$ from Belle and BaBar.
Introduction for $B \to D^{(*)}\tau\bar{\nu}$

- In the SM, mediated by $W^\pm$.
- Expectation from the SM:
  - $B (B \to D^*\tau\bar{\nu})$: 1.4%
  - $B (B \to D\tau\bar{\nu})$: 0.7%


- In extended models, can be affected by charged Higgs.

  A. S. Cornell et al., PRD 81, 115008 (2010).

- Related to form factor (different systematics compared to $B \to \tau\nu$).
- Additional information from polarization.
Introduction for $B \to D^{(*)}\tau\nu$

- Interesting recent updates from BaBar:
  - Combining $D^*\tau\nu$ and $D\tau\nu$, deviated from SM by $3.4\sigma$.
  - Type II of two Higgs doublet models disfavored by 99.8%.

$R(D^{(*)})$: ratio between $D^{(*)}\tau\nu$ and $D^{(*)}\ell\nu$.
Blue: this result, red: Type II of 2HDM.

arXiv:1205.5442, presentation by C. Bozzi
Methods for $B \rightarrow D^{(*)} \tau \nu$ at Belle

Exploit that a B meson pair is generated by $e^+e^- \rightarrow \Upsilon(4S) \rightarrow BB$.

- **Inclusive tag**: reconstruct signal decay products without neutrinos, and tag the other B meson using all the remaining particles. Signal extraction by invariant mass for tag side $M_{tag}$ and/or momentum of D in $e^+e^-$ frame for signal side $P_{D0}$.

- **Hadronic tag**: tag B in hadronic decays $B \rightarrow D^{(*)} \pi$, etc., and see the recoil. Signal extraction by missing mass squared in the event $M_{miss}^2$ and extra energy in electromagnetic calorimeter $E_{extra}^{ECL}$ (detected energy for neutrinos).
B** \rightarrow D^* \tau \nu** by inclusive tag from Belle

- Using 535 M BB.
- First observation of signal (5.2\sigma).

$$\mathcal{B}(D^{*+}\tau^- \bar{\nu}_\tau) = [2.02^{+0.40}_{-0.37}(\text{stat}) \pm 0.37(\text{syst})] \%$$

consistent with SM: 1.4\%

Syst. from tag efficiency, sig efficiency, etc.
(largest, estimated from control sample B** \rightarrow D^* \pi^+)**

<table>
<thead>
<tr>
<th>Subchannel</th>
<th>$$N_s$$</th>
<th>$$\mathcal{B}$$(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$$\bar{D}^0 \rightarrow K^+ \pi^-, \tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$$</td>
<td>19.5^{+5.8}_{-5.0}</td>
<td>2.44^{+0.74}_{-0.65}</td>
</tr>
<tr>
<td>$$\bar{D}^0 \rightarrow K^+ \pi^- \pi^0, \tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$$</td>
<td>11.9^{+6.0}_{-5.2}</td>
<td>1.69^{+0.84}_{-0.74}</td>
</tr>
<tr>
<td>$$\bar{D}^0 \rightarrow K^+ \pi^-, \tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$$</td>
<td>29.9^{+10.0}_{-9.1}</td>
<td>2.02^{+0.68}_{-0.61}</td>
</tr>
<tr>
<td>Combined</td>
<td>60^{+12}_{-11}</td>
<td>2.02^{+0.40}_{-0.37}</td>
</tr>
</tbody>
</table>

(No result for D** \tau \nu**.)

