Leptonic & semileptonic B decays at Belle

Youngmin Yook
yookym@gmail.com

Yonsei University
Seoul, Korea
Outline

Semileptonic $B$ decays:

$B \rightarrow h\ell\nu_\ell \ (\ell = e, \mu)$

$(B^0 \rightarrow \pi^+\ell\nu, B^+ \rightarrow \pi^0\ell\nu, B^0 \rightarrow \rho^+\ell\nu, B^+ \rightarrow \rho^0\ell\nu, B^+ \rightarrow \omega\ell\nu, B^+ \rightarrow \eta(')\ell\nu)$

Leptonic $B$ decays:

$B^+ \rightarrow \ell^+\nu_\ell \left\{ \begin{array}{c} B^+ \rightarrow e^+\nu_e, B^+ \rightarrow \mu^+\nu_\mu \\ B^+ \rightarrow \tau^+\nu_\tau \end{array} \right\}$

We fully reconstructed a $B$-meson in order to handle the invisible neutrinos
Hadronic Tagging Method

Complete tagging of a B in Y(4S)->BB

→ Constrain the charge, flavor, 4-momentum of the recoil-B
→ Results in very high-purity (but with low efficiency)
→ Good continuum (e^+e^- → u,d,s,c) suppression
→ Reconstructs rare modes with neutrinos

Reconstructed by hadronic tagging

Missing mass of the recoil-B analyzable

Reprocessed Data: improved detection efficiency for low p_T tracks and neutral particles

Modified Hadronic Tag: Neurobayes algorithm + Addition of more B/D tagging modes

→ increased statistics, better sensitivity

July 5, 2012

Leptonic & Semileptonic Decays at Belle @ ICHEP 2012
Measurements of $|V_{ub}|$ from Exclusive $B \rightarrow h\ell\nu$

$(h = \pi^+, \pi^0, \rho^+, \rho^0, \omega, \eta, \eta', \text{ Lepton includes } e \text{ and } \mu)$

- Precision measurement of the $B \rightarrow X_u \ell\nu$ branching fraction
- With increased and reprocessed data and new hadronic tagging

With exclusive $B \rightarrow \pi\ell^+\nu_\ell$, for instance, $|V_{ub}|$ can be extracted from the differential decay rate

$$\frac{d\Gamma(B \rightarrow \pi\ell^+\nu_\ell)}{dq^2} = \frac{G_F^2|V_{ub}|^2}{24\pi^3}|p_\pi|^3|f_+(q^2)|^2$$

Theory input is needed to determine the form factor $f_+(q^2)$. 
- Full \( \Upsilon(4S) \) data used (\( N(B\bar{B}) = 772M / 711fb^{-1} \))
- Signal yield extracted from maximum-likelihood fit to \( M_{\text{miss}}^2 \)

\[
M_{\text{miss}}^2 = (E_{CM} - E_{B_{\text{tag}}} - E_{B_{\text{sig}}})^2 - (P_{B_{\text{tag}}} - P_{B_{\text{sig}}})^2
\]

\( E \) and \( P_{B_{\text{tag}}} \): Energy and momentum of the tagged-\( B \)
\( E \) and \( P_{B_{\text{sig}}} \): Energy and momentum of signal side \( B \) particles

The cleanest measurement of these modes!

\( B^+ \rightarrow \pi^0 \ell^+ \nu \)

\( B^0 \rightarrow \pi^- \ell^+ \nu \)

**signal**

\( B \rightarrow \rho \ell \nu \)

**other** \( X_u \ell \nu \)

**continuum**

\( B \rightarrow X_c \ell \nu \)

*stat. error only for \( N_{\text{sig}} \)*

Major systematic uncertainty from hadronic tag efficiency

\(~ 5.0\%\)
Great achievements in clean signal extraction of $B^+ \rightarrow \rho^0 l\nu$ and $B^+ \rightarrow \omega l\nu$!
Branching Ratios of the $B \rightarrow h\ell\nu$

