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

$B$ DECAYS TO $\tau$ LEPTONS

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Talk Outline

- Introduction
- Purely leptonic decay $B \rightarrow \tau \nu$
- Semileptonic decay $B \rightarrow D(\ast) \tau \nu$
- Future Prospect
- Summary

Special thanks to Dr. Y. Horii (cf. his talk at Beauty2013)

$B \rightarrow \tau \nu \ / \ B \rightarrow D(\ast) \tau \nu$

Sensitive for NP ($H^+, \ldots$)

Key flavor physics observables in the LHC era!
$B^- \to \tau^- \nu$ in SM

- Proceed via W-exchange, helicity suppressed.

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

- Parameters
  - B decay constant: \( f_B = 191 \pm 9 \) MeV
    - HPQCD, PRD86
  - CKM matrix: \( |V_{ub}| = (4.15 \pm 0.49) \times 10^{-3} \)
    - \( b \to u \ell \nu \), PRD86

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

Can be obtained also from a global CKM fit
Charged Higgs Effect in $B \rightarrow \tau \nu$

- Charged Higgs exchange interferes with the helicity suppressed W-exchange.

\[ \frac{B r}{r_H} = \frac{B r_{SM} \times r_H}{1 - g_S} \]

- Example of Br modification

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

Type II 2HDM, W. S. Hou, PRD 48, 2342 (1993),

\[ \frac{B r}{r_H} = \frac{B r_{SM} \times r_H}{1 - g_S} \]
Analysis for $B \to \tau \nu$

**Tagging side:**

- **Hadronic tags**
  \[ B_{\text{tag}} \to D^{(*)}\pi/\rho \text{ etc.} \]

- **Semileptonic tags**
  \[ B_{\text{tag}} \to D^{(*)}\ell \nu \text{ etc.} \]

- **Inclusive tags**
  Used for Belle $B \to D^{*}\tau \nu$

**Signal side:**

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

**Graph:**

- **Semileptonic tag**
  - MC expectation
  - BG

- **Signal** (Br=$1.79 \times 10^{-4}$)
Status for $B \to \tau \nu$ before ICHEP 2012

\[ B = [1.79^{+0.56}_{-0.49} \text{(stat)}^{+0.46}_{-0.51} \text{(syst)}] \times 10^{-4} \]
\[ B = [1.80^{+0.57}_{-0.54} \text{(stat)} \pm 0.26 \text{(syst)}] \times 10^{-4} \]
\[ B = [1.54^{+0.38}_{-0.37} \text{(stat)}^{+0.29}_{-0.31} \text{(syst)}] \times 10^{-4} \]
\[ B = [1.7 \pm 0.8 \text{(stat)} \pm 0.2 \text{(syst)}] \times 10^{-4} \]

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

Relation with $\sin 2\Phi_1$. Tension (2.8σ) with CKM fit prediction.
**B → τ ν by Semileptonic Tag**

**Belle**
- PRD 82, 071101(R) (2010).
- Use 657 M BB.
- B=[1.54$^{+0.38}_{-0.37}$]$^{+0.29}_{-0.31}$]$\times10^{-4}$.

**BaBar**
- PRD 81, 051101(R) (2010).
- Use 459 M BB.
- B=[1.7±0.8±0.2]$\times10^{-4}$.

(Counting method employed.)
Belle at ICHEP2012

(w.r.t. Belle2006)

- Use 772M BB (full) data $\times 1.7$
- Improved tracking eff. by reprocessing data
- Improved hadronic tags $\times 2.2$
  (NueroBayes algorithm)
- Improved signal selection efficiency $\times 1.8$
  (in trade of S/N)
- Newly added $K_L$ veto
- Better understanding of peaking background
- 2D fit in $(E_{ECL}, M_{miss}^2)$ for signal extraction

$Br(B \rightarrow \tau \nu) = [0.72^{+0.27}_{-0.25} \pm 0.11] \times 10^{-4}$

Published in PRL110, 131801 (2013)!
\( B \to \tau \, \nu \) by Hadronic Tag at Belle, Mode Independence

As a check, we fit by floating the yields for different \( \tau \) modes.

\( \tau \to e \nu \nu \), \( \tau \to \mu \nu \nu \), \( \tau \to \pi \nu \) cross-feeds in \( \tau \to \pi \nu \) candidates as signal.

