$B$ decays to $\tau$ leptons at Belle

$B \rightarrow \tau \nu / D \tau \nu$

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Tau 2010 @ Manchester
Take Outline

• Introduction
• Purely leptonic decay $B \rightarrow \tau \nu$
• Semileptonic decay $B \rightarrow D^{(*)} \tau \nu$
• Prospects
• Summary

$\tau$ as a probe to New Physics in $B$ decays.
Charged Higgs in $b \to \tau$

- Extensions of the SM, which require $>2$ Higgs doublets, generate new flavor-changing interactions at tree-level via exchange of a charged Higgs.

- The $H^+$ coupling is proportional to the fermion mass, and it is natural to look at (semi-)leptonic $B$ decays into a $\tau$ in the final state.

\[
\mathcal{H}^{\text{eff}} = 2\sqrt{2} G_F V_{qb} \left\{ (\bar{b}_L \gamma^\mu q_L) (\bar{\nu}_L \gamma_\mu \tau_L) - \frac{m_b m_\tau}{m_B^2} g_S (\bar{b}_R q_L) (\bar{\nu}_L \tau_R) \right\};
\]

Effective scalar coupling:

\[
g_S = \frac{M_H^2 \tan^2 \beta}{M_H^2} \frac{1}{(1 + \epsilon_0 \tan \beta)(1 + \epsilon_\tau \tan \beta)},
\]

SUSY Loop correction $\epsilon_0 = \epsilon_\tau = 0$ in Type-II 2HDM
Within SM, proceed via W annihilation.

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

From \( f_B |V_{ub}| \)

\[
f_B = 190 \pm 13 \text{ MeV} \quad \text{HPQCD, 0902.1815v2}
\]

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

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

From CKM fit (w/o \( B \to \tau\nu \) in the input)

\[
Br_{CKM \, fit}^{\tau\nu} = (0.763^{+0.113}_{-0.061}) \times 10^{-4} \quad \text{CKM fitter @ ICHEP2010}
\]

\[
Br_{CKM \, fit}^{\tau\nu} = (0.805 \pm 0.071) \times 10^{-4} \quad \text{UT fit @ ICHEP2010}
\]
Charged Higgs exchange interferes with the helicity suppressed $W$-exchange.

The $Br$ becomes larger or smaller:

$$Br = Br_{SM} \times r_H, \quad r_H = \left| 1 - g_s \right|^2$$

Type-II 2HDM

$$Br = Br_{SM} \times r_H, \quad r_H = \left( 1 - \frac{m_B^2}{m_H^2} \tan^2 \beta \right)^2$$

If $\mu$ is also measured, lepton universality can be tested.

$\rightarrow$ SUSY correction etc.
Analysis for $B \to \tau \nu$

Tagging side:
- Hadronic tags: $B_{\text{tag}} \to D^{(*)}\pi/\rho$ etc.
- Semileptonic tags: $B_{\text{tag}} \to D^{(*)}l\nu$ etc.
- Inclusive tags: Used for Belle $B \to D^{*}\tau\nu$

Signal side: $B_{\text{sig}} \to l \nu$
- Detect charged track(s)
- Missing energy due to $\nu$'s
- No extra activities in EM calorimeter ($E_{\text{ECL(extra)}}$)

S/N

Eff

$\Upsilon$(4S)

$e^+$ $\ell^+$

$e^-$ $\nu$

$\pi$

$K$

$\bar{\nu}$

$\ell^-$

Arbitrary Unit

MC expectation

BG

signal (Br=1.79x10^{-4})
Belle $B \to \tau\nu$ w/ Hadronic Tag

449M $\bar{B}B$

PRL 97, 251802 (2006)

$B_{\text{tag}}$ reconstruction:

\[ B^+ \to \bar{D}^{(*)0} + \pi^+ / \rho^+ / a_1^+ / D_s^{(*)+} \]

\[ \to \bar{D}^0 \pi^0 / \bar{D}^0 \gamma \quad \to D_s^+ \gamma \]

\[ M_{bc} = \sqrt{E_{\text{beam}}^2 - (\sum_i \bar{p}_i)^2} \]

\[ \Delta E = \sum_i E_i - E_{\text{beam}} \]

Signal region: $-0.08 < \Delta E < 0.06$ GeV, $M_{bc} > 5.27$ GeV/c$^2$

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

\[ N_S = 24.1^{+7.6}_{-6.6} \text{ (stat)}^{+5.5}_{-6.3} \text{ (syst)} \]

in all $E_{\text{ECL}}$ region.

3.5$\sigma$ (incl. syst.)

