Rare and forbidden B and tau decays in Belle

24 July, 2014

(on behalf of Belle Collaboration)

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• KEKB and Belle Experiment

• Leptonic Decays: $B^+ \rightarrow e^+\nu_e$ and $B^+ \rightarrow \mu^+\nu_\mu$

• Search for Massive Neutral Leptons
  • $B^+ \rightarrow l^+X^0$ ($X^0$ : something massive)
  • $B \rightarrow (X)l\nu_{\text{heavy}}$ ($X$ : meson)

• Lepton Flavor Violation in Tau Decays: $\tau \rightarrow l^+hh'$

• Summary
KEKB and Belle Experiment

- 4π detector + known initial state → perfect environment for studies of B decays with neutrinos in final state
- Collected full data set: ~710 fb\(^{-1}\) at \(\Upsilon(4S)\) → 772 × 10^6 BB-bar pairs
$B^+ \rightarrow e^+\nu_e$ and $B^+ \rightarrow \mu^+\nu_\mu$

Y. Yook, et al., arXiv:1406.6356v1
Physics Motivation

SM Predictions:
\[ \mathcal{B}(B \rightarrow e\nu) \sim 10^{-11} \]
\[ \mathcal{B}(B \rightarrow \mu\nu) \sim 10^{-7} \]
\[ \mathcal{B}(B \rightarrow \tau\nu) \sim 10^{-4} \]

- A clean process for the measurement of \( f_B^2 \cdot |V_{ub}|^2 \) within the SM
- Evidence of \( B^+ \rightarrow \tau^+\nu \) from Belle and BABAR experiments
  - \([0.72^{+0.27}_{-0.25} \text{ (stat)} \pm 0.11 \text{ (syst)}] \times 10^{-4}\) \( \text{PRL 110, 131801 (2013)} \)
  - \([1.8^{+0.9}_{-0.8} \text{ (stat)} \pm 0.4 \text{ (bkg. syst)} \pm 0.2 \text{ (other syst)}] \times 10^{-4}\) \( \text{PRD 77, 011107(R) (2008)} \)
Physics Motivation

- New Physics (NP) contributions might interfere with SM and modify SM expectation
- Most prominent: $H^\pm$ from 2-Higgs-Doublet-Models (2HDM) in MSSM

\[
\mathcal{B}(B^+ \to l^+\nu_l)_{2HDM} = \mathcal{B}(B^+ \to l^+\nu_l)_{SM} \times \left(1 - \tan^2 \beta \frac{m_B^2}{m_H^2}\right)^2
\]

- In NP models with MFV (Minimal Flavor Violation), the ratios are expected to be nearly unmodified from SM expectations
- In GUT model, the ratios $R^{e\mu}$ and $R^{e\tau}$ may increase to more than one order of magnitude above SM expectation due to the enhancement of the electron mode

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V. Cirigliano et al., Nucl. Phys. B 728, 121 (2005)

Hadronic Tagging Method

M. Feindt et al., NIMA 654, 432 (2011)

- Complete tagging of a B in $\Upsilon(4S) \to BB$-bar decays
- Full reconstruction of a $B_{\text{tag}}$ in a hadronic channel:
  - taking over 1000 decay chains into account
  - $B.F.(\Upsilon(4S) \to BB$-bar) $\sim 96\%$
- Constrain the charge, flavour, four-momentum of $B_{\text{tag}}$ and $B_{\text{sig}}$
- Results in high purity and increased efficiency, $\sim 0.28\%$ (old method: 0.14%)
- Good suppression of $e^+e^- \to qq$-bar ($q = u, d, s, c$)
- Good ways to reconstruct modes with invisible particle
Analysis Strategy

- On signal side, one single track (e or μ) required
- 2-body decay: clear signature in $B_{\text{sig}}$ rest frame

Signal extraction variable: $p_l^B$  
(lepton momentum at the rest frame of $B_{\text{sig}}$)
- Sharp-peaking near 2.64 GeV/c
- Very clean signal with low BG

Background estimation:
- Fit the sideband of $p_l^B$ (2-2.5 GeV/c)  
  → extrapolate the BG into the signal region  
  (~2.6-2.7 GeV/c)
- Dedicated MC modeling for peaking BG at signal region
**Signal Extraction**

- No signal events observed
  - Upper limit is calculated using Feldman-Cousins method

\[
\mathcal{B}(B^+ \rightarrow l^+ \nu) < \frac{S_{90}}{2 \epsilon_s N_{B^+ B^-}}
\]

<table>
<thead>
<tr>
<th>$B \rightarrow l \nu$</th>
<th>$\epsilon_s$ [%]</th>
<th>$N_{bkg}$</th>
<th>$N_{obs}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\nu$</td>
<td>0.086</td>
<td>0.10 ± 0.04</td>
<td>0</td>
</tr>
<tr>
<td>$\mu\nu$</td>
<td>0.102</td>
<td>0.26$^{+0.09}_{-0.08}$</td>
<td>0</td>
</tr>
</tbody>
</table>

$\mathcal{B}(B \rightarrow e\nu) < 3.4 \times 10^{-6}$ @ 90% C.L.

