B → l ν (l = τ, μ, e)

Belle results and outlook for Belle II

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\( B \to l \nu \) in Standard Model

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

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

\[
B(\ell = \tau) > B(\ell = \mu) > B(\ell = e)
\]

\( f_B \): B meson decay constant. Can be calculated from Lattice QCD.

\( V_{ub} \): CKM matrix element. Can be measured from \( b \to ul\nu \) decays.

Both can also be obtained from a CKM global fit.
Possible effect of $H^\pm$ for $B \rightarrow l\nu$

- $B \rightarrow l\nu$ could be affected by charged Higgs.

- Example of modifications:

$$B(B^- \rightarrow l^- \bar{\nu}_l) = B(B^- \rightarrow l^- \bar{\nu}_l)_{SM} \times r_H$$

where common $r_H$ is considered for $l = e, \mu, \text{and} \tau$.

$$r_H = \left(1 - \tan^2 \beta \frac{m^2_B}{m^2_H}\right)^2$$

type II of two Higgs doublet model (2HDM).

$$r_H = \left(1 - \frac{\tan^2 \beta}{1 + \tilde{c}_0 \tan \beta} \frac{m^2_B}{m^2_H}\right)^2$$

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

Exploit that a $B$ meson pair is generated by $e^+e^- \rightarrow \Upsilon(4S) \rightarrow BB$ for “seeing” multiple neutrinos.

Two independent tags are used.

- **Hadronic tag**: tag $B$ in hadronic decays $B \rightarrow D(\ast)\pi$, etc.
- **Semileptonic tag**: tag $B$ in semileptonic decays $B \rightarrow D(\ast)\nu_l$. $(l = e$ or $\mu)$
Summary for $B \to \tau \nu$ in early 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): $B = (1.67 \pm 0.30) \times 10^{-4}$

Discrepancy (2.8σ) with CKM fit prediction.
Data samples used for $B \rightarrow \tau \nu$

We focus on latest results obtained from Belle.
**B → τν by hadronic tag, increased tagged events**

- **Improved hadronic tag:**
  - Add decay modes \(B → D\pi\pi\pi\), etc. which have several final-state particles.
  - Use NeuroBayes package for a better separation with backgrounds.

![Graph showing data points](image)

- Classical tag on previous data
- New tag on full data (reprocessed)
- New tag on previous data

- Beam-energy-constrained \(B\) mass \([GeV/c^2]\)

- Purity also improved.

**3.0 times larger tagged events in total**

(Efficiency slightly larger if signal side is \(B → τν\).)
B→τν by hadronic tag, method of signal extraction

- Use τ→eνν, μνν, πν, and ρν.
- Events including X±, π⁰, K_L (new) rejected.
- Signal extraction based on two variables.
  - $E_{ECL}$: remaining energy in electromagnetic calorimeter.
  - $M_{miss}^2$: missing mass squared (new, removing tight momentum requirements for e, μ, π, and ρ).
- Sensitivity for B→τν improved by a factor of about 25% (5% by including K_L veto, 20% by the new signal extraction method).
- Result less sensitive to the backgrounds which peak at $E_{ECL} = 0$ GeV.
B→τν by hadronic tag, signal extraction

Simultaneous fit to different τ decay samples. Figures shown for the sum of different τ decays.


- Signal yield: $62^{+23}_{-22}$ (stat) ±6 (syst).
- $B(B \rightarrow \tau \nu) = [0.72^{+0.27}_{-0.25}$ (stat) ±0.11 (syst)] × 10^{-4}.

Systematic error due to background PDFs, tag efficiency, $K_L$ veto efficiency, ...

(Projection for all $M_{\text{miss}}^2$ region.)

(Projection for $E_{\text{ECL}} < 0.2$ GeV)

Significance: 3.0σ (including syst)
**B → τν by hadronic tag, 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⁻νₑνₜ</td>
<td>15.5±11.2</td>
<td>2.98 × 10⁻⁴</td>
</tr>
<tr>
<td>μ⁻νₘνₜ</td>
<td>25.6±15.1</td>
<td>3.12 × 10⁻⁴</td>
</tr>
<tr>
<td>π⁻νₜ</td>
<td>7.8±9.5</td>
<td>1.76 × 10⁻⁴</td>
</tr>
<tr>
<td>ρ⁻νₜ</td>
<td>13.6±18.7</td>
<td>3.37 × 10⁻⁴</td>
</tr>
</tbody>
</table>

Consistent results.

Rare unobserved BG decays (e.g. B → μνγ) would show up in individual signal modes.
B → τν by semileptonic tag

- Using 657 M BB (85% of full data).
- Evidence of signal (3.6σ).