Rare unobserved BG decays (e.g. \( B \to \mu \nu \gamma \)) would show up in individual signal modes.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Number of signal</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e^- \bar{\nu}<em>e \nu</em>\tau )</td>
<td>( 15.5^{+11.2}_{-9.4} )</td>
<td>( 2.98 \times 10^{-4} )</td>
</tr>
<tr>
<td>( \mu^- \bar{\nu}<em>\mu \nu</em>\tau )</td>
<td>( 25.6^{+15.1}_{-13.8} )</td>
<td>( 3.12 \times 10^{-4} )</td>
</tr>
<tr>
<td>( \pi^- \nu_\tau )</td>
<td>( 7.8^{+9.5}_{-7.9} )</td>
<td>( 1.76 \times 10^{-4} )</td>
</tr>
<tr>
<td>( \rho^- \nu_\tau )</td>
<td>( 13.6^{+18.7}_{-16.1} )</td>
<td>( 3.37 \times 10^{-4} )</td>
</tr>
</tbody>
</table>

Consistent results.
BaBar at ICHEP2012

- Use 468M BB (full) data sample
- Use four $\tau$ decay channels
  - $e\nu\nu$, $\mu\nu\nu$, $\pi\nu$, $\rho\nu$
- Expanded set of hadronic tag modes
  - including $B \rightarrow J/\psi X$
  - $\sim x 2$ w.r.t. BaBar2008

$$Br(B \rightarrow \tau\nu) = [1.83 \pm 0.24] \times 10^{-4}$$
Status for $B \to \tau \nu$ after ICHEP 2012

Belle combined: $\mathcal{B} = (0.96 \pm 0.26) \times 10^{-4}$

BaBar combined: $\mathcal{B} = (1.79 \pm 0.48) \times 10^{-4}$

A naive world average: $\mathcal{B} = (1.15 \pm 0.23) \times 10^{-4}$

Tension weakened.
Constraint on Charged Higgs from $B \to \tau \, \nu$

- Assume Type-II 2HDM.

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

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

- Use
  - $B(B \to \tau \, \nu) = (1.15 \pm 0.23) \times 10^{-4}$
  - $B(B \to \tau \, \nu)_{\text{SM}} = (1.11 \pm 0.28) \times 10^{-4}$

where $B(B \to \tau \, \nu)_{\text{SM}}$ is obtained from

- $f_B = (191 \pm 9)$ MeV (HPQCD, PRD86)
- $|V_{ub}| = (4.15 \pm 0.49) \times 10^{-3}$ (PDG, PRD86)

Stringent constraint on $\tan \beta$ and $m_H$ obtained.

Note: constraint strongly depends on $f_B$ and $|V_{ub}|$. 
\[ \textbf{B} \rightarrow \textbf{D} \, \tau \, \nu \]

- \( \textbf{B} \rightarrow \textbf{D} \, \tau \, \nu \) is another process sensitive to the charged Higgs, and complementary to \( \textbf{B} \rightarrow \tau \, \nu \).
  - Relatively large \( \text{Br} \sim 0.8\% \)
  - Different theory systematics:
    - free from \( V_{ub} \) and \( f_B \) ambiguity.
    - depends on the \( \textbf{B} \rightarrow \textbf{D} \) form factors, which can be deduced from \( \textbf{D} \, \ell \, \nu \) data.
- \( |V_{cb}| \) and a part of QCD effects canceled by taking ratios.

\[
\mathcal{R}(D) = \frac{\mathcal{B}(\overline{B} \rightarrow D \tau^- \overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \rightarrow D \ell^- \overline{\nu}_\ell)}, \quad \mathcal{R}(D^*) = \frac{\mathcal{B}(\overline{B} \rightarrow D^* \tau^- \overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \rightarrow D^* \ell^- \overline{\nu}_\ell)}
\]

\( \text{B} \rightarrow \text{D} \ell \nu \) decay is measured precisely; \( \text{Br}(\text{B} \rightarrow \text{D}^0 \ell \nu) = (2.26 \pm 0.11)\% \)

- Possible observables additional to the ratios:
  - \( \tau \) polarization, \( D^* \) polarization, \( q^2 \) distribution, ...

