Exclusive charmed/charmless semileptonic decays of $B$ mesons

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on behalf of the Belle Collaboration

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- Charmed semileptonic decays
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Introduction

To test the unitarity of the CKM matrix and to search physics BSM it is important to measure values of the matrix elements. The easiest way to measure the elements $|V_{ub}|$ and $|V_{cb}|$ is to extract them from semileptonic $B$-meson decays where QCD uncertainties are under control.

Quark level

Decay rate is $\sim$ to $|V_{ub}|^2$ or $|V_{cb}|^2$
To test the unitarity of the CKM matrix and to search physics BSM it is important to measure values of the matrix elements. The easiest way to measure the elements $|V_{ub}|$ and $|V_{cb}|$ is to extract them from semileptonic $B$-meson decays where QCD uncertainties are under control.

**Hadron level**

Form factors are needed!
To test the unitarity of the CKM matrix and to search physics BSM it is important to measure values of the matrix elements. The easiest way to measure the elements $|V_{ub}|$ and $|V_{cb}|$ is to extract them from semileptonic $B$-meson decays where QCD uncertainties are under control.

Sides of the UT are still less accurate than angles $\Rightarrow$ we need more precise study of semileptonic decays especially charmless for $|V_{ub}|$ element.

Using full data set collected at $B$-factories and more advanced analysis techniques as well as theory development we can expect steady improvement of our knowledge of $B$ semileptonic decays.
Exclusive charmed/charmless semileptonic decays of $B$ mesons

**PEP-II/BABAR (1999-2008)**

- **On resonances:**
  - $\Upsilon(4S)$: $433 \text{ fb}^{-1}$
  - $\Upsilon(3S)$: $30 \text{ fb}^{-1}$
  - $\Upsilon(2S)$: $14 \text{ fb}^{-1}$
  - Off reson./scan: $54 \text{ fb}^{-1}$
  - Total: $550 \text{ fb}^{-1}$

**KEKB/Belle (1999-2010)**

- **On resonances:**
  - $\Upsilon(5S)$: $121 \text{ fb}^{-1}$
  - $\Upsilon(4S)$: $711 \text{ fb}^{-1}$
  - $\Upsilon(3S)$: $3 \text{ fb}^{-1}$
  - $\Upsilon(2S)$: $25 \text{ fb}^{-1}$
  - $\Upsilon(1S)$: $6 \text{ fb}^{-1}$
  - Off reson./scan: $100 \text{ fb}^{-1}$
  - Total: $>1 \text{ ab}^{-1}$
Matrix element of $B \to X_q \ell \bar{\nu}_\ell$ decay at first order

$$\mathcal{M}(B \to X_q \ell \bar{\nu}_\ell) = \frac{G_F}{\sqrt{2}} V_{qb} L^\mu H_\mu, \quad L^\mu = \bar{u}_\ell \gamma^\mu (1 - \gamma^5) \nu_\ell$$

Hadron current $H_\mu$ depends on specific final state.

The differential decay rate for $B \to D^{(*)} \ell \bar{\nu}_\ell$ process ($\ell = e, \mu$) can be expressed in terms of $w = v_B \cdot v_D = (m_B^2 + m_D^2 - q^2) / 2m_B m_D$, $(1 \leq w \leq w_{\text{max}})$

$$\frac{d\Gamma(\bar{B} \to D^{\ast} \ell \bar{\nu})}{dw \, d\cos \theta_\ell \, d\cos \theta_\nu \, d\chi} = \frac{G_F^2 |V_{cb}|^2}{48\pi^3} m_{D^\ast}^3 \sqrt{w^2 - 1} P(w) |\mathcal{F}(w, \cos \theta_\ell, \cos \theta_\nu, \chi)|^2$$

$$\frac{d\Gamma(\bar{B} \to D \ell \bar{\nu})}{dw} = \frac{G_F^2 |V_{cb}|^2}{48\pi^3} (m_B + m_D)^2 m_D^3 (w^2 - 1)^{3/2} |\mathcal{G}(w)|^2$$

This parametrization explicitly exploits that in HQ limit $\mathcal{F}(1) = 1$ and $\mathcal{G}(1) = 1$.