$\mathcal{B}(B \rightarrow \mu\nu) < 2.7 \times 10^{-6}$

**Previous measurements @ 90% C.L.**

**Hadronic Tagging**

- $\mathcal{B}(B \rightarrow e\nu) < 5.2 \times 10^{-6}$
- $\mathcal{B}(B \rightarrow \mu\nu) < 5.6 \times 10^{-6}$ 342 fb$^{-1}$

**Babbar PRD 77, 091104 (2008)**

**Loose Tagging**

- $\mathcal{B}(B \rightarrow e\nu) < 9.8 \times 10^{-7}$ 253 fb$^{-1}$
  - Belle PLB 647, 67 (2007)
- $\mathcal{B}(B \rightarrow \mu\nu) < 1.0 \times 10^{-6}$ 426 fb$^{-1}$
  - Babbar PRD 79, 091101 (2009)
B$^+ \rightarrow l^+ X^0 :$ search for massive invisible particle $X^0$

$B \rightarrow (X)l^+ \nu_{\text{heavy}} :$ search for heavy neutrino

D. Liventsev, et al., PRD 87, 071102(R) (2013)
**B^+ → l^+X^0**

- Search for **new** neutrino-like, heavy fermion $X^0$
- Covered mass range: $0.1 \text{ GeV}/c^2 \sim 1.8 \text{ GeV}/c^2$
in steps of $0.1 \text{ GeV}/c^2$

- **Similar to** $B \rightarrow l\nu$ analysis
  - except:
    - looser momentum cut and
    - looser impact parameter selection

<table>
<thead>
<tr>
<th>mode</th>
<th>$p_{l}^{\text{lab}}$</th>
<th>$dz$ [cm]</th>
<th>$dr$ [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow l^+X$</td>
<td>$p_{l}^{\text{lab}} &gt; 1.0 \text{ GeV}/c$</td>
<td>$</td>
<td>dz</td>
</tr>
<tr>
<td>$B^+ \rightarrow l^+\nu$</td>
<td>$p_{l}^{\text{lab}} &gt; 1.8 \text{ GeV}/c$</td>
<td>$</td>
<td>dz</td>
</tr>
</tbody>
</table>

- **Similar systematics**
- $p_{l}^{B}$ also shows good separation
- Signal region optimized to lowest expected upper limit
Belle preliminary

**e mode**

\[ M_{X_0} = 1.8 \text{ GeV/c}^2 \]

<table>
<thead>
<tr>
<th>signal region</th>
<th>sideband region</th>
</tr>
</thead>
</table>

**μ mode**

\[ M_{X_0} = 1.8 \text{ GeV/c}^2 \]

<table>
<thead>
<tr>
<th>signal region</th>
<th>sideband region</th>
</tr>
</thead>
</table>

**B^+ \rightarrow l^+X^0**

Belle preliminary

Rare and forbidden B and tau decays in Belle

H.J. Hyun
• $m_\nu > 0$ from experimental data while SM assumes 0 mass

• Heavy neutrinos ($\nu_h$) are assumed in many models beyond the SM

• $\nu_h$ interacts only by mixing with a left-handed neutrino by a unitary transformation

• Search for $B \rightarrow (X) l^+ \nu_h$
  - if $\nu_h$ is Majorana, $\nu_h \rightarrow l^+_1 \pi^-$ or $l^-_1 \pi^+$
  - if $\nu_h$ is Dirac, $\nu_h \rightarrow l^-_1 \pi^+$

• Search range of heavy neutrino:
  $0.5 \text{ GeV/c}^2 \leq M(\nu_h) \leq 5.0 \text{ GeV/c}^2$

• Approach separately for large and small $M(\nu_h)$
  - $M(\nu_h) < 2.0 \text{ GeV/c}^2$ : look for $X = D$ or $D^*$ using recoil mass
  - $M(\nu_h) > 2.0 \text{ GeV/c}^2$ : look for $X = D^{(*)}$, light meson, nothing

