Measurement of $|V_{ub}|$ at Belle

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for
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Introduction

|V_{ub}| measurement
- Crucial to test the standard model of the CP violation.
- Both inclusive/exclusive $B \rightarrow X_u \ell \nu$ decays are useful.

Belle explores B tagging technique to extract $B \rightarrow X_u \ell \nu$ in good quality.
- Good signal-to-noise
- Sufficient statistics

In this talk, we report measurements of
- **Inclusive** $B \rightarrow X_u \ell \nu$ with fully reconstructed tag.
- **Exclusive** $B \rightarrow X_u \ell \nu$ with semileptonic decay tag.

Results are preliminary
Inclusive $B \rightarrow X_u l \nu$ w/ Fully Reconstructed Tag

- **Tagging side:**
  - Full reconstruction of $B_{\text{tag}}$ using hadronic decay modes.

- **Signal side:**
  - Lepton Detection
  - Neutrino reconstruction using $P_{\text{miss}}, E_{\text{miss}}$.
  - Reconstruction of $(m_X, q^2)$

```
K → π+ π-
B_{\text{tag}} → D^{(*)}π/ρ \text{ etc.}

\Gamma (4S) → e^- e^+
```

```
B_{\text{sig}} → X_u l \nu

m_X: \text{Hadronic inv. mass}
q^2: \text{Leptonic inv. mass}
```
Full Reconstruction of $B_{\text{tag}}$

- **Reconstructed modes (180 in total)**

  $$B^0 \rightarrow D^{(*)-} + \pi^+ / \rho^+ / a_1^+ / D^{(*)+}$$

  $$\bar{D}^0 \rightarrow 7 \text{ modes}$$

  $$D^- \rightarrow 6 \text{ modes}$$

  $$D^+ \rightarrow 2 \text{ modes}$$

  $$B^+ \rightarrow \bar{D}^{(*)0} + \pi^+ / \rho^+ / a_1^+ / D_S^{(*)+}$$

  $$\bar{D}_S^0 \rightarrow D^+ \gamma$$

- **$M_{bc}$ (beam constrained mass) distribution**

  140fb$^{-1}$ data

  **B$^0$ tag.**
  1.58 \times 10^5
  eff. = 0.21%
  purity = 47%

  **B$^+$ tag.**
  2.47 \times 10^5
  eff. = 0.33%
  purity = 50%

  Signal region: $M_{bc} > 5.26 \text{GeV/c}^2$, $-0.2 \text{ GeV} < \Delta E < 0.05 \text{ GeV}$
Reconstruction of Signal Side

Semileptonic lepton selection
- Lepton momentum \( P_l > 1.0 \text{ GeV/c} \)
- Lab. angle \( 26 \sim 140\text{deg.} \)
  + \( J/\psi \) veto, conversion veto etc.

Reduction of \( b\to c \) background
- Number of leptons \( N_l = 1 \)
- Total net charge \( \sum Q_i = 0 \)
- Missing mass \( -1.0 < MM^2 < 0.5 \text{ GeV}^2 \)
- Missing mom. Direction \( \cos \theta_{MM} < 0.95 \)
- Number of kaons \( N_{K^+} = N_{KS} = 0 \)

Phase space cut to minimize theory error
\[ m_X < 1.7 \text{ GeV/c}^2, \ q^2 > 8 \text{ GeV}^2 \]

※ same as our previous \((m_X, q^2)\) measurement with simulated annealing [PRL 92, 071802 (2004)]
Signal Yield Extraction

- Fit $M_{bc}$ distribution in each $m_X$ region with Gaussian+'Argus' to subtract the combinatorial background in the $B_{tag}$ sample.
- Fit the obtained $m_X$ distribution with expected $b \rightarrow u$ and $b \rightarrow c$ distribution.

$Nb \rightarrow u = 174 \pm 26$

- The number of semileptonic leptons is extracted by similar fitting on $M_{bc}$ before the $b \rightarrow u$ selection cut.

$N_{sl} = (5.07 \pm 0.4) \times 10^4$
Event Distribution in $m_X$ and $q^2$

- Event distribution in $m_X$ and $q^2$ with the normalization fixed to the fitting with the coarse bin.