The differential decay rate for $B \to X_u \ell \bar{\nu}_\ell$ process ($\ell = e, \mu$) can be expressed in similar way except in this case more convenient to use hadron recoil $q^2$ for form factor parametrizations because Light Cone Sum Rule can predict form factor behavior at $q^2 = 0$. 
Charmed semileptonic decays
$B^0 \rightarrow D^{*-} \ell \bar{\nu}_\ell$ untagged analysis at Belle

- Data sample is $710 \text{ fb}^{-1}$, $123427 \pm 636$ signal events.
- Fit in 40 bins of $w$, $\cos \theta_\ell$, $\cos \theta_V$ and $\chi$ to obtain phenomenological form factor parameters based on Nucl. Phys. B 530, 153 (1998) [hep-ph/9712417].
- Fit result:
  \begin{align*}
  \mathcal{F}(1) |V_{cb}| &= (34.6 \pm 0.2 \pm 1.0) \times 10^{-3} \\
  \rho^2 &= 1.214 \pm 0.034 \pm 0.009 \\
  R_1(1) &= 1.401 \pm 0.034 \pm 0.018 \\
  R_2(1) &= 0.864 \pm 0.024 \pm 0.008 \\
  \chi^2/\text{ndf} &= 138.8/155
  \end{align*}

$\mathcal{B}(B^0 \rightarrow D^{*-} \ell \bar{\nu}_\ell) = (4.58 \pm 0.03 \pm 0.26)\%$
\[ \mathcal{F}(1) = 0.9077(51)(88)(84)(90)(30)(33) \] [PoS LATTICE 2010 (2010) 311]

\[ |V_{cb}| = (39.54 \pm 0.50_{\text{EXP}} \pm 0.74_{\text{LQCD}}) \times 10^{-3} \]
Exclusive $B \rightarrow D \ell \bar{\nu}_\ell$


$|V_{cb}| = (39.70 \pm 1.42_{\text{EXP}} \pm 0.89_{\text{LQCD}}) \times 10^{-3}$
Comparison with inclusive $|V_{cb}|$

HFAG EOF2011 inclusive (kinetic)

$m_c$ constraint

$B \rightarrow X_s \gamma$ constraint

HFAG EOF2011 exclusive

$B \rightarrow D \ell \bar{\nu}_\ell$

$B \rightarrow D^* \ell \bar{\nu}_\ell$

$|V_{cb}| \times 10^3$
\[ B^+ \rightarrow D_s^{(*)-} K^+ \ell \bar{\nu}_\ell \text{ at Belle (preliminary)} \]

\[ X_{\text{mis}} = \frac{E_{\text{beam}} - E_{\text{vis}} - |P_{\text{vis}}|}{\sqrt{E_{\text{beam}}^2 - m_B^2}} \]

Data set 605 fb\(^{-1}\)

High mass region (above \(D_sK\)) of charm semileptonic decays is not well known. Theory can use new measurement to improve description of this region.

Select signal in \(D_s \rightarrow \phi(K^+K^-)\pi\) mode, remaining particles must be consistent with \(B\) meson decay hypothesis in semileptonic mode.

<table>
<thead>
<tr>
<th>(X_c)</th>
<th>(B \times 10^4)</th>
<th>significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D_s^- K^+)</td>
<td>(3.0 \pm 0.9_{-0.8}^{+1.1})</td>
<td>3.4(\sigma)</td>
</tr>
<tr>
<td>(D_s^{*-} K^+)</td>
<td>(2.9 \pm 1.6_{-1.0}^{+1.1})</td>
<td>(&lt; 5.6) at 90% CL</td>
</tr>
<tr>
<td>Combined</td>
<td>(5.9 \pm 1.2 \pm 1.5)</td>
<td>6(\sigma)</td>
</tr>
</tbody>
</table>

consistent with BABAR result PRL\(107\)(2011)041804 [arXiv:1012.4158]

\[ B(B^+ \rightarrow D_s^{(*)-} K^+ \ell \bar{\nu}_\ell) = [6.13_{-1.03}^{+1.04} \text{(stat.)} \pm 0.43 \text{(syst.)} \pm 0.51(B(D_s))] \times 10^{-4} \]
Charmless semileptonic decays