$\mathcal{B}(B^0 \rightarrow \pi^- \ell^+\nu_\ell) = (1.49 \pm 0.09 \pm 0.07) \times 10^{-4}$
$\mathcal{B}(B^+ \rightarrow \pi^0 \ell^+\nu_\ell) = (0.80 \pm 0.08 \pm 0.04) \times 10^{-4}$
$\mathcal{B}(B^0 \rightarrow \rho^- \ell^+\nu_\ell) = (3.17 \pm 0.27 \pm 0.18) \times 10^{-4}$
$\mathcal{B}(B^+ \rightarrow \rho^0 \ell^+\nu_\ell) = (1.86 \pm 0.10 \pm 0.09) \times 10^{-4}$
$\mathcal{B}(B^+ \rightarrow \omega \ell^+\nu_\ell) = (1.09 \pm 0.16 \pm 0.08) \times 10^{-4}$
$\mathcal{B}(B^+ \rightarrow \eta \ell^+\nu_\ell) = (0.42 \pm 0.12 \pm 0.05) \times 10^{-4}$
$\mathcal{B}(B^+ \rightarrow \eta' \ell^+\nu_\ell) < 0.57 \times 10^{-4} \text{ @ } 90\%CL.$

[Belle Preliminary Results]

→ Significantly improved branching ratios compared to the past results.
Values of $|V_{ub}|$ from $\mathcal{B}(B \to \pi \ell \nu)$

$|V_{ub}|$ (CKM fitter 2012) = $[3.14^{+0.21}_{-0.10}] \times 10^{-3}$

| $X_u \ell \nu$ | Theory | $q^2$ [GeV$^2$] | $|V_{ub}| \times 10^3$ |
|----------------|--------|----------------|---------------------|
| $\pi^0 \ell \nu$ | KMOW$^{[1]}$ | <12 | 3.30 ± 0.22 ± 0.09$^{+0.35}_{-0.30}$ |
| | Ball/Zwicky$^{[2]}$ | <16 | 3.62 ± 0.20 ± 0.10$^{+0.60}_{-0.40}$ |
| | FNAL$^{[3]}$ | >16 | 3.30 ± 0.30 ± 0.09$^{+0.36}_{-0.30}$ |
| | HPQCD$^{[4]}$ | >16 | 3.45 ± 0.31 ± 0.09$^{+0.58}_{-0.38}$ |
| $\pi^+ \ell \nu$ | KMOW$^{[1]}$ | <12 | 3.38 ± 0.14 ± 0.09$^{+0.36}_{-0.32}$ |
| | Ball/Zwicky$^{[2]}$ | <16 | 3.57 ± 0.13 ± 0.09$^{+0.59}_{-0.39}$ |
| | FNAL$^{[3]}$ | >16 | 3.69 ± 0.22 ± 0.09$^{+0.41}_{-0.34}$ |
| | HPQCD$^{[4]}$ | >16 | 3.86 ± 0.23 ± 0.10$^{+0.66}_{-0.44}$ |


Calculation of $|V_{ub}|$ from different theory input for each $q^2$ range.
A Clean Process for the Measurement of $f_B$, $|V_{ub}|^2$

Helicity Suppression:
Branching fraction proportional to $m_{\ell}^2$

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


Deviation from Standard Model can indicate New Physics such as 2HDM(type2) or lepto-quark.

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

**MC study** – signal enhanced plot for muon mode

\(<1 \text{ expected BG, signal for both } e, \mu>\)

**Low BG, very clean signal distribution**
Most of the signal efficiency error from signal shape uncertainty estimated with \( B^+ \rightarrow D^0 \pi^+ \) control samples.

**Data Unblind!**

Upper Limit calculated by POLE (Feldman-Cousins method)

\[
\begin{align*}
\mathcal{B}(B \rightarrow e\nu) &< 3.5 \times 10^{-6} \ (90\% C.L.) \\
\mathcal{B}(B \rightarrow \mu\nu) &< 2.5 \times 10^{-6} \ (90\% C.L.)
\end{align*}
\]

<table>
<thead>
<tr>
<th>( N_{\text{expected BG}} )</th>
<th>( 0.11^{+0.75}_{-0.06} )</th>
<th>( 0.33^{+0.10}_{-0.08} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \epsilon_{\text{signal}} )</td>
<td>( 9.1 \pm 1.5 \times 10^{-4} )</td>
<td>( 1.15 \pm 0.18 \times 10^{-3} )</td>
</tr>
<tr>
<td>( N_{\text{data observed}} )</td>
<td>0</td>
<td>0</td>
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</tbody>
</table>

