$B \rightarrow D^{(*)} \tau^+ \nu_\tau$ and $B^+ \rightarrow \tau^+ \nu_\tau$

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Summary
Motivation

**Expected decay rates**

\[ \mathcal{O}(10^{-3} - 10^{-2}) \]

- \( B \to D^{(*)} \tau^+ \nu_\tau \)
- \( B^+ \to \tau^+ \nu_\tau \)

**Examples of SM amplitudes**

- Small hadronic effects; theoretically clean.
- Sensitive to New Physics

**Poorly known:** multiple \( \nu \)'s in final states \( \Rightarrow \) experimentally difficult!
Experimental Techniques

**B** decay with missing energy

- e.g. $B^+ \rightarrow D^{*0}\tau^+\nu$

**signature:**

- $D^*, l/\pi +$ invisible

**at B-factories:**

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

**B**<sub>tag</sub> reconstruction:

- **BB**<sup>-</sup> event
- identify particles belonging to $B_{sig}$
- kinematical constraints on $B_{sig}$

$$ \vec{p}_{sig} = -\vec{p}_{tag} $$

**Two methods of B**<sub>tag</sub> reconstruction:

- Select $B_{sig}$ candidate and check whether remaining particles consistent with $B$ decay
  ("inclusive" $B_{tag}$ reconstruction)
- Reconstruct $B_{tag}$ (in exclusive mode) and check whether remaining particles consistent with $B_{sig}$ ("exclusive" $B_{tag}$ reconstruction)
$B \rightarrow \tau \nu_{\tau}$ event at B-factories

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

$B^-_{\text{sig}} \rightarrow \tau^- (\rightarrow e^- \nu \nu) \nu_{\tau}$

Belle candidate event
purely leptonic B decay: theoretically very clean, SM BF:

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

\[ BF(B^+ \rightarrow \tau^+\nu_\tau) = (1.20 \pm 0.25) \times 10^{-4} \]

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

Providing \( f_B \) is known

\[ |V_{ub}| = (4.32 \pm 0.16 \pm 0.29) \times 10^{-3} \]  
HFAG ICHEP08

\[ f_B = 190 \pm 13 \text{MeV}, \]  
HPQCD arXiv:0902.1815

**Higgs effects to branching fraction:**

\[ BF(B^+ \rightarrow \tau^+\nu_\tau) = BF(B^+ \rightarrow \tau^+\nu_\tau)_{SM} \times r_H \]

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

W. S. Hou, PR D 48, 2342 (1993)
Reconstruct $B_{\text{tag}}$ (in exclusive mode)

Reconstruct $B_{\text{tag}}$ in hadronic mode:

\[
\Delta E = \sum E_i - E_{\text{beam}} \\
M_{\text{ES}} = \sqrt{E_{\text{beam}}^2 - (\sum p_i)^2}
\]

Reconstruct $B_{\text{tag}}$ in semileptonic mode $B \rightarrow D^{*0} \tau \nu$:

![Graphs and data plots](image)
**B → τν - signal side**

**signal side signature:**

\[ X + \text{nothing} \]

\[ X = \rho^\pm, \pi^\pm, (3\pi)^\pm, e^\pm, \mu^\pm \]

\[ E_{ECL}: \text{residual energy in calorimeter} \]

for signal: \( E_{ECL} \approx 0 \)

validate \( E_{ECL} \) simulation using

\[ B \rightarrow D^{*0}\nu \] control sample

![Diagram showing signal side signature](image)
B$\rightarrow\tau\nu_{\tau}$ - results

Visible products of $\tau$ decay

$h = \rho^\pm, \pi^\pm, (3\pi)^\pm, l = e^\pm, \mu^\pm$

81% of all modes

Hadronic tag

Find $17.2^{+5.3}_{-4.7}$ signal events from a fit to a sample of 54 events.