• Data sample is 349 fb$^{-1}$, 7181 ± 279 $\pi^+\ell\nu$ and 3446 ± 208 $\pi^0\ell\nu$ events from binned maximum-likelihood fit

• $d\mathcal{B}/dq^2$ in 6 bins

\[ \mathcal{B}(B^0 \rightarrow \pi^+\ell\nu) = (1.41\pm0.05\pm0.07) \times 10^{-4} \]

assuming isospin symmetry
$B^0 \rightarrow \pi^+ \ell \bar{\nu}_\ell$ loose neutrino analysis at BABAR

- Data sample is 422.6 fb$^{-1}$, 11778 ± 435 πℓν events from fit
- $d\mathcal{B}/dq^2$ in 12 bins
- 0.3 % statistical correlation with untagged analysis

$$\mathcal{B}(B^0 \rightarrow \pi^+ \ell \bar{\nu}_\ell) = (1.42 \pm 0.05 \pm 0.07) \times 10^{-4}$$
$B^0 \rightarrow \pi^+ \ell \bar{\nu}_\ell$ loose neutrino analysis at Belle

- Data sample is 605 fb$^{-1}$, 21486 ± 548 $\pi\ell\nu$ events from fit
- $q^2$ bins for fit: 13 for $\pi\ell\nu$, 3 for $X_u\ell\nu$, 4 for $X_c\ell\nu$, continuum fixed

$$B(B^0 \rightarrow \pi^+ \ell \bar{\nu}_\ell) = (1.49\pm0.04\pm0.07) \times 10^{-4}$$

FNAL/MILC + Data + $Z$-expansion fit:

$$|V_{ub}| = (3.43 \pm 0.33) \times 10^{-3}$$
**$B^+ \to \omega \ell \bar{\nu}_\ell$ untagged analysis at BABAR**

- Submitted to PRD [arXiv:1205.6245]
- Data sample is $426 \text{ fb}^{-1}$, $1041 \pm 133$
  $\omega \ell \nu$ signal candidates from fit
- $d \mathcal{B}/dq^2$ in 5 bins
- Supersedes previous BABAR result
- Signal selection by Neural Net
- Yield extracted by binned maximum-likelihood fit in three dimensions ($\Delta E$, $m_{ES}$, $q^2$)

$B(B^+ \to \omega \ell \bar{\nu}_\ell) = (1.15 \pm 0.15 \pm 0.12) \times 10^{-4}$
Recently new reconstruction procedure of $B$ hadronic decays based on NeuroBayes package has been introduced in Belle. [NIM A654 (2011)]

New procedure tries to reconstruct $B$-meson in more than 1100 exclusive hadronic decay channels.

Compared to the previous cut based algorithm it offers roughly twice efficiency gain and about $2.1 \times 10^6$ of $B^\pm$ and $1.4 \times 10^6$ of $B^0$ with 710 fb$^{-1}$ collected at $\Upsilon(4S)$ resonance.

Hadronic tag has been calibrated with charm semileptonic decays with precision 4.2 % for $B^+$ and 4.5 % for $B^0$.
$B \rightarrow \pi \ell \bar{\nu}_\ell$ with hadronic tag at Belle

$B^+ \rightarrow \pi^0 \ell \bar{\nu}_\ell$

$B^0 \rightarrow \pi^+ \ell \bar{\nu}_\ell$

Full $\Upsilon(4S)$ dataset 710 fb$^{-1}$

New hadronic tag with Neural Net.

Yield extracted by binned maximum likelihood fit

Very clean signal with virtually no background

Fit in 13 bins of $q^2$ for $B^0 \rightarrow \pi^+ \ell \bar{\nu}_\ell$
and in 7 bins for $B^+ \rightarrow \pi^0 \ell \bar{\nu}_\ell$

<table>
<thead>
<tr>
<th>$\pi^+$</th>
<th>Yield</th>
<th>$B \times 10^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$461 \pm 28$</td>
<td>$1.49 \pm 0.09 \pm 0.07$</td>
<td></td>
</tr>
<tr>
<td>$\pi^0$</td>
<td>$230 \pm 22$</td>
<td>$0.80 \pm 0.08 \pm 0.04$</td>
</tr>
</tbody>
</table>