Most of the signal efficiency error from signal shape uncertainty estimated with \( B^+ \rightarrow D^0 \pi^+ \) control samples.

\[
BF = \frac{\text{Yield}}{N(B \bar{B}) \times \epsilon_{\text{sig}}}
\]
Current results on $B \rightarrow \tau \nu$

**Babar Hadronic**
$1.70 \pm 0.87 \pm 0.20$

**Babar Semileptonic**
$1.80^{+0.57}_{-0.54} \pm 0.26$

**Belle Semileptonic**
$1.54^{+0.38}_{-0.37} ^{+0.29}_{-0.31}$

**Belle Hadronic**
$1.79^{+0.56}_{-0.49} ^{+0.46}_{-0.51}$

**SM**
$1.20 \pm 0.25$

$$ B^+ \rightarrow \tau^+ \nu\tau $$

Relation with $\sin 2\Phi_1$. Direct Meas. $(\pm 1\sigma)$

**Tension with the CKM UT constraints?**

Past hadronic tag analysis from Belle with 1-D fit to $E_{ECL}$

$N(B\bar{B}) = 449M$

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

$(3.5\sigma)$

PRL 97, 251802 (2006)
Major differences from 2006 analysis

- Reprocessing of full Belle data set (2011)
  → Improved detection efficiencies of low $p_T$ tracks and neutral particles
- Added 322M more $B\bar{B}$ data in addition to previous 449M
- New sophisticated hadronic tagging algorithm
  → Based on neural net & Bayesian interpretation
  → More $B/D$ decay modes included for the tag
- Signal extraction by 2D fit to $(E_{ECL}, M_{miss}^2)$
  → Improved handling of peaking backgrounds

Definition of variables

\[ M_{miss}^2 = (E_{CM} - E_{B_{tag}} - E_{B_{sig}})^2 - (P_{B_{tag}} - P_{B_{sig}})^2 \]

$E$ and $P_{B_{tag}}$: Energy and momentum of the tagged-$B$
$E$ and $P_{B_{sig}}$: Energy and momentum of signal side $B$ particles
$E_{ECL}$ = Extra energy in ECL aside from those contributed via tagged-$B$ and signal-$B$ constituents

\[ \tau^- \to e^- \bar{\nu}_e \nu_\tau \]
\[ \tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau \]
\[ \tau^- \to \pi^- \bar{\nu}_\pi \nu_\tau \]
\[ \tau^- \to \rho^- \bar{\nu}_\rho \nu_\tau \]
**The fitting variables**

- **Signal combined**
  - All Background

- **MC**

The most powerful separation variable!

---

$B^+ \rightarrow \tau^+ \nu_{\tau}$

Using these variables for 2D histogram PDF fitting.

**Improves the signal significance by about 20%**

Use of 2-D fitting will reduce the sensitivity to peaking backgrounds in $E_{ECL}$.

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Peaking background **enhanced** sample

$B^0$-tagged Data

![Graph](image)

$B^0$-tagged total

- without reconstructed KL
- with reconstructed KL

Background rejection using the $K_L$ is introduced

$\Rightarrow$ Effective to reduce the peaking background

**Improves the signal significance by about 5%**

Belle full data + improvement of analysis

Expected signal significance : $6.3\sigma$ for $\text{Br}(B \rightarrow \tau\nu)=1.65 \times 10^{-4}$
Validation of Analysis
Validated with Data

1. Sophisticated B tagging algorithm
2. Background rejection using $K_L$
3. $E_{ECL}$ and $M_{miss}^2$ signal/BG shape of MC

Reconstruction efficiencies calibrated with Data

Confirmed with Control Samples

$B^+ \rightarrow \tau^+ \nu_\tau$

$E_{ECL}$ (GeV)

$M_{miss}^2$ (GeV$^2$/c$^4$)

$B(B^- \rightarrow D^{*0}\ell^-\bar{\nu}_\ell) = [5.60 \pm 0.22 (stat) \pm 0.28 (syst)]\%$

Consistent with the PDG world average: (5.68 \pm 0.19)\%
Unblind the Data!

2D ML fit to $E_{ECL} - M_{miss}^2$ Fit to Data Results.