M. Tanaka, R. Watanabe, PRD87, 034028 (2013)
B→D(*) τ ν from BaBar

- PRL 109, 101802 (2012).
- arXiv:1303.0571, submitted to PRD.
- Use 471 M BB (full data).
- Improved hadronic tag by more modes.
- Boosted decision tree for event selection.

- \( R(D) = \frac{B(D \tau \nu)}{B(Dl\nu)} = 0.440\pm0.058\pm0.042 \)
- \( R(D^*) = \frac{B(D^* \tau \nu)}{B(D^*l\nu)} = 0.332\pm0.024\pm0.018 \)
- Systematic uncertainties from D** BG, BG PDFs, BG yields, etc.
The possibility that the measured R(D) and R(D*) both agree with the SM predictions is excluded at the $3.4 \sigma$ level.

($\sigma$ for 1-D Gaussian function)
B→D(\(^(*)\)) \(\tau\) \(\nu\) from BaBar and Type-II 2HDM

Blue: this result, red: Type-II 2HDM.

The combination of R(D) and R(D\(^\ast\)) excludes the Type-II 2HDM at 99.8% C.L. for any value of tan \(\beta\) /m\(_{H}\).

Note: Type III and q\(^2\) spectra in arXiv:1303.0571.
B→D(*) τ ν from Belle

• Inclusive tags
  • B_{tag}'s are reconstructed by the four-vector sum of the tracks w/o recon. of the intermediate mesons.
  • PRL99, 191807 (2007), 535M BB
    • First observation of B^0 → D^* - τ^+ ν (5.2σ)
  • PRD82, 072005(2010), 657M BB

• Hadronic tags
  • Hep-ex/0910.4301, 657M BB, Preliminary
**B→D(∗) τ ν from Belle**

**A. Bozek’s averages (KEK-FF 2013):**

\[
\begin{align*}
R(D) &= 0.430 \pm 0.091 \\
R(D^*) &= 0.405 \pm 0.047
\end{align*}
\]

Deviation from SM

\[
\begin{align*}
1.4 \sigma \\
3.0 \sigma
\end{align*}
\]

Combined \(3.3 \sigma\)

**Constraint on Type-II 2HDM:**

Experimental \(R(D(∗))\) dependence on \(\tan β / m_H\) not considered. Experimental correlation between \(R(D)\) and \(R(D^*)\) not considered.

Correlation btw \(R(D)\) and \(R(D^*)\) neglected conservatively.

Y. Horii personal, private communication with Y. Sakaki, R. Watanabe, and M. Tanaka.
Prospect at Belle II

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

- $B \rightarrow \tau \nu$
  - Precision ~ a few %

- Need better precision for $f_B |V_{ub}|$.

- $B \rightarrow \mu \nu$, eν
  - $5\sigma$ observation expected for $B(B\rightarrow\mu \nu)_{\text{SM}}$ at ~10 ab⁻¹.
  - $O(10^{-8})$ sensitivity at 50 ab⁻¹.
  - Interesting to compare w/ $B\rightarrow\tau \nu$

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2-parameter nonuniversal Higgs model
H. Baer, V. Barger, and A. Mustafayev, PRD85, 075010

- $\mu > 0$, $m_h = 125\pm1\text{ GeV}$, $m_t = 173.3\text{ GeV}$
- WA (2007)
- Belle II (50 ab⁻¹)
- Charged Higgs constraint (Type-II 2HDM)

- $\Delta \exp \sim 1/\sqrt{L}$,
- $\Delta f_B |V_{ub}| = 4\%$

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- $\tan\beta$ vs. $H^+$ Mass (GeV/c²)
- $\mu > 0$, $m_h = 125\pm1\text{ GeV}$, $m_t = 173.3\text{ GeV}$
  - blue: $m_0 < 5\text{ TeV}$, orange: $m_0 < 20\text{ TeV}$
Request for theory

• It is of great importance to improve precision for the SM prediction;
  • $f_B |V_{ub}|$ for $B \to \tau \nu$
  • **Form factors** for $B \to D \tau \nu$

Present error
$\Delta f_B \sim 5\%$
$\Delta |V_{ub}| \sim 10\% + \text{incl. vs excl. saga}$

Recent Lattice QCD (FNAL/MILC)
Predicts $R(D)=0.316(12)(7)$
$\sim 1s$ higher than the previous estimates
Summary

• $B \to \tau \nu$ and $B \to D^{(*)} \tau \nu$ are powerful tools for both testing the SM and searching for NP (charged Higgs,…).