• Background suppression
  - QED background : by $N(\text{track}) > 4$
  - Decays with similar topology : by strict lepton ID, vertex quality, and distance $l^-\pi^+$ vertex
  - Combinatorial background : by distance btw the closest associated hit in SVD/CDC to vertex of $\nu_h$
Upper limits on $\nu_h - \nu_l$ mixing ($|U_l|$) are obtained in the range $0.5 \text{ GeV/c}^2 \leq M(\nu_h) \leq 5.0 \text{ GeV/c}^2$

Corresponding upper limit for the product branching fraction (for $M((\nu_h) = 2 \text{ GeV/c}^2$)

$$B(B \to (X)\nu_h) \times B(\nu_h \to l\pi^+) < 7.2 \times 10^{-7} \text{ for } l = e \text{ or } \mu$$
Lepton Flavor Violation in Tau Decays

\[ \tau \rightarrow l^+ hh' \]

\( l \): electron or muon, \( h(\nu) \): charged pion or kaon

Y. Miyazaki, et al., PLB 719 (2013) 346
Lepton Flavor Violation in Tau Decays

• Probability of LFV decays of charged lepton is extremely small in the SM

\[ B(\tau \rightarrow l\nu) \sim \left( \frac{\Delta m^2}{m^2_W} \right)^2 < 10^{-54} \]

• Many models beyond the SM predict LFV decays with the branching fractions up to \( \leq 10^{-8} \). As a result, observation of LFV is a clear signature of New Physics

• \( \tau \) lepton is a good tool to search for the LFV decays due to the enhanced couplings to the new particles as well as large number of LFV decay modes

• Study of the different \( \tau \) LFV decay modes allows us to test various NP models
Data Set and Method

- **854 fb⁻¹** data sample used
  - collected at or below \( \Upsilon(4S) \) and \( \Upsilon(5S) \) resonances
- **In total of 14 modes** were investigated
  - 8 LFV \( \tau^\pm \rightarrow l^+h^++h'^- \) and 6 lepton-number-violating \( \tau^- \rightarrow l^+h^++h'^- \) decays
    (\( l \): electron or muon, \( h, h' \): pions or Kaons)

- Blind analysis performed
  - Search for signal events on the \( M_{\text{inv}} \) vs. \( \Delta E \) plane
    \( M_{\text{inv}} \approx M_\tau, \Delta E = E_{\text{LFV}} - E_{\text{beam}} \approx 0 \)
  - Tag one \( \tau \) by its 1-prong decay \( (B_{1\text{-prong}} \sim 85\%) \), the other \( \tau \) is required to produce the LFV final state

- Background suppression
  - Opening angle btw missing momentum \( (p_{\text{miss}}) \) and charged track on the tag side: \( \cos\theta_{\text{CM tag-miss}} \)
  - Selection on the thrust: \( T \)
  - Missing mass:
    \[ m_{\text{miss}}^2 = E_{\text{miss}}^2 - p_{\text{miss}}^2 = (E_{\text{total}} - E_{\text{vis}})^2 - p_{\text{miss}}^2 \]
Results

- One event in the signal region was found for $\tau \rightarrow \mu^+\pi^\mp\pi^\mp$ and $\tau \rightarrow \mu^-\pi^+\pi^-$, no events for the other 12 modes.
- For all modes the number of observed signal events agree with the number of expected background events.

$$B(\tau \rightarrow lhh') < \frac{S_{90}}{2N_{\tau\tau}\epsilon}$$

- Obtained upper limits at 90% C.L.: $B(\tau \rightarrow lhh') < (2.0 \sim 8.6) \times 10^{-8}$

previous result with 671 fb$^{-1}$: $(3.3 \sim 16) \times 10^{-8}$

Results on LFV of $\tau$ decays

48 different LFV modes were studied at Belle.

The world best upper limits were obtained.

Recently, first U.L. for BNV and LNV $\tau$ decays with protons is obtained from LHCb.

A study of decays with neutrinos in the final state is possible using the hadronic tagging method.

Most stringent limits on $B^+ \rightarrow l^+\nu$ are obtained:
- $\mathcal{B}(B \rightarrow e\nu) < 3.4 \times 10^{-6}$ @90% C.L.
- $\mathcal{B}(B \rightarrow \mu\nu) < 2.7 \times 10^{-6}$ @90% C.L.