$\pi \ell \bar{\nu}_\ell$ $X_u \ell \bar{\nu}_\ell$ cross feed $p \ell \bar{\nu}_\ell$ cross feed $B \bar{B}$ $q \bar{q}$
New Belle result supersedes previous result with hadronic tag.

| Theory | $q^2$, GeV/c$^2$ | $|V_{ub}| \times 10^3$ |
|--------|-----------------|-------------------|
| LCSR1  | $< 12$          | $3.30 \pm 0.22 \pm 0.09 \pm 0.35$ |
| LCSR2  | $< 16$          | $3.62 \pm 0.20 \pm 0.10 \pm 0.60$ |
| HPQCD  | $> 16$          | $3.45 \pm 0.31 \pm 0.09 \pm 0.38$ |
| FNAL/MILC | $> 16$ | $3.30 \pm 0.30 \pm 0.09 \pm 0.36$ |

New results

Babar untagged (12 bins): $B \to \pi^0 l^+ l^-$

- $1.48 \pm 0.15 \pm 0.07$
- $1.49 \pm 0.09 \pm 0.07$ (New results)

Average: $B^0 \to \pi^0 l^+ l^-$

- $1.42 \pm 0.03 \pm 0.04$

$\chi^2$/dof = 7.4/11 (CL = 77.00 %)

| Theory | $q^2$, GeV/c$^2$ | $|V_{ub}| \times 10^3$ |
|--------|-----------------|-------------------|
| LCSR1  | $< 12$          | $3.30 \pm 0.22 \pm 0.09 \pm 0.35$ |
| LCSR2  | $< 16$          | $3.62 \pm 0.20 \pm 0.10 \pm 0.60$ |
| HPQCD  | $> 16$          | $3.45 \pm 0.31 \pm 0.09 \pm 0.38$ |
| FNAL/MILC | $> 16$ | $3.30 \pm 0.30 \pm 0.09 \pm 0.36$ |

$\chi^2$/dof = 58.9/31
$B \rightarrow \rho \bar{\nu}_\ell$ with hadronic tag at Belle

**Belle Preliminary**

$b + \rightarrow \rho^0 \ell \bar{\nu}_\ell$

- **Belle Preliminary**

- **Data - Unfolded**
  - BB
  - BZ
  - MS
  - ISGW2
  - UKQCD

- **Stat. errors only**

- **Fit in 11 bins of $q^2$ for $B^+ \rightarrow \rho^0 \ell \bar{\nu}_\ell$ and in 6 bins for $B^0 \rightarrow \rho^+ \ell \bar{\nu}_\ell$**

<table>
<thead>
<tr>
<th>$X_u$</th>
<th>Yield</th>
<th>$B \times 10^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho^+$</td>
<td>$338\pm28$</td>
<td>$3.17 \pm 0.27 \pm 0.18$</td>
</tr>
<tr>
<td>$\rho^0$</td>
<td>$632\pm35$</td>
<td>$1.86 \pm 0.10 \pm 0.09$</td>
</tr>
</tbody>
</table>

$\rho \bar{\nu}_\ell \ X_u \ell \bar{\nu}_\ell$ cross feed $B \bar{B}$ $q\bar{q}$
\( B \rightarrow \rho \ell \bar{\nu}_\ell \) branching fraction comparison & \( |V_{ub}| \)

New Belle result supersedes previous result with hadronic tag.