4.6$\sigma$ stat. significance $\Rightarrow$ 3.5$\sigma$ (syst. included)

FIRST EVIDENCE
B→τντ - results

N_{sig} = 154^{+36}_{-35} (stat) ^{+20}_{-22} (syst)
⇒ B(B→τν) = (1.65^{+0.38+0.35}_{-0.37-0.37}) \times 10^{-4}

Obtained Br(B^{-}→D^{*0}lν) = 6.0±0.2 (stat) %
B→τντ - results

Hadronic tag

**PRD**-RC 77, 011107 (2008)

- On-resonance Data
- total background prediction
- combinatorial background
- Signal MC (scaled to BF=3x10^{-2})

**Events/0.125 GeV**

Hadronic tag (383MBB) \( \mathcal{B}(B \to \tau \nu) = (1.8^{+0.9}_{-0.8} \pm 0.4 \pm 0.2) \times 10^{-2} \)

Semileptonic tag (459MBB) \( \mathcal{B}(B \to \tau \nu) = (1.7 \pm 0.8 \pm 0.2) \times 10^{-2} \)

Hadronic tag (449MBB) \( \mathcal{B}(B \to \tau \nu) = (1.79^{+0.56+0.46}_{-0.49-0.51}) \times 10^{-2} \)

Semileptonic tag (657MBB) \( \mathcal{B}(B \to \tau \nu) = (1.65^{+0.38+0.35}_{-0.37-0.37}) \times 10^{-2} \)
B → \tau \nu_\tau - results

Naïve world average
\[ Br(\tau \nu) = [1.73 \pm 0.35] \times 10^{-4} \]

Effect of Charged Higgs
\[ Br = Br_{SM} \times r_H, \]
\[ r_H = \left( 1 - \frac{m_\nu^2 \tan^2 \beta}{m_H^2} \frac{1}{1 + \epsilon_0 \tan \beta} \right)^2 \]
\[ \tan \beta = \frac{v_u}{v}, \quad \text{SUSY Loop correction} \]
\[ \epsilon_0 = 0 \quad \text{for Type-II 2HDM} \]

\[ Br_{SM}(\tau \nu) = [1.20 \pm 0.25] \times 10^{-4} \]

Based on \( f_B \) from HPQCD and |\( V_{ub} \)| from HFAG (BLNP, ICHEP08)

Constraint on charged Higgs

Type-II 2HDM

95%CL excluded
$B \rightarrow \tau \nu \tau$ - results

Naïve world average

$\text{Br}(\tau \nu) = [1.73 \pm 0.35] \times 10^{-4}$

$\text{Br}(\tau \nu)_{\text{CKM fit}} = [0.786^{+0.179}_{-0.083}] \times 10^{-4}$

Output of a CKM fit without including $B \rightarrow \tau \nu \tau$ in the fit (CKM fitter, Beauty 09)

The measured Br is 2.4 $\sigma$ higher than the value predicted by the CKM fit.
Alternative theory uncertainties:

- free from $f_B$, depends on the $B \rightarrow D^{(*)}\tau\nu_\tau$ formfactors;
- $|V_{cb}|$ cancels out in the ratio $R = \text{BF}(B \rightarrow D\tau\nu_\tau)/\text{BF}(B \rightarrow D\nu_j)$

3-body decay $\Rightarrow$ more observables;
- $q^2$-distribution, $\tau$ polarization, $D^*$ polarization; possible $\mathcal{O}(1)$ effects from NP

inclusive $\text{BF}(b \rightarrow c\tau\nu_\tau) = (2.48 \pm 0.26)\%$ from LEP


Universality between: H-b-u vertex measured in $B \rightarrow \tau\nu_\tau$
- H-b-c vertex measured in $B \rightarrow D\tau\nu_\tau$
- H-b-t vertex measured in direct production by LHC.
$B \to D^{(*)}\tau^+\nu_\tau$

**Reconstruct $B_{tag}$ inclusively**

$$\Delta E_{tag} = \Sigma E_i - E_{beam}$$

$$M_{tag} = \sqrt{E_{beam}^2 - (\Sigma p_i)^2}$$

**Control sample:**

$B^0_{sig} \to D^-\pi^+$

**Verify $B_{tag}$ reconstruction**

**Clean signature:**

$D^-\ell^+ + p_{mis}$

**Apply all the tag-side selection criteria**

**Signal MC**

**Data**

**MC**
\[ B^0 \rightarrow D^*-\tau^+\nu_\tau \] - analysis

**Background suppression**

\[ \tau \rightarrow e\nu\nu \quad (3\nu) \]