Performed search for heavy neutral lepton-like particles:
- $B^+ \rightarrow l^+X^0$, where $X^0$ can be any invisible (and possibly massive) fermion particle and in preliminary results, the upper limits are $O(10^{-6})$ for $0.1 \text{ GeV}/c^2 < M_X < 1.8 \text{ GeV}/c^2$.
- U.L. on mixing of $\nu_h-\nu_l$ is set in the mass range of $0.5 \text{ GeV}/c^2 \sim 5.0 \text{ GeV}/c^2$.

Up to now, no hints for NP contribution from leptonic B decays.

We studied 48 different LFV modes in tau decays, 46 of them were analyzed with almost full data sample and obtained upper limits on the branching fractions are of the order of $10^{-8}$. 
BACKUP SLIDES
Integrated luminosity of B factories

> 1 ab\(^{-1}\)
On resonance:
\(\Upsilon(5S): 121 \text{ fb}^{-1}\)
\(\Upsilon(4S): 711 \text{ fb}^{-1}\)
\(\Upsilon(3S): 3 \text{ fb}^{-1}\)
\(\Upsilon(2S): 25 \text{ fb}^{-1}\)
\(\Upsilon(1S): 6 \text{ fb}^{-1}\)
Off reson./scan:
\(~ 100 \text{ fb}^{-1}\)

\(~ 550 \text{ fb}^{-1}\)
On resonance:
\(\Upsilon(4S): 433 \text{ fb}^{-1}\)
\(\Upsilon(3S): 30 \text{ fb}^{-1}\)
\(\Upsilon(2S): 14 \text{ fb}^{-1}\)
Off resonance:
\(~ 54 \text{ fb}^{-1}\)
B tagging Purity-Efficiency

Missing mass distributions for $B^0 \rightarrow D^{*+} l^+ \nu_l$ decays of new and classical full reconstruction tool.
Background Suppression

$|\cos\theta_{\text{thrust}}|$  

$B$: low momentum  
~0.3 GeV/c  

2-jet like continuum:  
high momentum, ~5 GeV/c

\[ \theta_{\text{thrust}}: \text{angle between the thrust axis of } B_{\text{tag}} \text{ particle and the lepton's momentum in CM frame} \]

\[ E_{\text{ECL}} = E_{\text{Total}} - E_{B_{\text{tag}}} - E_{l} \]

No extra energy deposits in the ECL  
(apart from the lepton and $B_{\text{tag}}$)

BEACH2014  
Rare and forbidden $B$ and tau decays in Belle  
H.J. Hyun
**Event Selection**

**Particle identity**
- $L_e > 0.9$
- $L_\mu > 0.9$

**Track quality**
- $|dz| < 2.0$ cm
- $|dr| < 0.5$ cm

**Continuum suppression**
- $|\cos\theta_{\text{thrust}}| < 0.9$ for e mode
- $|\cos\theta_{\text{thrust}}| < 0.8$ for $\mu$ mode

**Quality of tagged-B meson**
- $|\Delta E| < 0.05$ GeV
- $M_{bc} > 5.27$ GeV/c$^2$
- $O_{\text{NB}} > 10^{-6}$

$E_{\text{ECL}}$ : remaining energy of ECL calorimeter

$p_{B_l}^\text{signal}$ : signal lepton’s momentum in the signal B rest frame

$p_{B_l}^\text{peak}$ changes by mass of $X^0$

$\rightarrow$ $p_{B_l}^\text{cut}$ should be optimized for each $X^0$ mass

**Fitting signal**

**Fitting background**

**Fitting peaking background**
<table>
<thead>
<tr>
<th>M(X) (GeV/c^2)</th>
<th>e mode</th>
<th>μ mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Statistical uncertainty</td>
<td>Total uncertainty</td>
</tr>
<tr>
<td>0.1</td>
<td>1.72%</td>
<td>6.1%</td>
</tr>
<tr>
<td>0.2</td>
<td>2.18%</td>
<td>6.2%</td>
</tr>
<tr>
<td>0.3</td>
<td>1.70%</td>
<td>6.1%</td>
</tr>
<tr>
<td>0.4</td>
<td>1.73%</td>
<td>6.1%</td>
</tr>
<tr>
<td>0.5</td>
<td>1.53%</td>
<td>6.0%</td>
</tr>
<tr>
<td>0.6</td>
<td>1.74%</td>
<td>6.1%</td>
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<tr>
<td>0.7</td>
<td>1.71%</td>
<td>6.1%</td>
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<tr>
<td>0.8</td>
<td>1.71%</td>
<td>6.1%</td>
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<td>6.1%</td>
</tr>
<tr>
<td>1.0</td>
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<td>1.1</td>
<td>1.63%</td>
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<td>1.3</td>
<td>1.83%</td>
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<td>1.4</td>
<td>1.72%</td>
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<td>1.5</td>
<td>1.75%</td>
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<tr>
<td>1.6</td>
<td>1.74%</td>
<td>6.1%</td>
</tr>
<tr>
<td>1.7</td>
<td>1.80%</td>
<td>6.1%</td>
</tr>
<tr>
<td>1.8</td>
<td>1.75%</td>
<td>6.1%</td>
</tr>
</tbody>
</table>