$m_X$ distribution ($q^2 > 8\text{GeV}^2$)

$q^2$ distribution ($m_X > 1.7\text{GeV}/c^2$)

Inclusive $B \rightarrow X_u l \nu$

- $140\text{fb}^{-1}$

- Subtracted with the Expected $b \rightarrow c$ bkg.
Partial Branching Fraction

### Relative partial branching fraction

\[
\frac{\Delta B(B \rightarrow X_u \ell \nu)}{B(B \rightarrow X \ell \nu)} = \frac{N_{b \rightarrow u}}{N_{sl}} \times F \times \frac{1}{\varepsilon_{sel}^{b \rightarrow u}} \times \frac{\varepsilon_{frec}^{sl}}{\varepsilon_{frec}^{b \rightarrow u}} \times \frac{\varepsilon_{l}^{sl}}{\varepsilon_{l}^{b \rightarrow u}}
\]

**Corrections:**

- Unfolding the \(m_X/q^2\) resol. 0.984 ± 0.014
- \(b \rightarrow u\) selection efficiency: 0.274
- Full recon. efficiency ratio:
  \[0.75 ± 0.048\]
- Fraction of semileptonic leptons with \(P_l > 1.0\)GeV/c

### Partial branching fraction

\[
Br(B \rightarrow X \ell \nu) = 0.1073 ± 0.0028 \quad \text{(PDG2004)}
\]

140fb\(^{-1}\) preliminary

\[
\Delta B(B \rightarrow X_u \ell \nu) = \left[0.99 ± 0.15 ± 0.18 ± 0.04 ± 0.07\right] \times 10^{-3}
\]

\(m_X < 1.7\) GeV/c\(^2\), \(q^2 > 8\) GeV\(^2\)

2004/8/17
|\( V_{ub} |\) Determination

- Extrapolation to the total br.
  \[ B(B \to X_u \ell \nu) = \Delta B(B \to X_u \ell \nu) / f_u \]
- New determination of b-quark shape function (SF) parameters from Belle’s \( B \to X_s \gamma \) photon spectrum.
  \[ \pm \text{Higher order correction (FN \to BLL)} \]
  \[ \pm \text{Contribution from sub-leading SF + W.A.} \]
  \[ f_u = 0.294 \pm 0.044 \]

\[
B(B \to X_u \ell \nu) = \left[ 3.37 \pm 0.50 \pm 0.60 \pm 0.14 \pm 0.24 \pm 0.50 \right] \times 10^{-3}
\]

PDG formula \( |V_{ub}| = 0.00424 \left[ B(B \to X_u \ell \nu) \frac{1.61 \text{ps}}{0.002 \tau_B} \right]^{1/2} \) +latest HQ parameters

\[
|V_{ub}| = \left[ 5.54 \pm 0.42 \pm 0.50 \pm 0.12 \pm 0.19 \pm 0.42 \pm 0.27 \right] \times 10^{-3}
\]

\[ \text{stat. syst. } b \to u. \quad b \to c. \quad f_u \quad \text{Br} \to |V_{ub}| \]

140fb\(^{-1}\) preliminary
Exclusive $B \rightarrow X_u \ l \ \nu$ w/ Semileptonic Decay Tag

- New method for clean extraction of $B \rightarrow \pi \ l \ \nu, \ \rho \ l \ \nu$ decays.

![Diagram of B meson decays]

**Tagging side**

$B_{\text{tag}} \rightarrow D(\ast) \ l \ \nu$

**Signal side**

$B_{\text{sig}} \rightarrow \pi, \ \rho \ l \ \nu$

"Double semileptonic" decay.
**Analysis Method**

**Exclusive $B \rightarrow X_u \ell \nu$**

**Tag side reconstruction**

$B_{\text{tag}} \rightarrow D^{*+} \ell^- \overline{\nu} / D^+ \ell^- \overline{\nu}$

- $D^0 \pi^+ / D^+ \pi^0$
- 4 decay modes
- 7 decay modes

**Signal side reconstruction**

$B_{\text{sig}} \rightarrow X_u \ell^+ \nu$

- $\pi^+$ or $\pi^+ \pi^0$

$P_\ell > 0.8 \text{ GeV} / c$

$N(\pi^-) = 1, N(\pi^0) \leq 1$

**Kinematics of double semileptonic decay**

Back-to-back correlation of the two $B$ constrains their direction to the intersection of the 2 cones.

$x_B = \pm \sqrt{1 - \frac{1}{\sin^2 \theta_{12}} (\cos^2 \theta_B + \cos^2 \theta_B - 2\cos \theta_B \cos \theta_B \cos \theta_{12})}$.