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

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^- \to 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^- \to \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^- \to \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)
Summary for $B \to \tau \nu$ (latest)

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

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

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

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

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

Consistent with CKM fit prediction.
Constraint on charged Higgs

- Assume Type II of two Higgs doublet model.

\[ B(B \to \tau \nu) = B(B \to \tau \nu)_{\text{SM}} \times r_H \quad r_H = \left( 1 - \frac{m_B^2}{m_H^2} \tan^2 \beta \right)^2 \]

Note: exclusion region strongly depends on the central values of \( f_B \) and \( |V_{ub}| \).
In this calculation, we use \( f_B = 191 \pm 9 \text{ MeV} \) (HPQCD, PRD86, 034506) and \( |V_{ub}| = (4.15 \pm 0.49) \times 10^{-3} \) (PDG2012, inclusive + exclusive \( b \to u \nu \) decays).
B→μν/ev by hadronic tag

• Use 711 fb^-1 (full data).
• Hadronic tag as done for B→τν.
• Signal extraction by momentum of μ/e in B rest frame: p_l^B.
• Requirement is applied for E_{ECL}.

\[ \mathcal{B}(B^- \rightarrow \mu^- \bar{\nu}_\mu) < 2.5 \times 10^{-6} \]
\[ \mathcal{B}(B^- \rightarrow e^- \bar{\nu}_e) < 3.5 \times 10^{-6} \]

(90% C.L.)

Errors dominated by statistical uncertainties.

BG yield obtained by sideband fit. UL estimated by Feldman-Cousins method.
B→μν/ev by inclusive tag

- Use 253 fb⁻¹ (36% of data).
- First reconstruct signal μ/e.
  - Requirement on momentum of μ/e.
- Then reconstruct the other B meson using all the remaining particles.
  - Signal extraction by fitting beam-energy-constrained mass $M_{bc}$.

\[ \mathcal{B}(B^- \rightarrow \mu^- \bar{\nu}_\mu) < 1.7 \times 10^{-6} \quad (90\% \text{ C.L.}) \]
\[ \mathcal{B}(B^- \rightarrow e^- \bar{\nu}_e) < 9.8 \times 10^{-7} \]

Errors dominated by statistical uncertainties.
SuperKEKB collider

- Design luminosity: $8 \times 10^{35}$ cm$^{-2}$s$^{-1}$ ($\times40$ of KEKB).
  - Achieved by small beam sizes ($\times20$) and high currents ($\times2$).
- Target of integrated luminosity: $50$ ab$^{-1}$ ($\times50$ of KEKB).

Will reach 50 ab$^{-1}$ in 2022.

Commissioning starts in 2015.
Belle II detector

**K_\text{L} and muon detector:**
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

**EM Calorimeter:**
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)

**Beryllium beam pipe**
2 cm diameter

**Vertex Detector**
2 layers DEPFET + 4 layers DSSD

**Central Drift Chamber**
He(50%):C_2H_6(50%), Small cells, long lever arm, fast electronics

**Particle Identification**
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

**Designed for high event rate and beam BG.**
Improved vertex resolution and particle ID.
Considerations for $B \to l\nu$ at Belle II

- **Data increased ($\times 50$).**
  - Both statistical and systematic errors reduce. (Main systematic uncertainties estimated by data.)

- **Particle ID improved (mis-ID rate for $K^\pm/\pi^\pm$ of % level).**
  - Background due to mis-ID decreases. (Many $K^\pm/\pi^\pm$ used in tag-side reconstruction.)

- **Beam background increased ($\times 10-20$).**
  - Signal has larger tail in $E_{ECL}$ distribution, while BG has also larger $E_{ECL}$ value.
Prospects for Belle II (√luminosity assumption)

\[ B \to \tau \nu \]

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

\[ B(B \to \tau \nu) = 0.5 \times 10^{-4} \]
\[ B(B \to \tau \nu) = 1.5 \times 10^{-4} \]

- Central values of \( B(B \to \tau \nu) = 1 \times 10^{-4} \), \( f_B = 190 \) 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 \( B(B \to \tau \nu) \).

Strong dependence on central values of \( B(B \to \tau \nu) \) and \( |V_{ub}| \).
Prospects for Belle II (\sqrt{s} luminosity assumption)

\[ B \rightarrow \tau \nu \]

- **Assuming 2-parameter nonuniversal Higgs model**, we expect

\[ H. \text{Baer, V. Barger, and A. Mustafayev, PRD85, 075010} \]

\[ \mu > 0, \ m_h = 125 \pm 1 \text{ GeV}, \ m_t = 173.3 \text{ GeV} \]

\[ \text{blue: } m_0 < 5 \text{ TeV, orange: } m_0 < 20 \text{ TeV} \]

\[ B \rightarrow \mu \nu, \ ev \]

- **5\sigma** observation expected for \( B(B \rightarrow \mu \nu)_{SM} \) at \( \sim 10 \text{ ab}^{-1} \).

- \( \mathcal{O}(10^{-8}) \) sensitivity at 50 \text{ ab}^{-1}. **Interesting to compare with** \( B \rightarrow \tau \nu \).
Summary

• $B \rightarrow l \nu$ ($l = \tau, \mu, e$) is a good probe for constraining new-physics models.

• **Update on hadronic tag** from Belle in summer 2012.

• All results are consistent with SM within the errors.

• Constraint on charged Higgs (Type II of 2HDM) discussed.

• Strong relation with $f_B$ and $|V_{ub}|$.

