B→τν and B→D(*)τν at Belle and BaBar

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B→τν in the Standard Model

• In the SM, annihilation process mediated by W±.

\[ B^- \rightarrow W^- \rightarrow \tau^- \bar{\nu}_\tau \]

• The branching ratio is calculated by

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

which is about \(1 \times 10^{-4}\) depending on \(f_B^2\) and \(|V_{ub}|\). “Helicity suppression”

• \(f_B\): B meson decay constant. \(f_B = (191 \pm 9)\) MeV [lattice, HPQCD, PRD86].

• \(V_{ub}\): CKM matrix element. \(|V_{ub}| = (4.15 \pm 0.49) \times 10^{-3}\) [\(b \rightarrow u\nu\), PDG, PRD86].

Both can also be obtained from a CKM global fit.
Possible Effect of $H^\pm$ for $B \to \tau \nu$

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

![Diagram of $B \to \tau \nu$](image)

- Example of modifications:

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

  where $r_H$ is a modification factor:

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

type II two Higgs doublet model (2HDM).

\[
 r_H = \left(1 - \frac{\tan^2 \beta}{1 + \tilde{\epsilon}_0 \tan \beta} \frac{m_B^2}{m_H^2}\right)^2
\]

A. G. Akeroyd and S. Recksiegel,
J. Phys. G 29, 2311 (2003),
higher order correction in SUSY models.
Methods for Analyzing $B \rightarrow \tau \nu$

Very challenging at hadron colliders due to multiple neutrinos. At the B factories, we tag one of the B mesons in $e^+e^- \rightarrow \Upsilon(4S) \rightarrow BB$.

$B_{\text{tag}}$ reconstructed from

- hadronic decays $B \rightarrow D^{(*)}\pi$, etc.,
- semileptonic decays $B \rightarrow D^{(*)}\nu \nu$.

$B_{\text{sig}}$ extracted by using

- extra energy ("$E_{\text{ECL}}$" or "$E_{\text{extra}}$"),
- missing mass squared ("$M_{\text{miss}}^2$").
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): $B = (1.67 \pm 0.30) \times 10^{-4}$

Tension (2.8$\sigma$) with CKM fit prediction.

Relation with $\sin 2\Phi_1$. Direct Meas. CKM fit
Updates on $B \rightarrow \tau \nu$ at ICHEP 2012

Belle

- Use 772 M BB (full data) with Had. tag.
- Tag improved, 2-D signal extraction.

\[ B = \left[ 0.72^{+0.27}_{-0.25} \pm 0.11 \right] \times 10^{-4}. \]

BaBar

- Use 468 M BB (full data) with Had. tag.

\[ B = \left[ 1.83^{+0.53}_{-0.49} \pm 0.24 \right] \times 10^{-4}. \]
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: $\mathcal{B} = (1.15 \pm 0.23) \times 10^{-4}$

$\mathcal{B} = [0.72^{+0.27}_{-0.25} \text{(stat)} \pm 0.11 \text{(syst)}] \times 10^{-4}$

$\mathcal{B} = [1.83^{+0.53}_{-0.49} \text{(stat)} \pm 0.24 \text{(syst)}] \times 10^{-4}$

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

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

Tension weakened.

Direct Meas.  CKM fit

Measurements
Constraint on Charged Higgs from $B \to \tau \nu$

- Assume **Type-II 2HDM**.

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

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

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

  where $B(B \to \tau \nu)_{SM}$ 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 $|V_{ub}|$.**
Introduction for $B \rightarrow D^{(*)} \tau \nu$

- Could be affected by charged Higgs in extended models.

- $|V_{cb}|$ and a part of QCD effects canceled by taking ratios.

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

$B \rightarrow D^{(*)} \tau \nu$ decays measured precisely, e.g. $\mathcal{B}(B^- \rightarrow D^0 \ell^- \nu) = (2.26 \pm 0.11)\%$.