$B^+ \rightarrow \tau^+ \nu_\tau$

Previous hadronic tag result at Belle $\mathcal{B} = [1.79^{+0.56}_{-0.49}(\text{stat})^{+0.46}_{-0.51}(\text{syst})] \times 10^{-4}$ → 1.9σ difference
$B^+ \rightarrow \tau^+ \nu_\tau$

New Result

Babar SL: $1.70 \pm 0.8 \pm 0.2$
PRD81:051101(2010)

Babar Had.: $1.80^{+0.57}_{-0.54} \pm 0.26$
arXiv:1008.0104

Babar Ave.: $1.76 \pm 0.49$
arXiv:1008.0104

Belle SL: $1.54^{+0.38}_{-0.37} \pm 0.29$
PRD82:071101(2010)

Belle Had.: $0.72^{+0.27}_{-0.25} \pm 0.11$
ICHEP 2012

Belle: $0.96 \pm 0.22 \pm 0.13$
Combination ICHEP 2012

WA (private):
$1.14 \pm 0.23$

$BR(B \rightarrow \tau \nu) \times 10^4$
Summary

- With reprocessed data and improved hadronic tagging of $B$, Belle extends its sensitivity to semileptonic and leptonic decays.

- Many recent results on exclusive semileptonic decays (clean measurements of $B \rightarrow \pi \ell \nu$, $B \rightarrow \rho \ell \nu$, and related modes). $\frac{d\Gamma(B \rightarrow \pi \ell \nu)}{dq^2}$ is used to extract $|V_{ub}|$.

- New results for ICHEP2012 on purely leptonic modes: $B \rightarrow \ell \nu$ ($\ell = e, \mu$) and $B \rightarrow \tau \nu$

- $B \rightarrow \mu \nu$: The best constraint to date using hadronic tags.

- Un-blinded new $B \rightarrow \tau \nu$ result with hadronic tags. New result will move the world average much closer to the result from the CKM unitarity triangle fit.
BACK-UP SLIDES
$\mathcal{L}_{\text{peak}} = 21.1 \text{ nb}^{-1} \text{s}^{-1}$

**Belle Detector**

- Superconducting cavities (HERF)
- KEKB B-Factory
- Si vtx. det.
- 2 lyr. DSSD
- 14/15 lyr. RSC-Fe
- Csl(Tl) 1.5m
- TDR converter
- 8 GeV $e^+$
- 3.5 GeV $e^-$
- Central Drift Chamber
- small cell + He/C$_2$H$_6$
- $\mu / K^0$ detection

**Graph:**

- $\int L \, dt = 1039 \text{ fb}^{-1}$
- KEKB
- PEP-II

**Data Points:**

- $Y(5S): 121 \text{ fb}^{-1}$
- $Y(4S): 711 \text{ fb}^{-1}$
- $Y(3S): 3 \text{ fb}^{-1}$
- $Y(2S): 25 \text{ fb}^{-1}$
- $Y(1S): 6 \text{ fb}^{-1}$

**Scan Data:**

- $> 1 \text{ ab}^{-1}$
- Off resonance:
  - $Y(4S): 433 \text{ fb}^{-1}$
  - $Y(3S): 30 \text{ fb}^{-1}$
  - $Y(2S): 14 \text{ fb}^{-1}$
  - $100 \text{ fb}^{-1}$

- $550 \text{ fb}^{-1}$
- Off resonance:
  - $54 \text{ fb}^{-1}$
Hadronic Tagging Method

Same purity level, more signal BB


\[ M_{bc} = \sqrt{E_{\text{beam}}^2 - p_B^2} \]

*Previous algorithm*

Signal: \( \sim 135\,000 \),
Purity: \( \sim 26\% \)

Signal: \( \sim 66\,000 \),
Purity: \( \sim 26\% \)

Michael Feindt (2011)
**Signal Event Selection**

\[ B^+ \rightarrow \ell^+ \nu_\ell \ (\ell = e, \mu) \]

- **e**: electron probability > 0.9 for e-mode study
- **μ**: muon probability > 0.9, \( \chi^2 > 0 \) for μ-mode study

\[ dr < 0.05 cm, \ dz < 1.5 cm \]

\[ |\Delta E^{tag}| < 0.05 GeV: \text{ quality of the tagged-}B \text{ reconstruction} \]

\[ \ln(N_{B output}) > -6: \text{ consistancy with } N(BB)^{tag} \text{ count condition} \]