• One of the main topics at Belle II.
  • Sensitivity % level for $B \rightarrow \tau \nu$ and better than SM expectation for $B \rightarrow \mu \nu$. 
Backup slides
**K_L veto**

- Background rejection using $K_L$ is introduced.
- Effective to reduce peaking backgrounds.
- Improves the statistical significance by about 5%.

*Figures show $B^0$-tagged total events without and with reconstructed $K_L$.***
**KL veto**

- Efficiency difference in data and MC calibrated by $D^0 \rightarrow \Phi K_S$, $\Phi \rightarrow K_SK_L$ (normalized by $\Phi \rightarrow K^+K^-$).
- Validity checked using $B^0 \rightarrow D^*\pi^+$, $D^* \rightarrow D\pi^-$, $D \rightarrow K_L\pi^0$.

Check done also for $B \rightarrow \tau\nu$ BG in $E_{ECL}$ sideband data.

w/ $K_L$ veto, w/o $K_L$ veto efficiency correction  

w/ $K_L$ veto, w/ $K_L$ veto efficiency correction
Signal PDFs for $E_{ECL}$ and $M_{\text{miss}}^2$

Signal PDF for $E_{ECL}$ is checked using $D^*\nu$ control sample.

Signal PDF for $M_{\text{miss}}^2$ is affected by momentum resolutions. Since $M_{\text{miss}}^2$ for $B\to\tau\nu$ has wide distribution, do not apply correction.
Peaking backgrounds

- At least one of $E_{ECL}$ and $M_{miss}^2$ distributions have difference from signal. Result is less sensitive to peaking backgrounds.

- If BR is known, error of BR and MC statistics in Syst.

- If BR is not known, assume SM value in the nominal fit. SM value $\pm 50\%$ and MC statistics in Syst.
Systematic uncertainties

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

- Uncertainties due to background PDFs are estimated by varying the background yields by BR and MC-statistics errors.

- Uncertainties due to tag efficiency and K\(_L\) veto are estimated by using a clean control sample B\(\rightarrow\)D\(^*\)l\(\nu\).

\((l = e \text{ or } \mu)\)

<table>
<thead>
<tr>
<th>Source</th>
<th>(\mathcal{B}) syst. error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal PDF</td>
<td>4.2</td>
</tr>
<tr>
<td>[Background PDF]</td>
<td>8.8</td>
</tr>
<tr>
<td>Peaking background</td>
<td>3.8</td>
</tr>
<tr>
<td>[(B_{\text{tag}}) efficiency]</td>
<td>7.1</td>
</tr>
<tr>
<td>Particle identification</td>
<td>1.0</td>
</tr>
<tr>
<td>(\pi^0) efficiency</td>
<td>0.5</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>0.3</td>
</tr>
<tr>
<td>(\tau) branching fraction</td>
<td>0.6</td>
</tr>
<tr>
<td>MC efficiency statistics</td>
<td>0.4</td>
</tr>
<tr>
<td>[(K_L^0) efficiency]</td>
<td>7.3</td>
</tr>
<tr>
<td>(N_{B+B^-})</td>
<td>1.3</td>
</tr>
<tr>
<td>Total</td>
<td>14.7</td>
</tr>
</tbody>
</table>
Comparison with the previous hadronic-tag result

<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 ($\times10^8$)</td>
<td>4.49</td>
<td>4.49</td>
</tr>
<tr>
<td>Efficiency ($\times10^{-4}$)</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>$\mathcal{B}(B^- \rightarrow \tau^-\bar{\nu}_\tau)$ ($\times10^{-4}$)</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 $\mathcal{B} \sim (0.6\pm0.4) \times 10^{-4}$ (1.9σ from old result).
Comparison with $B \to D(\ast) \tau\nu$

Compare constraints on $\tan\beta/m_H$ assuming Type II.

**Belle, $B \to \tau\nu$**
- 95% C.L. excluded

**BaBar, $B \to \tau\nu$**
- $V_{ub}$ from exclusive $b \to u$
- $V_{ub}$ from inclusive $b \to u$

**$B \to D\tau\nu$**
- Preferred

**$B \to D^*\tau\nu$**
- Preferred

BaBar, arXiv:1205.5442

$B \to \tau\nu$, $D\tau\nu$, and $D^*\tau\nu$ prefer different regions of $\tan\beta/m_H$.

Type II disfavored...?
Need further studies.
Comparison with CKM fit (ICHEP2012)

![Graph showing comparison between CKM fit and measurements](image)

- **Graph Explanation**: The graph compares the CKM fit with and without BR(B → τν) to the measurements (WA) in the context of the CKM fit. The plot illustrates the p-value distribution for different values of BR(B → τν) × 10^4 and sin 2β.

- **Key Observations**:
  - The CKM fit w/o BR(B → τν) is represented by a green shaded area.
  - Measurements (WA) are marked by a blue line.
  - The significance level, 1.6σ, indicates a notable deviation.

- **Legend**:
  - CKM fit w/o BR(B → τν)
  - Measurements (WA)
NUHM2

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