\[
n(v_h) = 2 N_{BB} B(B \rightarrow v_h) B(v_h \rightarrow l\pi) \frac{m \Gamma}{p} \int \varepsilon(x) dx
\]

\[
= |U_\alpha|^2 |U_\beta|^2 2 N_{BB} f_1(m) f_2(m) \frac{m}{p} \int \varepsilon(x) dx
\]

Number of neutrinos detected

→ Expect upper limit of branching fraction

Obtained yield and expectation from MC
generic MC (unscaled)
data

<table>
<thead>
<tr>
<th>mode</th>
<th>MC expected</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\pi$</td>
<td>1.7 ± 0.7</td>
<td>6 ± 2.4</td>
</tr>
<tr>
<td>$\mu\pi$</td>
<td>2.3 ± 0.9</td>
<td>2 ± 1.4</td>
</tr>
<tr>
<td>$e\mu\pi + \mu e\pi$</td>
<td>4.0 ± 1.2</td>
<td>3 ± 1.7</td>
</tr>
</tbody>
</table>
Event Selection

\( \tau \rightarrow l^+hh' \)

**Fig. 1.** (a) \( P(K/\pi) \) for muon tracks, (b) \( P(p/\pi) \) and (c) \( P(p/K) \) for hadronic tags, for \( \tau^{-} \rightarrow \mu^{-}\pi^{+}\pi^{-} \) candidate events. Signal MC (\( \tau^{-} \rightarrow \mu^{-}\pi^{+}\pi^{-} \)) distributions are normalized arbitrarily while the background MC distributions are normalized to the data luminosity. The selected regions are indicated by arrows.

**Table 1**

<table>
<thead>
<tr>
<th>Mode</th>
<th>( P(K/\pi) )</th>
<th>( T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau \rightarrow \mu\pi\pi )</td>
<td>–</td>
<td>( 0.90 &lt; T &lt; 0.98 )</td>
</tr>
<tr>
<td>( \tau \rightarrow \mu K\pi )</td>
<td>&gt; 0.9</td>
<td>( 0.92 &lt; T &lt; 0.98 )</td>
</tr>
<tr>
<td>( \tau \rightarrow \mu K K )</td>
<td>&gt; 0.8</td>
<td>( 0.92 &lt; T &lt; 0.98 )</td>
</tr>
<tr>
<td>( \tau \rightarrow e\pi\pi )</td>
<td>–</td>
<td>( 0.90 &lt; T &lt; 0.97 )</td>
</tr>
<tr>
<td>( \tau \rightarrow e K\pi )</td>
<td>&gt; 0.8</td>
<td>( 0.90 &lt; T &lt; 0.97 )</td>
</tr>
<tr>
<td>( \tau \rightarrow e K K )</td>
<td>&gt; 0.6</td>
<td>( 0.90 &lt; T &lt; 0.98 )</td>
</tr>
</tbody>
</table>

**Fig. 2.** Invariant mass distribution of three charged tracks on the signal side with the pion mass assigned to each track (\( M_{3\pi\pi} \)) for \( \tau^{-} \rightarrow \mu^{-}\pi^{+}K^{-} \) candidate events. Signal MC (\( \tau^{-} \rightarrow \mu^{-}\pi^{+}K^{-} \)) distributions are normalized arbitrarily while the background MC distributions are normalized to the data luminosity. The selected regions are indicated by the arrow.
\( \tau \rightarrow l^+hh' \) Opening angle and Signal region

Invariant mass distribution and scatter plot btw \( M_{\mu\pi\pi} \) and \( \Delta E \) after continuum reduction selection for the \( \mu-\pi+\pi^- \) mode.

- red: signal MC
- open: generic \( \tau\tau \) MC
- yellow filled: continuum MC
- crossed points: data