  *Key flavor physics observables in the LHC era!*

• Recent $B \to \tau \nu$ results have weakened the tension with CKM fit.

• Recent $B \to D^{(*)} \tau \nu$ results disfavor SM and type-II two Higgs doublet model at a level of $>3\sigma$.
  - Final result from Belle using full data coming soon.

• It is very important to measure $B \to \tau \nu / D^{*} \tau \nu$ with a few % precision.

  *Belle II will start physics run in 2016!*
Backup
Charged Higgs in $b \rightarrow \tau$

- 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;

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

SUSY Loop correction $\varepsilon_0 = \varepsilon_\tau = 0$ in Type-II 2HDM
Tag for $B \rightarrow \tau \nu$

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

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

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

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

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

- Modes: $B \rightarrow D^{(*)}\ell\nu$.
- Efficiency = ~1%.
- More background.
- $p_{B_{\text{sig}}}$ not determined.
Comparison for $B \rightarrow \tau \nu$ Using Hadronic Tag at Belle

- New analysis is based on improved tag, loose event selection, and reprocessed data.
- Most of the data after the selection are independent from old analysis.
- Assuming that all events in old analysis are included in new analysis, the remaining data sample in \( N_{BB} = 4.49 \times 10^8 \) provides \( BR \sim (0.6\pm0.4) \times 10^{-4} \) (1.9\( \sigma \) from old result).

<table>
<thead>
<tr>
<th>Tag</th>
<th>PRL 97 (2006)</th>
<th>This analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of $B \overline{B}$ events ($\times 10^8$)</td>
<td>4.49</td>
<td>4.49</td>
</tr>
<tr>
<td>Efficiency ($\times 10^{-4}$)</td>
<td>3.0</td>
<td>11.2</td>
</tr>
<tr>
<td>Signal yield</td>
<td>24.1$^{+7.6}_{-6.6}$</td>
<td>54.1$^{+18.8}_{-17.4}$</td>
</tr>
<tr>
<td>$\mathcal{B}(B^- \rightarrow \tau^- \overline{\nu}_\tau)$ ($\times 10^{-4}$)</td>
<td>1.79$^{+0.56}_{-0.49}$</td>
<td>1.08$^{+0.37}_{-0.35}$</td>
</tr>
</tbody>
</table>
$B^{\pm} \to D^{(*)} \tau \nu$ by Hadronic Tag from Belle

- Using 657 M BB.
- Simultaneous fit to both subsets.
- $D^{(*)}\ell\nu$ as control sample and normalization.
- Evidence for signals.
  
  \[
  R(D^0 \tau^- \bar{\nu}_\tau / D^0 l^- \bar{\nu}_\tau) = 0.70^{+0.19}_{-0.18} (\text{stat})^{+0.11}_{-0.09} (\text{syst}) \\
  3.8\sigma
  \]

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

  \[
  B(D^0 \tau^- \bar{\nu}_\tau) = [1.51^{+0.41}_{-0.39} (\text{stat})^{+0.24}_{-0.19} (\text{syst}) \pm 0.15 (\text{norm})] \%
  \]

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

Syst. from PDFs and cross-feeds.

BG: Dlν, D*lν, D**lν, DX, ...

arXiv:0910.4301
Summary for $B \to D^{(*)} \tau \nu$ from Belle

$B(D^{*0} \to \tau \bar{\nu}_\tau) = [2.12^{+0.28}_{-0.27}(\text{stat}) \pm 0.29(\text{syst})] \%$
$B(D^{*0} \to \tau \bar{\nu}_\tau) = [3.04^{+0.89}_{-0.66}(\text{stat})^{+0.40}_{-0.47}(\text{syst}) \pm 0.22(\text{norm})] \%$
$B(D^{*+} \to \tau \bar{\nu}_\tau) = [2.02^{+0.40}_{-0.37}(\text{stat}) \pm 0.37(\text{syst})] \%$
$B(D^{*+} \to \tau \bar{\nu}_\tau) = [2.56^{+0.75}_{-0.66}(\text{stat})^{+0.31}_{-0.22}(\text{syst}) \pm 0.10(\text{norm})] \%$


- Good agreement btw the results for inclusive and hadronic tags.
- Not significant but slightly larger than SM expectations.