**[Continuum Suppression]**

For e-mode search: \( |\cos \theta_{thrust}| < 0.9 \)

For μ-mode search: \( |\cos \theta_{thrust}| < 0.8 \) to suppress fake π, K’s

\[ M_{bc}^{tag} > 5.27 \text{ GeV} \quad E_{ECL} < 0.5 \text{ GeV} \]

\[ 2.6 < p_\ell^B < 2.7 \text{ GeV}: \text{ this variable is planned to be optimized. However for the MC study we assume the cut described.} \]
Background MC Validation \( B^+ \rightarrow \ell^+ \nu_\ell \) \( (\ell = e, \mu) \)

Comparison of data and MC at \( p^B_\ell \) sideband region: \( 2.0 < p^B_\ell < 2.5 \) (GeV/c)
Background MC PDF Modeling

Electron mode

\[ B^+ \rightarrow \ell^+ \nu_\ell \ (\ell = e, \mu) \]

- \( b \rightarrow c \) (data x5)
- \( b \rightarrow u \nu \) (data x20)
- \( b \rightarrow s, d \) or leptonic (data x50)
**Background MC PDF Modeling**

Muon mode

\[ B^+ \rightarrow \ell^+ \nu_\ell \ (\ell = e, \mu) \]

- \( b \rightarrow c \) (data x5)
- \( b \rightarrow s, d \) (data x50)
- \( b \rightarrow ul\nu \) (data x20)
- \( b \rightarrow \mu\nu\gamma \) (data x500)

Next = 61 +/- 8

Next = 132 +/- 11

Next = 46 +/- 7

Next = 264 +/- 16
**Signal Shape Correction with Data** \( B^+ \rightarrow \ell^+ \nu_\ell \ (\ell = e, \mu) \)

with \( B \rightarrow D^0 \ell \nu \) \( D^0 \rightarrow K^- \pi^+ \), \( K^- \pi^+ \pi^- \), \( K^- \pi^+ \pi^0 \), (\( D^0 \rightarrow K^- \pi^+ \) here)

![Graphs and histograms showing signal shape correction with data for \( B^+ \rightarrow \ell^+ \nu_\ell \) decays.](image-url)
The best $B_{tag}$ candidate selection:
Largest $N_{tag}$, the Neural-network output of hadronic tagging.

Variables of the tagged-$B$
\[ \Delta E = E_{taggedB} - E_{beam} \]
\[ M_{bc} = \sqrt{E_{beam}^2 - |p_B^*|^2} \]
### Selection criteria for the $B_{\text{sig}}$ reconstruction.

- $\tau^- \rightarrow \mu^- \bar{\nu}_e \nu_\tau$
- $\tau^- \rightarrow e^- \bar{\nu}_\mu \nu_\tau$
- $\tau^- \rightarrow \pi^- \nu_\tau$
- $\tau^- \rightarrow \rho^- \nu_\tau$

One signal-side track in $|\Delta z| < 3$ cm and $|\Delta r| < 0.5$ cm

No extra track in $|\Delta z| < 75$ cm and $|\Delta r| < 15$ cm

No signal-side $\pi^0$

One signal-side $\pi^0$

- $|M_{\pi^- \pi^0} - M_{\rho^-}| < 0.15$ GeV

No $K_L$ candidate reconstructed from KLM

- $-0.86 < \cos \theta_{\text{miss}}^* < 0.95$

- $M_{\text{miss}}^2 > 0.7$ (GeV/c$^2$)$^2$

- $E_{\text{ECL}} < 1.2$ GeV
Tagging efficiency calibration

**Signal** \( E_{ECL}, M^2_{miss} \) **Shape validation**

- B tagging efficiency is calibrated with the \( E_{ECL} \) sideband data
  - Same event topology as signal.
  - MC expectations for both signal and background are corrected.