Exploit signal-side variables:

- Visible energy: \( E_{\text{vis}} < 8.3 \) GeV
- Missing mass: \( M^2_{\text{M}} \equiv (E_{\text{mis}} - (p_{\text{D}} + p_{e/\pi})/|p_B|)^2 \)
- Virtual W mass: \( M^2_{\text{W}} \equiv (E_{\text{b}} - E_{\text{D}})^2 - (p_{\text{sig}} - p_{\text{D}})^2 \)

\[ E_{\text{mis}} \equiv E_{\text{beam}} - E_{\text{D}} - E_e : 1.9 < E_{\text{mis}} < 2.6 \text{ GeV} \]
**B^0 \rightarrow D^{*-} \tau^+ \nu_\tau - results**

**SIGNAL YIELD** \( N_s = 60^{+12}_{-11} \text{ 6.7}\sigma \) (5.2\sigma with syst.)

from a combined maximum likelihood fit (with a single BF) to 3 \( M_{\text{tag}} \) distributions

**FIRST OBSERVATION**

\[ BF(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau) = (2.02^{+0.40}_{-0.37} \text{ (stat)} \pm 0.37 \text{ (syst)}) \times 10^{-2} \]

**CROSS-CHECKS**

- **Combined Data**
  - Combinatorial background
  - Peaking background (\( D^{*-}\text{eV} \))

- **M^2_{\text{mis}}**
  - **DATA**
    - Signal
    - Background
  - **MC**

PRL 99, 191807 (2007)
B^+ \rightarrow D^{(*)0} \tau^+ \nu_\tau

Extension of the same analysis for B^+ decays.

• D^{*0} \rightarrow D^0 cross-feeds ⇒ simultaneous extraction of signals in B^+ \rightarrow D^{*0} \tau^+ \nu_\tau and B^+ \rightarrow D^0 \tau^+ \nu_\tau;

• signal extraction from UML fit to 2 observable M_{tag} and P_{D^0} (P_{D^0} = momentum of \bar{D}^0 in \gamma(4S) rest frame);

• simultaneous fit to 13 decay chains with floating 2 signal BF’s and 13 background normalizations;

Signal sub-decay modes:

D^{*0} \rightarrow \bar{D}^0 \pi^0
τ \rightarrow e\nu\nu, \quad \bar{D}^0 \rightarrow K^+\pi^-
τ \rightarrow e\nu\nu, \quad \bar{D}^0 \rightarrow K^+\pi^-\pi^0
τ \rightarrow \pi\nu, \quad \bar{D}^0 \rightarrow K^+\pi^-
τ \rightarrow \mu\nu\nu, \quad \bar{D}^0 \rightarrow K^+\pi^-
τ \rightarrow \mu\nu\nu, \quad \bar{D}^0 \rightarrow K^+\pi^-\pi^0
$B^+ \rightarrow D^{(*)0} \tau^+ \nu_{\tau}$ - analysis

Fit scale factors for the background components:

- $B \rightarrow D^* l \nu$,
- $B \rightarrow D l \nu$,
- $B \rightarrow D^{**} l \nu$,
- other $B$ decays,
- $c\bar{c}$-continuum,
- $u\bar{d} \bar{d}$-continuum

using experimental distributions in sidebands

- **background calibration**

![Diagrams and histograms showing analysis of $B^+ \rightarrow D^{(*)0} \tau^+ \nu_{\tau}$](image)

- $\Delta E_{\text{tag}}$ vs $R2$
- $E_{\text{vis}}$ vs $\Delta E_{\text{miss}}$
- $M_{\text{tag}}$ vs $5.27$

III III III

- III combinatorial bggr.
- enhanced hadronic
- $B$ decays

II

- II semileptonic,
- enhanced $B \rightarrow D^{**} l \nu$

I

- I $B \rightarrow D^{(*)} l \nu$
- dominate
B⁺ → D(⁎)⁰τ⁺ντ - results

N(\overline{D}⁰τ⁺ντ) = 446^{58}_{-56} \ 8.1\sigma

BF(B⁺ → \overline{D}⁰τ⁺ντ) = (2.12^{+0.28}_{-0.27} \pm 0.29) \times 10^{-2}

N(\overline{D}⁰τ⁺ντ) - 146^{+42}_{-41} \ 3.5\sigma \ \text{first evidence}

BF(B⁺ → D⁰τ⁺ντ) = (0.77^{+0.22}_{-0.22} \pm 0.12) \times 10^{-2}
$B^+ \rightarrow D^{(*)0} \tau^+ \nu_\tau$

- 238M $B\bar{B}$
- Hadronic tags.
- Signal characterized by large $MM^2$.
- Simultaneous extraction of $D\tau\nu/D^{*}\tau\nu$.
- Also measure decay distributions for the first time.