PRL 99, 191807 (2007)
$B^\pm \rightarrow D^{(*)}\tau\nu$ by inclusive tag from Belle

- Using 657 M BB.
- Simultaneous fit to both subsets.
- Observation for $D^{*}\tau\nu$ (8.1$\sigma$).
  \[ B(D^{*0}\tau^-\bar{\nu}_\tau) = [2.12^{+0.28}_{-0.27}(\text{stat}) \pm 0.29(\text{syst})]\% \]
  \hspace{1cm} \text{SM: 1.4\%}

- Evidence for $D\tau\nu$ (3.5$\sigma$).
  \[ B(D^0\tau^-\bar{\nu}_\tau) = [0.77 \pm 0.22(\text{stat}) \pm 0.12(\text{syst})]\% \]
  \hspace{1cm} \text{SM: 0.7\%}

Syst. from reconstruction of $B_{\text{tag}}$ and $B_{\text{sig}}$, etc. Estimation using control samples: $B^\pm \rightarrow D^{(*)}\pi^\pm$.

PRD 82, 072005 (2010)
\(B^0 \rightarrow D(*)\tau\nu\) by hadronic tag from Belle

- Using 657 M BB.
- Simultaneous fit to both subsets.
- \(D(*)\nu\tau\) as control sample and normalization.
- Excess and evidence for signals.

\[
R(D^+\tau^-\bar{\nu}_\tau/D^+l^-\bar{\nu}_\tau) = 0.48^{+0.22}_{-0.19}(\text{stat})^{+0.06}_{-0.05}(\text{syst}) \quad 2.6\sigma
\]

\[
R(D^{*+}\tau^-\bar{\nu}_\tau/D^{*+}l^-\bar{\nu}_\tau) = 0.48^{+0.14}_{-0.12}(\text{stat})^{+0.06}_{-0.04}(\text{syst}) \quad 4.7\sigma
\]

\[
B(D^+\tau^-\bar{\nu}_\tau) = [1.01^{+0.46}_{-0.41}(\text{stat})^{+0.13}_{-0.11}(\text{syst}) \pm 0.10(\text{norm})] \%
\]

\[
B(D^{*+}\tau^-\bar{\nu}_\tau) = [2.56^{+0.75}_{-0.66}(\text{stat})^{+0.31}_{-0.22}(\text{syst}) \pm 0.10(\text{norm})] \%
\]

Syst. from PDFs and cross-feeds.

BG: \(D\nu\), \(D^*\nu\), \(D^{**}\nu\), DX, ...

arXiv:0910.4301
\( B^\pm \rightarrow D^{(*)} \tau \nu \) by hadronic tag from Belle

- Using 657 M BB.
- Simultaneous fit to both subsets.
- \( D^{(*)}\nu \) as control sample and normalization.
- Evidence for signals.

\[
R(D^0 \tau^- \bar{\nu}_\tau / D^0 l^- \bar{\nu}_\tau) = 0.70_{-0.18}^{+0.19}(\text{stat})_{-0.09}^{+0.11}(\text{syst}) \quad 3.8\sigma
\]

\[
R(D^{*0} \tau^- \bar{\nu}_\tau / D^{*0} l^- \bar{\nu}_\tau) = 0.47_{-0.10}^{+0.11}(\text{stat})_{-0.07}^{+0.06}(\text{syst}) \quad 3.9\sigma
\]

\[
B(D^0 \tau^- \bar{\nu}_\tau) = [1.51_{-0.39}^{+0.41}(\text{stat})_{-0.24}^{+0.24}(\text{syst}) \pm 0.15(\text{norm})]\%
\]

\[
B(D^{*0} \tau^- \bar{\nu}_\tau) = [3.04_{-0.66}^{+0.69}(\text{stat})_{-0.47}^{+0.40}(\text{syst}) \pm 0.22(\text{norm})]\%
\]

Syst. from PDFs and cross-feeds.