- Confirmed by reconstructing \( B^- \rightarrow D^{*} l^- \bar{\nu}_l, D^{*} \rightarrow D^0 p^0, D^0 \rightarrow K p \) as signal

\[ B(B^- \rightarrow D^{*} l^- \bar{\nu}_l) = [5.60 \pm 0.22 \text{(stat)} \pm 0.28 \text{(syst)}] \% \]

Consistent with the PDG world average: (5.68+/-0.19)\%
Comparison of the tagged-B mode ratio
→ Good MC/Data agreement
→ Common scale applicable

\[ E_{ECL} \text{ sideband region: } 0.4 < E_{ECL} < 1.2 \text{GeV} \]
$E_{ECL}$ sideband region

Data

$5x$ Data amount of MC

Crystal Ball function

Bifurcated Gaussian

Argus

No contamination

Photon contamination

Others

$B^+ \rightarrow \tau^+ \nu_{\tau}$

Tagging efficiency calibration

<table>
<thead>
<tr>
<th>Group ID</th>
<th>Modes</th>
<th>Correction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$D^{*0}\pi^-, D^0\pi-, D^0K^-$</td>
<td>$1.07 \pm 0.07$</td>
</tr>
<tr>
<td>B</td>
<td>$D^{*0}\pi^-\pi^0, D^0\pi^-\pi^0$</td>
<td>$0.79 \pm 0.07$</td>
</tr>
<tr>
<td>C</td>
<td>$D^{*0}\pi^-\pi^-\pi^+, D^0\pi^-\pi^-\pi^+, D^+\pi^-\pi^-, D^{*0}\pi^-\pi^-\pi^+\pi^0$</td>
<td>$0.50 \pm 0.04$</td>
</tr>
<tr>
<td>D</td>
<td>$D^{*0}D_s^-, D^{*0}D_s^-, D^0D_s^-, D^0D_s^-, J/\psi K^-, J/\psi K^+\pi^-, J/\psi K^-\pi^0, J/\psi K_S\pi^-$</td>
<td>$0.96 \pm 0.12$</td>
</tr>
</tbody>
</table>
**$K_L$ efficiency calibration**

- It is essential to estimate the $K_L$ reconstruction efficiency with KLM in **data**.
  - The dominant component is the low momentum $K_L$ from $D$ decays in the background of $B \rightarrow \tau \nu$.
- The $K_L$ efficiency in data is calibrated using $D^{*+} \rightarrow D^0 \pi^+$, $D^0 \rightarrow \phi K_s$, $\phi \rightarrow K_s K_L$ decays.

Typical $K_L$ efficiency at 1GeV/c $\sim 11\%$

Reconstructed $m_{D^*}-m_D$ distribution in data

Estimated $K_L$ reconstruction efficiency confirmed with the B decay including $K_L$

$B^0 \rightarrow D^{*+} \pi^+$, $D^* \rightarrow D^0 \pi^+$, $D^0 \rightarrow K_L \pi^0$
$K_L$ rejection efficiency correction

Efficiency of $K_L^0$ Rejection
Data: $0.860 \pm 0.013$
MC: $0.824 \pm 0.005$
Data/MC: $1.04 \pm 0.02$
Background MC Validation

The MC $E_{ECL}$ and $M_{miss}^2$ distributions are confirmed by the BG control samples.
Background MC Validation

The MC $E_{ECL}$ and $M_{miss}^2$ distributions are confirmed by the BG control samples.

July 5, 2012

Leptonic & Semileptonic Decays at Belle @ ICHEP 2012
Corrections for data/MC differences

- Hadronic Tag efficiency correction
- $K^0_L$ rejection efficiency correction
- Branching fraction of peaking background modes, event by event correction
## Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal Yield</td>
<td>11.2</td>
</tr>
<tr>
<td>$N_{B\bar{B}}$</td>
<td>1.3</td>
</tr>
<tr>
<td>Reconstruction efficiency</td>
<td></td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.4</td>
</tr>
<tr>
<td>Br. of $\tau$</td>
<td>0.6</td>
</tr>
<tr>
<td>PID efficiency</td>
<td>1.0</td>
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<tr>
<td>$\pi^0$ efficiency</td>
<td>0.4</td>
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<tr>
<td>Tracking</td>
<td>0.3</td>
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<tr>
<td>$K_L^0$ veto</td>
<td>7.3</td>
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<tr>
<td>Tagging efficiency</td>
<td>8.5</td>
</tr>
<tr>
<td>Total</td>
<td>15.9</td>
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</table>

[Multiplicative uncertainties]  