<table>
<thead>
<tr>
<th></th>
<th>$R(%)$</th>
<th>$N_s$</th>
<th>Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \tau\nu$</td>
<td>$31.4\pm17.0\pm4.9$</td>
<td>$35.6\pm19.4$</td>
<td>1.8(1.8)</td>
</tr>
<tr>
<td>$D^+ \tau\nu$</td>
<td>$48.9\pm16.5\pm6.9$</td>
<td>$23.3\pm7.8$</td>
<td>3.3(3.6)</td>
</tr>
<tr>
<td>$D^{*0} \tau\nu$</td>
<td>$34.6\pm7.3\pm3.4$</td>
<td>$92.2\pm19.6$</td>
<td>5.3(5.8)</td>
</tr>
<tr>
<td>$D^{*+} \tau\nu$</td>
<td>$20.7\pm9.5\pm0.8$</td>
<td>$15.5\pm7.2$</td>
<td>2.7(2.7)</td>
</tr>
<tr>
<td>$D^0 \tau\nu + D^+ \tau\nu$</td>
<td>3.6 (4.9) $\sigma$</td>
<td></td>
<td></td>
</tr>
</tbody>
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\[ B^+ \rightarrow D^{(*)0} \tau^+ \nu_\tau \]

- 238M $\overline{B}B$
- Hadronic tags.
- Signal characterized by large $\text{MM}^2$.
- Simultaneous extraction of $D\tau\nu/D^{*}\tau\nu$.
- Also measure decay distributions for the first time.

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</tr>
<tr>
<td>$D^{*+} \tau \nu$</td>
<td>$20.7 \pm 9.5 \pm 0.8$</td>
</tr>
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$D^0 \tau \nu + D^+ \tau \nu$: 3.6 (4.9) $\sigma$
$B^+ \rightarrow D^{(*)0} \tau^+ \nu_\tau$

$B(B \rightarrow D\tau^+ \nu) = (0.86 \pm 0.24 \pm 0.11 \pm 0.06)\% \ (3.6\sigma)$

$B(B \rightarrow D^*\tau^+ \nu) = (1.62 \pm 0.31 \pm 0.10 \pm 0.05)\% \ (6.2\sigma)$

First measurement of kinematic distributions: $q^2, |\mathbf{p}_\ell^*|$
$B^+ \rightarrow D^{(*)0} \tau^+ \nu_\tau$

- 657M $B\bar{B}$
- Hadronic tags.
- Extract signals in $(MM^2, E_{ECL})$ distribution.
- Simultaneous extraction of $D_{\tau\nu}/D^{*\tau\nu}$.

<table>
<thead>
<tr>
<th>$D^{0} \tau \nu$</th>
<th>$D^{+} \tau \nu$</th>
<th>$D^{*0} \tau \nu$</th>
<th>$D^{*+} \tau \nu$</th>
</tr>
</thead>
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<tr>
<td>$R(%)$</td>
<td>$Ns$</td>
<td>Signif.</td>
<td></td>
</tr>
<tr>
<td>70.2</td>
<td>98.6</td>
<td>3.8(4.4)</td>
<td></td>
</tr>
<tr>
<td>$18.9$</td>
<td>$+21.6$</td>
<td>$10.6$</td>
<td></td>
</tr>
<tr>
<td>$-18.0$</td>
<td>$-19.3$</td>
<td>$-10.2$</td>
<td></td>
</tr>
<tr>
<td>$+11.0$</td>
<td>$+6.3$</td>
<td>$+6.2$</td>
<td></td>
</tr>
<tr>
<td>$-9.1$</td>
<td>$-5.4$</td>
<td>$-7.2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$98.6$</td>
<td>$99.8$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$+26.3$</td>
<td>$+22.2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$-25.0$</td>
<td>$-22.3$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$3.8$</td>
<td>$3.9$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$4.4$</td>
<td>$5.2$</td>
<td></td>
</tr>
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$B^0 \rightarrow D^- \tau^+ \nu$
**Summary of $B^+ \rightarrow D^{(*)0}\tau^+\nu_{\tau}$**