BG: \( D \nu, D^* \nu, D^{**} \nu, DX, \ldots \)

arXiv:0910.4301
Summary and comparison for $B \rightarrow D^{(*)} \tau \bar{\nu}$

- Good agreement btw the results for inclusive and hadronic tags.
- Not significant but slightly larger than SM expectations.
- Consistent with values of BaBar (combined for charged and neutral):
  
  \[
  \mathcal{B}(D^* \tau^- \bar{\nu}_\tau) = [1.76 \pm 0.13(\text{stat}) \pm 0.12(\text{syst})] \%
  \]
  
  \[
  \mathcal{B}(D \tau^- \bar{\nu}_\tau) = [1.02 \pm 0.13(\text{stat}) \pm 0.11(\text{syst})] \%
  \]

(Belle does not have official combined values.)
Introduction for $B \rightarrow \tau \nu$

- In the SM, annihilation process mediated by $W^\pm$.

- Branching fraction proportional to $f_B^2 |V_{ub}|^2$.

$$B (B^- \rightarrow \tau^- \bar{\nu}_\tau) = \frac{G_F m_B m_\tau^2}{8 \pi} \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

- $f_B$: B meson decay constant. $(190 \pm 13) \text{ MeV}$ from HPQCD.
- $V_{ub}$: CKM matrix element. $(3.89 \pm 0.44) \times 10^{-3}$ from PDG.
- Expected branching fraction = $(0.96 \pm 0.25) \times 10^{-4}$. Different systematics compared to $B \rightarrow D^{(*)}\tau\nu$.
Effect of charged Higgs for $B \to \tau \nu$

- Branching fraction of $B \to \tau \nu$ could be affected by charged Higgs.

\[ B^-(B \to \tau \nu) = B(B \to \tau \nu)_{SM} \times r_H \]

where

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

- An example of the modifications is:

- Comparison with $B \to \mu \nu$ and $B \to e \nu$: test of lepton universality.

Type II of two Higgs doublet model, W. S. Hou, PRD48, 2342 (1993)
Methods for $B \rightarrow \tau \nu$

Exploit that a B meson pair is generated by $e^+e^- \rightarrow \Upsilon(4S) \rightarrow BB$.

- Two independent tags are used.
- **Hadronic tag**: tag $B$ in hadronic decays $B \rightarrow D^{(*)}\pi$, etc.
- **Semileptonic tag**: tag $B$ in semileptonic decays $B \rightarrow D^{(*)}l\nu$.
- Signal extraction by *extra energy in electromagnetic calorimeter*, which corresponds to detected energy for neutrinos ($\sim 0$ for signal).
Using 449 M BB.

First evidence of signal (3.5σ).

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

Syst. from BG PDF, tag efficiency, etc.

<table>
<thead>
<tr>
<th>( \tau ) decay</th>
<th>( N_{\text{obs}} )</th>
<th>( N_s )</th>
<th>( N_b )</th>
<th>( \mathcal{B}(10^{-4}) )</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}_{-2.8}</td>
<td>8.8^{+1.1}_{-1.1}</td>
<td>2.57^{+1.38}_{-1.27}</td>
<td>2.2\sigma</td>
</tr>
<tr>
<td>( e^- \bar{\nu}<em>e \nu</em>\tau )</td>
<td>12</td>
<td>4.1^{+3.3}_{-2.6}</td>
<td>9.0^{+1.1}_{-1.1}</td>
<td>1.50^{+1.20}_{-0.95}</td>
<td>1.4\sigma</td>
</tr>
<tr>
<td>( \pi^- \nu_\tau )</td>
<td>9</td>
<td>3.8^{+2.7}_{-2.1}</td>
<td>3.9^{+0.8}_{-0.8}</td>
<td>1.30^{+0.89}_{-0.70}</td>
<td>2.0\sigma</td>
</tr>
<tr>
<td>( \pi^- \pi^0 \nu_\tau )</td>
<td>11</td>
<td>5.4^{+3.9}_{-3.3}</td>
<td>5.4^{+1.6}_{-1.6}</td>
<td>4.54^{+3.26}_{-2.74}</td>
<td>1.5\sigma</td>
</tr>
<tr>
<td>( \pi^- \pi^+ \pi^- \nu_\tau )</td>
<td>9</td>
<td>3.0^{+3.5}_{-2.3}</td>
<td>4.8^{+1.4}_{-1.4}</td>
<td>6.42^{+7.58}_{-5.42}</td>
<td>1.0\sigma</td>
</tr>
</tbody>
</table>