First evidence!
Candidate Event

\[ B^+ \rightarrow \overline{D^0} \pi^+ \]
\[ \downarrow K^+ \pi^- \pi^+ \pi^- \]
\[ B^- \rightarrow \tau^- \nu \]
\[ \downarrow e^- \nu \nu \]
Belle $B \rightarrow \tau \nu$ w/ Semileptonic Tag

**657M $B\bar{B}$**

submitted to PRD-RC, arXiv:1006.4201

$B_{\text{tag}}$ reconstruction

$B^+ \rightarrow D^{*0|\pi^0} + \nu, \ D^0|\nu$

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

$D^0 \rightarrow K^- \pi^+, \ K^- \pi^+ \pi^- \pi^+, \ K^- \pi^+ \pi^0$

$\cos \theta_{B, D(*)} = \frac{2E_{\text{beam}} E_{D(*)} - m_B^2 - M_{D(*)}^2}{2P_B E_{D(*)}}$

$P_B = \sqrt{(E_{\text{beam}})^2 - m_B^2}$

$\text{Br}(\tau \nu) = [1.54^{+0.38}_{-0.37}^{+0.29}_{-0.31}] \times 10^{-4}$

$N_S = 143^{+36}_{-35} \text{ (stat)}$

$3.6 \sigma \text{ (incl. syst.)}$

$f_B |V_{ub}| = (9.3^{+1.2}_{-1.1} \pm 0.9) \times 10^{-4} \text{ GeV}$

MC w/o $D(*) \rightarrow \nu$ decays.
**Constraint on Charged Higgs**

K. Trabelsi @ ICHEP2010

**Belle**
- Hadronic tag (449MBB):
  \[ \text{Br}(\tau\nu) = [1.79^{+0.56+0.46}_{-0.49-0.51}] \times 10^{-4} \]
- Semileptonic tag (657MBB):
  \[ \text{Br}(\tau\nu) = [1.54^{+0.38+0.29}_{-0.37-0.31}] \times 10^{-4} \]

**BaBar**
- Hadronic tag:
  \[ \text{Br}(\tau\nu) = [1.80^{+0.57}_{-0.54} \pm 0.26] \times 10^{-4} \]
- Semileptonic tag:
  \[ \text{Br}(\tau\nu) = [1.70 \pm 0.87 \pm 0.20] \times 10^{-4} \]

**Effect of Charged Higgs (Type-II 2HDM)**


\[ Br = Br_{SM} \times \left( 1 - \frac{m_B^2 \tan \beta^2}{m_H^2} \right)^2 \]
Comparison to CKM fit

\[ Br(\tau\nu) = [1.68 \pm 0.31] \times 10^{-4} \]

The measured \( Br \) is \( \sim 2.8 \sigma \) higher than the value predicted by the CKM fit.
$B \rightarrow D \tau \nu$ is another process sensitive to the charged Higgs, and complementary to $B \rightarrow \tau \nu$.

- Relatively large $\text{Br} \sim 0.8\%$
- Different theory systematics:
  - free from $V_{ub}$ and $f_B$ ambiguity.
  - depends on the $B \rightarrow D$ form factors, which can be deduced from $D \tau \nu$ data.

- Three-body decay permits the study of decay distributions which discriminate between $W^+$ and $H^+$ exchange. Also $T$ polarization in $\tau \rightarrow \pi \nu$ mode.
- Universality between $H-b-c$, $(D\tau \nu)$, $H-b-u$ $(\tau \nu)$, $H-b-t$ (LHC).
Belle $B \rightarrow D^{(*)} \tau \nu$

- Inclusive $B_{\text{tag}}$ reconstruction.
  - Calculate $B_{\text{tag}}$ mass using 4 momentum vector of the tracks other than $D^*$ and ($e$, $\mu$, $\pi$).

$$M_{\text{tag}} = \sqrt{E_{\text{beam}}^2 - \left(\sum_{i \notin \text{sig}} p_i\right)^2}$$

- Background suppression
  - Visible energy
  - $X_{\text{mis}}$
    $$X_{\text{mis}} = \frac{E_{\text{mis}} - |\vec{p}_{D^*} + \vec{p}_{\ell/\pi}|}{|\vec{p}_B|}$$
    similar to $M_{\text{mis}}$ but $M_{\text{tag}}$ independent.
Belle $B \rightarrow D^{*-} \tau \nu$ (2007)

$$\text{Br}(B^0 \rightarrow D^{*-} \tau^+ \nu_{\tau}) = (2.02^{+0.40}_{-0.37} \pm 0.37) \times 10^{-2}$$

$N_S = 60^{+12}_{-11}$

$6.7\sigma$ ($5.2\sigma$ w/ systematic)

First Observation
Simultaneous extraction of signals in $B^+ \rightarrow D^{*0} \tau^+ \nu$ and $B^+ \rightarrow D^{0+} \tau^+ \nu$ taking into account $D^{*0} \leftrightarrow D^0$ cross-feeds.

Signal extraction from fit to 2-dim distributions in $M_{tag}$ and $P_{D^0}$ (momentum of $D^0$ in $Y(4S)$ rest frame).

Simultaneous fit to 13 decay chains with floating 2 signal BFs and 13 background normalizations.