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

K. Keirs and A. Soni, PRD 56, 5786 (1997), ...

M. Tanaka and R. Watanabe, PRD 87, 034028 (2013), ...
**B → D(∗)τν 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.

\[ R(D) = \frac{B(D\tau\nu)}{B(D\ell\nu)} = 0.440 \pm 0.058 \pm 0.042 \]

\[ R(D^*) = \frac{B(D^*\tau\nu)}{B(D^*\ell\nu)} = 0.332 \pm 0.024 \pm 0.018 \]

*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(*)_TV from BaBar and Type-II 2HDM

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

Exp. R(D(*)) dependency mainly from m_{miss}^2 dependency (reflection of q^2 dependency).

The combination of R(D) and R(D*) excludes the Type-II 2HDM at 99.8% C.L. for any value of tanβ/m_H.

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

A. Bozek’s averages shown at KEK-FF 2013:
(naive averages for inclusive and exclusive hadronic tags)

\[
R(D) = 0.430 \pm 0.091
\]

\[
R(D^*) = 0.405 \pm 0.047
\]

**SM deviations:**
- \(R(D): 1.4\sigma\)
- \(R(D^*): 3.0\sigma\)
- Combined: 3.3\sigma

Constraint on Type-II 2HDM:

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

Experimental \(R(D^*)\) dependence on \(\tan\beta/m_H\) not considered.
Experimental correlation between \(R(D)\) and \(R(D^*)\) not considered.
Comparison for $B \to \tau \nu$ and $B \to D^{(*)} \tau \nu$ Results

- Local minimum at about $\tan \beta/m_H = 0.5 \ [\text{GeV}^{-1}c^2]$ for $B \to D^{(*)} \tau \nu$ excluded by $B \to \tau \nu$ by $>5\sigma$.
- Stronger constraint may be obtained by combining all results.
- Should be careful: strong dependency on central values, correlations, ...
Summary

• $B \to \tau \nu$ and $B \to D^{(*)} \tau \nu$ interesting for a test of SM and a search for new physics.

• Recent $B \to \tau \nu$ results weaken the tension against CKM fit.

• Recent $B \to D^{(*)} \tau \nu$ results disfavor SM and type-II two Higgs doublet model by a level of $>3\sigma$.

• Final result from Belle using full data coming soon.

• Important to improve the precision at Belle II.
Backup slides
Tag for $B \to \tau \nu$

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

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

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

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

<table>
<thead>
<tr>
<th>Tag</th>
<th>PRL 97 (2006)</th>
<th>This analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of $B \bar{B}$ events ($\times 10^8$)</td>
<td>4.49</td>
<td>4.49, 3.22</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>$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau)$ ($\times 10^{-4}$)</td>
<td>$1.79^{+0.56}_{-0.49}$</td>
<td>$1.08^{+0.37}_{-0.35}$</td>
</tr>
</tbody>
</table>

- 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 $\mathcal{B} \sim (0.6\pm0.4) \times 10^{-4}$ ($1.9\sigma$ from old result).

![Graph showing BR(B to tau nu) versus NBB]

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**B → τν** by Hadronic Tag at Belle, Mode Independence

As a check, we fit by floating the yields for different $τ$ 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.

Rare unobserved BG decays (e.g. $B \rightarrow \mu\nu\gamma$) would show up in individual signal modes.
B → τν by Semileptonic Tag

**Belle**
- PRD 82, 071101(R) (2010).
- Use 657 M BB.
- $B = [1.54^{+0.38}_{-0.37}^{+0.29}_{-0.31}] \times 10^{-4}$.

**BaBar**
- PRD 81, 051101(R) (2010).
- Use 459 M BB.
- $B = [1.7^{+0.8}_{-0.2}] \times 10^{-4}$.

(Counting method employed.)
Prospects for Belle II (√Luminosity Assumption)

$B \rightarrow \tau \nu$

- Expected sensitivity: a few % at 50 ab$^{-1}$.
- For Type-II 2HDM, we show expected exclusion region at 95% C.L.:

- Central values of $B(B \rightarrow \tau \nu) = 1 \times 10^{-4}$, $f_B = 190$ MeV, and $|V_{ub}| = 4.15 \times 10^{-3}$ are assumed.
- Relative error of $f_B^2 |V_{ub}|^2$ assumed to be comparable to the one of measured $B(B \rightarrow \tau \nu)$.