Fitted by smooth PDFs.
B → \tau \nu by hadronic tag from BaBar

- Using 468 M BB.
- Evidence of signal (3.3\sigma).

\[ \mathcal{B} = \left[ 1.80^{+0.57}_{-0.54} \text{ (stat)} \pm 0.26 \text{ (syst)} \right] \times 10^{-4} \]

Syst. from BG PDF, tag efficiency, etc.

Fitted by histogram PDFs.

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>\epsilon \times 10^{-4}</th>
<th>Branching Fraction \times 10^{-4}</th>
<th>Significance \sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>\tau^+ \rightarrow e^+ \nu \bar{\nu}</td>
<td>2.73</td>
<td>0.39^{+0.89}_{-0.79}</td>
<td>0.5</td>
</tr>
<tr>
<td>\tau^+ \rightarrow \mu^+ \nu \bar{\nu}</td>
<td>2.92</td>
<td>1.23^{+0.89}_{-0.80}</td>
<td>1.6</td>
</tr>
<tr>
<td>\tau^+ \rightarrow \pi^+ \nu</td>
<td>1.55</td>
<td>4.0^{+1.5}_{-1.3}</td>
<td>3.3</td>
</tr>
<tr>
<td>\tau^+ \rightarrow \rho^+ \nu</td>
<td>0.85</td>
<td>4.3^{+2.3}_{-1.9}</td>
<td>2.6</td>
</tr>
<tr>
<td>combined</td>
<td>8.05</td>
<td>1.80^{+0.57}_{-0.54}</td>
<td>3.6</td>
</tr>
</tbody>
</table>

arXiv:1008.0104
**B → τν** by semileptonic tag from Belle

- Using 657 M BB.
- Evidence of signal (3.6σ).

\[ \mathcal{B} = [1.54^{+0.38}_{-0.37}\text{(stat)}^{+0.29}_{-0.31}\text{(syst)}] \times 10^{-4} \]

Syst. from BG PDF, tag efficiency, etc.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Signal yield</th>
<th>( \varepsilon ), ( 10^{-4} )</th>
<th>( \mathcal{B}, 10^{-4} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau^- \rightarrow e^- \bar{\nu}<em>e \nu</em>\tau )</td>
<td>73^{+23}_{-22}</td>
<td>5.9</td>
<td>1.90^{+0.59+0.33}_{-0.57-0.35}</td>
</tr>
<tr>
<td>( \tau^- \rightarrow \mu^- \bar{\nu}<em>\mu \nu</em>\tau )</td>
<td>12^{+18}_{-17}</td>
<td>3.7</td>
<td>0.50^{+0.76+0.18}_{-0.72-0.21}</td>
</tr>
<tr>
<td>( \tau^- \rightarrow \pi^- \nu_\tau )</td>
<td>55^{+21}_{-20}</td>
<td>4.7</td>
<td>1.80^{+0.69+0.36}_{-0.66-0.37}</td>
</tr>
<tr>
<td>Combined</td>
<td>143^{+36}_{-35}</td>
<td>14.3</td>
<td>1.54^{+0.38+0.29}_{-0.37-0.31}</td>
</tr>
</tbody>
</table>

Fitted by histogram PDFs.

**PRD 82, 071101(R) (2010)**
$\mathcal{B} \rightarrow \tau \nu$ by semileptonic tag from BaBar

- Using 459 M BB.
- Excess of signal (2.3σ).