Overlap between "inclusive" and "exclusive" $B_{\text{tag}}$ reconstruction Belle analysis is negligible (~0.2%)

```
syst. stat.
```

- "inclusive" $B_{\text{tag}}$ reconstruction
- "exclusive" $B_{\text{tag}}$ reconstruction

Belle preliminary 0910.4301[hep-ex] $B^* \rightarrow D^{*+}\tau^+\nu_{\tau}$

Belle 1005.2302[hep-ex] $B^* \rightarrow D^{0*}\tau^+\nu_{\tau}$ and PRL 99,191807(2007) $B^0 \rightarrow D^*\tau^+\nu_{\tau}$

Babar PRL 100,02180(2008)

Babar PRL 0901.4301[hep-ex] $B^+ \rightarrow D^{*+}\tau^+\nu_{\tau}$

Rich program of $B \rightarrow E_{\text{mis}}$ studies is being pursued in B-factories

- Measurements of (semi)tauonic-B decays are now well established and provide constraints on charged Higgs sector that are competitive with direct searches;
- High luminosity B-factories made possible studies of B meson decays to final states with $\tau$-leptons;
- Measured BF’s are consistent within experimental uncertainties with expectations of the SM but:
  
  \[
  \begin{align*}
  \text{large BF}(B \rightarrow \tau \nu) \\
  \text{large BF}(B \rightarrow D^* \tau \nu)
  \end{align*}
  \]

Looking forward for the Belle results with full data sample of 772 M $B\bar{B}$, it has been reprocessed with much improved charged particle tracking.

and to Super B-factories
BACKUP
Semileptonic vs purely leptonic

$B^{+/0} \rightarrow D^{(*)-\tau^+}\nu_\tau$

$B \rightarrow D^{(*)+}\tau^+\nu_\tau$ has more observables ($\tau$ and $D^*$ polarizations) than $B^+ \rightarrow \tau^+\nu_\tau$ decay

$B \rightarrow DT^+\nu_\tau$ are more sensitive to $H^+$ contribution but experimentally more challenging than $B^0 \rightarrow D^{*-\tau^+}\nu_\tau$ modes

$B^0 \rightarrow D^{*-\tau^+}\nu_\tau$ with longitudinally polarized $D^*$ are also sensitive to new physics

$B^0 \rightarrow D^{*-\tau^+}\nu_\tau$ are the main background for $B \rightarrow DT^+\nu_\tau$

$H_{bc}$ and $H_{bu}$ vertices complementary with $H_{tb}$ searches at LHC
Selection Criteria

- Optimized to maximize \( \text{FoM} = \frac{N_{\text{sig}}}{\sqrt{N_{\text{sig}} + N_{\text{BG}}}} \) in \( E_{\text{ECL}} < 0.2 \text{ GeV} \)
  - separately for \( \tau \rightarrow l\nu\nu \) and \( \pi \nu \) modes
- **Blind analysis**: \( E_{\text{ECL}} < 0.4 \text{ GeV} \) is masked until selection criteria are finalized

**Tagging side**
- Identified using a kinematic relation

\[
\cos \theta_{\text{BD}} = \frac{2E_B E_D \cos \theta - M_B^2 - M_D^2}{2P_B P_D \cos \theta}
\]

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

8/1 2008
34th International Conference on Higgs
$B^+ \rightarrow D^{(*)0} \tau^+ \nu_\tau$ Background

$B^+ \rightarrow \bar{D}^0 \tau^+ \nu_\tau$

$\tau \rightarrow e\nu\nu$

$\tau \rightarrow \mu\nu\nu$

$\tau \rightarrow \pi\nu$

$E_{vis}$

$\Delta E_{tag}$

$R_2$