Based on 675M $B\overline{B}$

hep-ex/1005.2302, submitted to PRL
**B → D \( \tau \nu \)** w/ Hadronic Tag

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

\[ R = \frac{Br(B \rightarrow D^{(*)}\tau\nu)}{Br(B \rightarrow D^{(*)}\ell\nu)} \]

<table>
<thead>
<tr>
<th></th>
<th>(R(%))</th>
<th>Ns</th>
<th>Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D^0\tau\nu)</td>
<td>70.2</td>
<td>98.6</td>
<td>3.8(4.4)</td>
</tr>
<tr>
<td>(D^+\tau\nu)</td>
<td>47.6</td>
<td>17.2</td>
<td>2.6(2.8)</td>
</tr>
<tr>
<td>(D^{*0}\tau\nu)</td>
<td>46.8</td>
<td>99.8</td>
<td>3.9(5.2)</td>
</tr>
<tr>
<td>(D^{*+}\tau\nu)</td>
<td>48.1</td>
<td>25.0</td>
<td>4.7(5.9)</td>
</tr>
</tbody>
</table>

**Belle preliminary**

**hep-ex/0910.4301**
B → D(*) τ ν Summary

- **Belle inclusive tag**
- **hadronic tag**

**Summary**

- **Belle**
  - \( B^+ \rightarrow \bar{D}^{*0} \tau^+ \nu \)
  - \( B^0 \rightarrow \bar{D}^{-} \tau^+ \nu \)
  - \( B^0 \rightarrow \bar{D}^{-} \tau^+ \nu \)

**BaBar hadronic tag**

**C.-H. Chen and C.-Q. Geng**

**JHEP 0610, 053 (2006)**

**Belle inclusive tag**

**PRL99, 191807 (2007)**

**arXiv:1005.2302**

**Belle hadronic tag**

**arXiv:0910.4301**

**BaBar hadronic tag**

**PRL100, 021801 (2008)**
experimental bounds on $\tan \beta / m_H$ in type-II 2HDM from averaged Belle and BaBar measurements\textsuperscript{10} of $R = \frac{B(B \to D\tau\nu_\tau)}{B(B \to D\ell\nu_\ell)} = 0.40 \pm 0.08$
Prospect

• Results using the full data set (~770MB\(\bar{B}\))
  - Present results: w/ 449M \(\bar{B}\) for hadronic tag
    w/ 657M \(\bar{B}\) for semileptonic tag
  - Reprocessed with improved tracking efficiency

• Improvement for the hadronic tag
  effective luminosity improved by factor x2
Prospect at Super-KEKB / Belle II

- $7\text{GeV} \ e^- \times 4 \text{GeV} \ e^+$
- $L_{\text{peak}} = 8 \times 10^{35}\text{cm}^{-2}\text{s}^{-1}$
- $L_{\text{int}} = 50\text{ab}^{-1}$

Assume $\Delta_{\text{exp}} \sim 1/\sqrt{L}$, $\Delta |V_{ub}| = \Delta f_B = 2.5\%$

KEKB upgrade has been approved.
- 5.8 oku yen (MUSD) for damping ring (FY2010)
- 100 oku yen for machine.

“Very Advanced Research Support Program” (FY2010-2012)

Construction started!
Summary

B decays to the $\tau$ lepton final states, $B \rightarrow \tau \nu$ and $B \rightarrow D \tau \nu$, are unique probe to New Physics.

Belle has measured both $B \rightarrow \tau \nu$ and $B \rightarrow D \tau \nu$ decays.
- $B \rightarrow \tau \nu$ w/ hadronic and semileptonic tags.
- $B \rightarrow D \tau \nu$ w/ inclusive and hadronic tags.

Significant constraints on the charged Higgs.

Results using the full data set and improved tagging efficiency will come in the near future.

Super-KEKB/Belle II will provide results with a few percent error, and will provide stringent test of NP.

Thank you!
Backup
Cont’d

\[
B(B \to D\tau\nu) \propto |V_{cb}|^2 \cdot f(F_V, F_S, g_S)
\]

Effective scalar coupling:

\[
g_S = \frac{M_B^2 \tan^2 \beta}{M_H^2} \frac{1}{(1 + \varepsilon_0 \tan \beta)(1 + \varepsilon_\tau \tan \beta)},
\]

SUSY Loop correction \((\varepsilon_0 = \varepsilon_\tau = 0 \text{ in Type-II 2HDM})\)

\[
\frac{d\Gamma(B \to D\tau\nu)}{dw} \propto |V_{cb}|^2 \left\{ (w^2 - 1) F_V(w)^2 \rho_V(w) + F_S(w)^2 \left[ 1 - g_S \frac{q^2/m_B^2}{1 - m_c/m_b} \right]^2 \rho_S(w) \right\}
\]

\[
d\Gamma(B \to D\tau\nu)/dw = \frac{d\Gamma(B \to D\nu_T [\to \pi\nu])}{dE_\pi d\cos \theta_{D\pi}} dw
\]

\[w = \frac{E_D}{m_D} = \frac{m_B^2 + m_D^2 - q^2}{2m_B m_D}\]

\[E_\pi = 1.8 \text{ GeV}\]

\[\cos \theta_{D\pi} = -1\]