<table>
<thead>
<tr>
<th>Source</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDF Histogram MC Statistics</td>
<td>+5.6</td>
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<tr>
<td>Signal $E_{ECL}$ Shape</td>
<td>+0.6</td>
</tr>
<tr>
<td>PHOTOS radiative correction</td>
<td>+0.0</td>
</tr>
<tr>
<td>Peaking BG, generic B</td>
<td>±1.3</td>
</tr>
<tr>
<td>Peaking BG, rare B</td>
<td>±1.9</td>
</tr>
<tr>
<td>Peaking BG, $b \to u\ell\nu$</td>
<td>±0.4</td>
</tr>
<tr>
<td>Efficiency ratio, MC stat</td>
<td>+0.1</td>
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<tr>
<td>$\tau$ branching fraction</td>
<td>+0.2</td>
</tr>
<tr>
<td>$\pi^0$ efficiency</td>
<td>±0.3</td>
</tr>
<tr>
<td>PID efficiency</td>
<td>+0.5</td>
</tr>
<tr>
<td>$K_L^0$ veto efficiency</td>
<td>+0.5</td>
</tr>
<tr>
<td>Tagging Efficiency in BG</td>
<td>±0.1</td>
</tr>
<tr>
<td>Total</td>
<td>±6.2</td>
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</table>

[Additive uncertainties]
**Fit Consistency Check**

In the fit for signal yield extraction, ratio between $\tau\nu$ components is fixed. Result of simultaneous fit floating each yield of $\tau\nu$ components

<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 obtained.
**Fit Consistency Check**

Comparison with different data range

Comparison with 1-D fit($E_{ECL}, M_{\text{miss}}^2$) and no $K_L^0$ Rejection

<table>
<thead>
<tr>
<th>Method/sample</th>
<th>Number of signal</th>
<th>Signal Eff.</th>
<th>Br. ($\times 10^{-4}$)</th>
<th>Significance (stat. only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal 2D fit</td>
<td>62.3$^{+23.1}_{-21.7}$</td>
<td>$1.12 \times 10^{-3}$</td>
<td>0.72$^{+0.27}_{-0.25}$</td>
<td>3.16</td>
</tr>
<tr>
<td>$E_{ECL}$ only</td>
<td>87.1$^{+26.5}_{-26.4}$</td>
<td>ditto</td>
<td>1.03$^{+0.32}_{-0.30}$</td>
<td>3.57</td>
</tr>
<tr>
<td>$M_{\text{miss}}^2$ only</td>
<td>67.9$^{+62.0}_{-58.8}$</td>
<td>ditto</td>
<td>0.78$^{+0.72}_{-0.68}$</td>
<td>1.16</td>
</tr>
<tr>
<td>without $K_L^0$ veto</td>
<td>65.3$^{+26.5}_{-25.0}$</td>
<td>$1.29 \times 10^{-3}$</td>
<td>0.65$^{+0.27}_{-0.25}$</td>
<td>2.81</td>
</tr>
</tbody>
</table>
Fit Consistency Check

Comparison with 1-D fit ($E_{ECL}, M_{\text{miss}}^2$) and no $K_L^0$ Rejection

Toy MC pseudo experiments generated from the yields of signal and BGs obtained from fit to the data.

Performed for 2-D and 1-D fits

Correlations of Statistical Significance between 2-D Fit and 1-D Fits
$MC$ distribution of $E_{ECL}$ and $M_{miss}^2$

$B^+ \rightarrow \tau^+ \nu_\tau$

Reconstructed from $\tau \rightarrow l\nu\nu$, $\pi\nu$, and $\rho\nu$.

Reconstructed from $\tau \rightarrow l\nu\nu$.

Reconstructed from $\tau \rightarrow \pi\nu$ and $\rho\nu$.

$E_{ECL}$
Signal (red): four signal tau modes combined.
BG (blue): all expected BGs for four signal tau modes combined.

$M_{miss}^2$
$\tau \rightarrow l\nu\nu$ signal (magenta): reconstructed as $\tau \rightarrow l\nu\nu$ (left), reconstructed as $\tau \rightarrow \pi\nu$ (right).
$\tau \rightarrow \pi\nu$, $\rho\nu$ signal (brown): reconstructed as $\tau \rightarrow \pi\nu$ and $\tau \rightarrow \rho\nu$. 
Peaking BG

- 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.