To have intersection, must be $0 \leq x_B^2 \leq 1$.
Calibration with $B_{\text{sig}} \rightarrow D^* l \nu$ Decays

Validity of the method for double semileptonic decay detection has been tested with

$$B_{\text{sig}} \rightarrow D^* \ell^+ \bar{\nu} \rightarrow D^0 \pi^- \rightarrow K^+ \pi^-$$

The ratio $N_{\text{obs}} / N_{\text{expected}} = 0.89 \pm 0.08$ is used to correct the MC efficiency for $\pi l \nu$ and $\rho l \nu$ detection.

The method works!
Signal Extraction

We extract $\pi l \nu / \rho l \nu$ signals simultaneously by fitting 2D $(m_X, x^2)$ distribution.

- Fitting components: $\pi l \nu, \rho l \nu, \text{other } X_u l \nu, \text{BB background}$.
- PDF’s are based on MC.
- Constraint for extracted $\text{Br}$: $\text{Br}(\pi l \nu)+\text{Br}(\rho l \nu) + \text{Br(\text{other } X_u l \nu)} = \text{Br}(X_u l \nu)$

**Fitting results for all $q^2$ data.**

<table>
<thead>
<tr>
<th>$\pi l \nu$ $(82 \pm 13)$</th>
<th>$\rho l \nu$ $(65 \pm 20)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_X$ GeV/c$^2$</td>
<td>Entries</td>
</tr>
</tbody>
</table>

$\pi l \nu$ decays are cleanly extracted!
Extraction of $q^2$ Distribution

- $q^2$ distribution is extracted by fitting the $(m_X, x^2)$ distribution for three $q^2$ intervals.

$m_X$ dist. for three $q^2$ intervals

Extracted $q^2$ dist.

At the present accuracy, the obtained $q^2$ dist. does not exclude any tested models.

$B_{total} = [1.76 \pm 0.28 \pm 0.20 \pm 0.03] \times 10^{-3}$

FF-dep.

140 fb$^{-1}$

Preliminary
|\(V_{ub}|\) from \(B^0 \rightarrow \pi^- l^+ \nu\)

- \(|V_{ub}|\) determined from \(B > 16 \text{GeV}^2\) \((B^0 \rightarrow \pi^- l^+ \nu)\) with lattice QCD.

- w/ quenched LQCD \([\text{FNAL/JLQCD/APE/UKQCD}]\)
  - Average \(\tilde{\Gamma}_{\text{thy}} = 1.92^{+0.32}_{-0.12} \pm 0.47\)
  - \((3.90 \pm 0.71 \pm 0.23^{+0.62}_{-0.48}) \times 10^{-3}\)

- w/ unquenched LQCD \([\text{FNAL/HPQCD}]\)
  - Preliminary results reported at Lattice’04.
    - \(\text{FNAL’04}\) \(\tilde{\Gamma}_{\text{thy}} = 1.96 \pm 0.51 \pm 0.39\)
      - \((3.87 \pm 0.70 \pm 0.22^{+0.85}_{-0.51}) \times 10^{-3}\)
    - \(\text{HPQCD}\) \(\tilde{\Gamma}_{\text{thy}} = 1.31 \pm 0.33\)
      - \((4.73 \pm 0.85 \pm 0.27^{+0.74}_{-0.50}) \times 10^{-3}\)

- \(140 \text{fb}^{-1},\) preliminary
  - 4th error from \(\tilde{\Gamma}_{\text{thy}}\)
  - FF-dep. in Br is small for \(\pi l \nu\) data

Exclusive \(B \rightarrow X_u l \nu\)
Summary

We have obtained preliminary $|V_{ub}|$ results from

- **Inclusive $B \rightarrow X_u \, l \, \nu$ w/ fully reconstructed tag.**
  - Results are compatible and consistent with the previous exp’s.

- **Exclusive $B \rightarrow X_u \, l \, \nu$ ($B^0 \rightarrow \pi \, l \, \nu$) w/ semileptonic decay tag.**
  - Results are compatible and consistent with the previous exp’s and inclusive results.
  - New method for clean signal extraction has been demonstrated.

- These measurements are promising approach at B-factories in the coming years!

| $Belle \, |V_{ub}|$ |
|----------------|
| Achieved with various methods |

<table>
<thead>
<tr>
<th>$Belle , \pi l \nu$ w/ LQCD (quenched)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle 2004</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$Belle , \pi l \nu$ w/ LQCD (unquenched, preliminary)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FNAL04</td>
</tr>
<tr>
<td>HPQCD</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>$Belle , X_u \nu$</th>
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<tbody>
<tr>
<td>Inclusive w/ full-recon.</td>
</tr>
<tr>
<td>$(m_X, q^2)$ w/ $\nu$-recon.</td>
</tr>
<tr>
<td>$P_\nu$ end-point</td>
</tr>
</tbody>
</table>
Backup Slides
Inclusive $B \rightarrow X_u \ell \nu$