Strong dependence on central values of $B(B \rightarrow \tau \nu)$ and $|V_{ub}|$. 
Prospects for Belle II (√Luminosity Assumption)

B→τν

• Assuming 2-parameter nonuniversal Higgs model, we expect

H. Baer, V. Barger, and A. Mustafayev, PRD85, 075010

μ>0, \( m_h = 125 \pm 1 \) GeV, \( m_t = 173.3 \) GeV

blue: \( m_0 < 5 \) TeV, orange: \( m_0 < 20 \) TeV

B→μν, ev

• 5σ observation expected for \( B(B\to\mu\nu)_{SM} \) at \( \sim 10 \) ab\(^{-1}\).

• \( \mathcal{O}(10^{-8}) \) sensitivity at 50 ab\(^{-1}\). Interesting to compare with \( B\to\tau\nu \).
Methods for Analyzing $B \to D^{(*)} \tau \nu$

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

- **Hadronic tag**: reconstruct $B_{tag}$ in hadronic decays $B \to D^{(*)}\pi$, etc., and detect signal using remaining particles (similarly to $B \to \tau \nu$).

- **Inclusive tag**: detect signal decay products excluding neutrinos, and reconstruct $B_{tag}$ using invariant mass for remaining particles $M_{tag}$.

\[
\begin{align*}
\text{K} & \quad \text{\pi}\pi' \quad \text{etc.} \\
\text{D}^{(*)} & \quad B_{tag} \quad \gamma(4S) \quad B_{sig} \\
\text{\pi}'s & \quad \text{etc.} \quad \mu, \text{e, } \pi, \text{ etc.} \\

\text{v} & \quad \text{v}'s \quad \text{\tau} \\
\text{D}^{(*)} & \quad \text{\nu} \quad \text{\nu}\text{'s}
\end{align*}
\]
**B^0 \rightarrow D^* \tau \bar{\nu}_\tau** by Inclusive Tag from Belle

- **PRL 99, 191807 (2007).**
- **Use 535 M BB.**
- **First observation of signal (5.2\sigma).**

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

Syst. from tag efficiency, sig efficiency, etc.

Largest, estimated from control sample \( B^0 \rightarrow D^{*-} \pi^+ \).

Consistent with SM value (1.41±0.07)% [C.-H. Chen and C.-Q. Geng, JHEP10, 053 (2006)].
B$^{\pm} \rightarrow $D$^{(*)}\tau \bar{\nu}$ by Hadronic Tag from Belle

- Using 657 M BB.
- Simultaneous fit to both subsets.
- D$^{(*)}\bar{\nu}$ 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: Dl\bar{\nu}, D^{*}\bar{\nu}, D^{**}\bar{\nu}, DX, ...

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

$B(D^{*0} \tau^- \bar{\nu}_\tau) = [2.12^{+0.28}_{-0.27} \text{(stat)} \pm 0.29 \text{(syst)}] \%$

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

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

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

$B(D^0 \tau^- \bar{\nu}_\tau) = [0.77 \pm 0.22 \text{(stat)} \pm 0.12 \text{(syst)}] \%$

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

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

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

D** Background for D(\(*)(\star)\n at BaBar

Simultaneous fit for signal candidates and Dπ^0l control sample.

Effect of small enhancement in higher region taken in Syst.
Examples of Various Checks for $B \to D^{(*)} \tau \nu$ from BaBar

Run periods, lepton modes

BDT requirements
Dependence on $\tan\beta/m_H$ for $B \to D^{(*)}_{TV}$ from BaBar
Constraint on Type III 2HDM from $B \to D^{(*)} \tau \nu$ by BaBar