$\mathcal{B} = [1.7 \pm 0.8\text{(stat)} \pm 0.2\text{(syst)}] \times 10^{-4}$

Syst. from BG yield, tag efficiency, etc.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$N_{\text{bg}}^{\text{data}}$</th>
<th>$N_{\text{obs}}$</th>
<th>Branching fraction ($\times 10^{-4}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$</td>
<td>$81 \pm 12$</td>
<td>121</td>
<td>$(3.6 \pm 1.4)$</td>
</tr>
<tr>
<td>$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$</td>
<td>$135 \pm 13$</td>
<td>148</td>
<td>$(1.3^{+1.8}_{-1.6})$</td>
</tr>
<tr>
<td>$\tau^+ \rightarrow \rho^+ \bar{\nu}_\tau$</td>
<td>$59 \pm 9$</td>
<td>71</td>
<td>$(2.1^{+2.0}_{-1.8})$</td>
</tr>
<tr>
<td>$\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$</td>
<td>$234 \pm 19$</td>
<td>243</td>
<td>$(0.6^{+1.4}_{-1.2})$</td>
</tr>
</tbody>
</table>

Counted in signal region.
(Region depends on $\tau$ modes.)

PRD 81, 051101 (2010)
Summary and comparison for $B \to \tau \nu$

HFAG average: $B = (1.67 \pm 0.30) \times 10^{-4}$

Belle, hadronic tag, 449M BB

BaBar, hadronic tag, 468M BB

Belle, semileptonic tag, 657M BB

BaBar, semileptonic tag, 459M BB

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

$B = [1.80^{+0.57}_{-0.54}(\text{stat}) \pm 0.26(\text{syst})] \times 10^{-4}$

$B = [1.54^{+0.38}_{-0.37}(\text{stat})^{+0.29}_{-0.31}(\text{syst})] \times 10^{-4}$

$B = [1.7 \pm 0.8(\text{stat}) \pm 0.2(\text{syst})] \times 10^{-4}$

Discrepancy by 2.8σ.
Improved hadronic tag at Belle

- More decay modes.
- Event selection by using NeuroBayes (neural network).
  - Efficiency and purity depend on requirement on NeuroBayes output.

Efficiency improved by a factor of ~2 at same purity.

Purity improved from 25% to 90% at same efficiency.

Effective for both $B \to D^{(*)}\tau\nu$ and $B \to \tau\nu$. Results coming soon.

NIMA 654, 432 (2011)
Summary

• $B \rightarrow D^{(*)}\tau\nu$ and $B \rightarrow \tau\nu$: interesting topics at B factories.
  • Discrepancies from SM.
  • Constraint on models with charged Higgs.

• Error dominated by statistical uncertainty. Many systematic uncertainties related to statistics.

• Further improvements expected at B factories by using improved methods and increased data sample.

• Expect precise measurements at super B factories.
Backup slides
Examples for the tagging

Hadronic tag for $B \rightarrow \tau \nu$ by BaBar

Semileptonic tag for $B \rightarrow \tau \nu$ by Belle

\[ m_{ES} = \sqrt{s/4 - p_B^2} \]

- Modes: $B \rightarrow D^{(*)}\pi$, etc.
- Efficiency = $\sim 0.2\%$.
- Less background.
- $p_{B\text{sig}}$ determined.

\[ \cos \theta_{B,D^{(*)}\ell} = \frac{2E_{\text{beam}}E_{D^{(*)}\ell}}{2p_B^{\text{cms}} \cdot p_{D^{(*)}\ell}^{\text{cms}}} - m_B^2 - M_{D^{(*)}\ell}^2 \]

- Modes: $B \rightarrow D^{(*)}\ell\nu$.
- Efficiency = $\sim 1\%$.
- More background.
- $p_{B\text{sig}}$ not determined.
B→D(*)\ell V from BaBar

R(D(*))\): ratio btw tau and l modes.
Blue: this result, red: Type II of 2HDM.

Type II of 2HDM is excluded by 99.8%...
Belle has possible statistical improvement for $B \to \tau \nu$, hadronic tag. (Data reprocessed to improve efficiencies for tracks and photons.)