### Systematic Uncertainties

**b$\rightarrow$u MC**
- statistics $= 4\%$
- model dep. $= 4.2\%$
  - Variate inclusive parameters within errors

**b$\rightarrow$c MC**
- statistics $= 15\%$
- model dep. $= 5\%$
  - $D\nu$ ($\rho_D = 1.19 \pm 0.19$) ... 5.6%
  - $D^*\nu$ ($\rho_{A1} = 1.51 \pm 0.13$) ... 3.9%
  - $D^{**}\nu$ ... 1.6%

**Detector sim. for b$\rightarrow$c & b$\rightarrow$u MC $= 6.5\%$**

Correlated errors, added/subtracted in linear for the two MC’s

**Adding:**
- Kaon ID $= 6\%$
- tracking $= 2\%$

**Subtracting:**
- Lept. sel. $= 1\%$
- $\gamma$ clusters $= 1\%$

**Systematic error of $R_{e^{\text{freco}}}$ and $R_{e^{\text{lept}}}$ ... 6.4\%**
Systematic Uncertainty

Exclusive $B \rightarrow X_u \ell \nu$

Major contribution

$D^*\ell\nu$ calibration
- Statistics of detected $D^*\ell\nu$ 8.3%
- Error of $Br(B^0 \rightarrow D^*\ell\nu)$ 4.3%

$B\bar{B}$ background shape
- tested $\Delta B(\pi \ell \nu)$ ($\Delta B(\rho \ell \nu)$) in MC by
  - removing charged track by 1%
    - $-4.2(+23.5)$ %
  - removing $\pi^0$ by 3%
    - $-1.1(+12.8)$ %
  - Replacing $K^\pm$ with $\pi^\pm$ by 2%
    - $-0.5(+16.6)$ %

Significant change in $\Delta B(\rho \ell \nu)$, due to the broad width of $\rho$ meson.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\pi^-\ell^+\nu$</th>
<th>$\rho^-\ell^+\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking efficiency</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\pi^0$ reconstruction</td>
<td>$-$</td>
<td>3</td>
</tr>
<tr>
<td>Lepton identification</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Kaon identification</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$D^*\ell\nu$ calibration</td>
<td>9.8</td>
<td>9.8</td>
</tr>
<tr>
<td>$Br(X_u\ell\nu)$ in the fitting</td>
<td>0.2</td>
<td>3.4</td>
</tr>
<tr>
<td>$B\bar{B}$ background shape</td>
<td>4.4</td>
<td>31.5</td>
</tr>
<tr>
<td>$\frac{N_{B\bar{B}}}{f_+/f_0}$</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$\chi_d$</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>total</td>
<td>11.5</td>
<td>33.5</td>
</tr>
</tbody>
</table>
B$\rightarrow\pi$ Form-Factor from LQCD

- Four quenched calculations from FNAL, JLQCD, APE and UKQCD (used in CLEO2003).
  - Average $\tilde{\Gamma}_{thy} = 1.92^{+0.32}_{-0.12} \pm 0.47$
  - Include 15% quenching error

- Preliminary unquenched results from FNAL and HPQCD (reported at Lattice’04).
  - FNAL (M.Okamoto)
    $\tilde{\Gamma}_{thy} = 1.96 \pm 0.51 \pm 0.39$
  - HPQCD (J.Shigemitsu)
    $\tilde{\Gamma}_{thy} = 1.31 \pm 0.33$

( $\tilde{\Gamma}_{thy}$ given for $q^2>16\text{GeV}^2$ )
Error of FF from Unquenched LQCD

**FNAL’04**
\[ \tilde{\Gamma}_{phy} = 1.96 \pm 0.51(stat.) \pm 0.39(syst.) \]
- Statistical: \( \sim 10\% \)
- Lattice-continuum matching: \( \sim 7\% \)
- Chiral extrapolation: \( \sim 6\% \)
- Discritization: \( \sim 5\% \)
\[ \times 2 \]

**HPQCD**
\[ \tilde{\Gamma}_{phy} = 1.31 \pm 0.33 [0.13(stat) \pm 0.30(syst)] \]
- Statistical: \( \sim 5\% \)
- Higher oder operator matching: \( \sim 9\% \)
- Chiral extrapolation: \( \sim 5\% \)
\[ \times 2 \]

Number given by M.Okamoto (FNAL) and J.Shigemitsu (HPQCD) in private communications.