$B^+ \rightarrow \tau^+ \nu_\tau$

- $D^{(*)}l\nu$
- $\pi^0l\nu$
- $l\nu\gamma$
- $X_s\nu\nu$

MC: data $\times$ 10 for $b \rightarrow c$.
MC: data $\times$ 20 for $b \rightarrow u$.
MC: data $\times$ 50 for $B \rightarrow l\nu\gamma$ modes.
MC: data $\times$ 50 for $b \rightarrow s,d$ modes.
Comparison with 2006 result

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>hadronic tag</td>
<td>1D fit to $E_{ECL}$</td>
<td>hadronic tag(new) 2D fit to ($E_{ECL}$, $M_{miss}^2$)</td>
</tr>
<tr>
<td>N(BB) (x 10^6)</td>
<td>(set A) 449</td>
<td>771</td>
</tr>
<tr>
<td>Efficiency (x 10^-4)</td>
<td>3.0</td>
<td>11.2</td>
</tr>
<tr>
<td>N(signal yield)</td>
<td>24.1^{+7.6}_{-6.6}</td>
<td>54.1^{+18.8}_{-17.4}</td>
</tr>
<tr>
<td>Br($B^+ \rightarrow \tau^+\nu$) (x 10^-4)</td>
<td>1.79^{+0.56}_{-0.49}</td>
<td>1.08^{+0.37}_{-0.35}</td>
</tr>
</tbody>
</table>

**SET A**: the data-set used in 2006

**SET A’**: corresponds to the data-set used in 2006, but reproduced

**SET B**: corresponds to the data-set not used in 2006

All events used for the New Analysis

<table>
<thead>
<tr>
<th></th>
<th>Old (set A) vs. New (set B)</th>
<th>New results. set A’ vs. set B</th>
<th>Old (set A) vs. New (set A’): 1.2σ difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difference</td>
<td>2.5σ difference</td>
<td>1.6σ difference</td>
<td></td>
</tr>
</tbody>
</table>

*Old result (set A) vs. New (only for non-overlapping events in the set A) 
BF(non-overlapping events) = (0.6 ± 0.4) x 10^{-4} → 1.9σ difference

---

conservative comparison

1. Only with statistical error.
2. Assuming all the signal candidates in the old analysis become signal candidates in the new analysis.

New analysis based on improved tag, loose event selection, and re-processed data.
Leptonic & Semileptonic Decays at Belle @ ICHEP 2012

\[ \mathcal{B}(B^+ \rightarrow \tau^+ \nu) = \mathcal{B}_{\text{SM}} \times \left(1 - \frac{m_B^2}{m_{H^+}^2} \tan^2 \beta\right)^2 \]

W. Hou, PRD 48, 2342 (1993)

for this plot, we use

\[ B_{\text{SM}}(B^+ \rightarrow \tau^+ \nu) = (1.20 \pm 0.25) \times 10^{-4} \]

using \( f_B \) (HPQCD), \( |V_{ub}| \) (HFAG)

Note:

\[ \mathcal{B}_{\text{SM}} = 0.83 \pm 0.08 \text{ (UTfit)} \]

\[ \mathcal{B}_{\text{SM}} = 0.733^{+0.121}_{-0.073} \text{ (CKMfitter)} \]

Sensitivity to \( H^+ \) is complementary to LHC direct searches

Belle @ ICHEP 2012
**$K_L^0$ Rejection**

**OLD P14.**

Toy Monte Carlo study with and without $K_L^0$ Rejection

(Input $B(B^+ \rightarrow \tau \nu) = 1.65 \times 10^{-4}$ for signal MC)

- **With rejection**
  - $\chi^2/ndf = 9.968/10$
  - Constant: 94.26
  - Mean: 6.321
  - Sigma: 1.058

- **Without rejection**
  - $\chi^2/ndf = 8.959/10$
  - Constant: 93.61
  - Mean: 6.058
  - Sigma: 1.065

Expected Significance = 6.32(6.06) with(without) $K_L^0$ Rejection

---

**The fitting variables**

- Signal combined
- All Background
- **MC**

The most powerful separation variable!

(For $E_{ECL} < 0.2$ GeV)

**MC**

$\tau \rightarrow \ell \nu \nu$

$D^{(*)}\pi$

$D^{(*)}\rho$

$\tau \rightarrow \pi \nu, \rho \nu$

**Using these variables for 2D histogram PDF fitting.**

Use of 2-D fitting will reduce the sensitivity to peaking backgrounds in $E_{ECL}$. 