### Hadronic tag at Belle (preliminary)

| \( \chi^2 \) | Theory | \( q^2 \), GeV/\( c^2 \) | \( |V_{ub}| \times 10^3 \) |
|---|---|---|---|
| \( \rho^0 \) | \( \chi^2 = 7.4/7 \) (CL = 39.00 \%) | LCSR | \( < 16 \) | \( 3.60 \pm 0.11 \pm 0.09 \pm 0.37 \) |
| | | Beyer/Melikhov | \( < 21 \) | \( 3.80 \pm 0.11 \pm 0.10 \pm 0.31 \) |
| | | UKQCD | \( < 21 \) | \( 3.72 \pm 0.10 \pm 0.09 \pm 0.34 \) |
| | | ISWG2 | \( < 21 \) | \( 4.02 \pm 0.11 \pm 0.10 \pm 0.34 \) |
| \( \rho^+ \) | \( \chi^2 = 7.4/7 \) (CL = 39.00 \%) | LCSR | \( < 16 \) | \( 3.48 \pm 0.17 \pm 0.10 \pm 0.32 \) |
| | | Beyer/Melikhov | \( < 21 \) | \( 3.64 \pm 0.15 \pm 0.10 \pm 0.30 \) |
| | | UKQCD | \( < 21 \) | \( 3.56 \pm 0.15 \pm 0.10 \pm 0.28 \) |
| | | ISWG2 | \( < 21 \) | \( 3.84 \pm 0.16 \pm 0.11 \pm 0.33 \) |

**Average:**

\( \bar{B}^0 \rightarrow \rho^- \ell \bar{\nu}_\ell \)

\[ \frac{B(B^+ \rightarrow \rho^0 \ell \bar{\nu}_\ell)}{B(B^+ \rightarrow \rho^0 \ell \bar{\nu}_\ell)} = 2 \frac{\tau_{B^0}}{\tau_{B^+}} \]
$B^+ \rightarrow \omega \ell \bar{\nu}_\ell$ and $B^+ \rightarrow \eta(\prime) \ell \bar{\nu}_\ell$ with hadronic tag at Belle

**Signal $X_u \ell \bar{\nu}_\ell$ cross feed $B \bar{B}$ $q\bar{q}$**

<table>
<thead>
<tr>
<th>$X_u$</th>
<th>Yield</th>
<th>$B \times 10^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega$</td>
<td>99$\pm$15</td>
<td>$1.09 \pm 0.16 \pm 0.08$</td>
</tr>
<tr>
<td>$\eta$</td>
<td>39$\pm$11</td>
<td>$0.42 \pm 0.12 \pm 0.05$</td>
</tr>
<tr>
<td>$\eta' $</td>
<td>6.1$\pm$4.7</td>
<td>$&lt; 0.57 @ 90%$ CL</td>
</tr>
</tbody>
</table>
$B^+ \rightarrow \omega, \eta l\bar{\nu}_l$ branching fraction comparison

**BELLE**
1.19 ± 0.32 ± 0.06
**BABAR**
1.14 ± 0.16 ± 0.08
**Average**
1.15 ± 0.14 ± 0.06

**HFAG End Of 2011**

**BABAR (untagged)**
0.31 ± 0.06 ± 0.08
**BABAR (SL)**
0.64 ± 0.20 ± 0.03
**CLEO**
0.44 ± 0.23 ± 0.11
**BABAR (loose untagged)**
0.36 ± 0.05 ± 0.04
**Average**
0.37 ± 0.04 ± 0.04

**New results**

**Belle had.tag**
0.05 ± 0.12 ± 0.42

**New results $B(B^+ \rightarrow \omega l^+ \nu)$ [$\times 10^{-4}$]**

**New results $B(B^+ \rightarrow \eta l^+ \nu)$ [$\times 10^{-4}$]**
Comparison with inclusive $V_{ub}$
Conclusion

- Exclusive measurements of $|V_{cb}|$ from $B \rightarrow D^* \ell \bar{\nu}_\ell$ and $B \rightarrow D \ell \bar{\nu}_\ell$ with new lattice results agree with a high precision.

- Branching fractions of $B^+ \rightarrow D^- K^+ \ell \bar{\nu}_\ell$ and $B^+ \rightarrow D_s^{*-} K^+ \ell \bar{\nu}_\ell$ measured separately at Belle, first $M_{D_s K}$ spectrum measurement.

- New untagged result $B^+ \rightarrow \omega \ell \bar{\nu}_\ell$ from BABAR

- New hadronic tag at Belle offers twice efficiency gain.

- Simultaneous fit to the three untagged measurements (BABAR 6 $q^2$ bins, BABAR 12 $q^2$ bins, Belle) and the FNAL/MILC calculations yields $|V_{ub}| = (3.23 \pm 0.30) \times 10^{-3}$.

- New measurement of $B \rightarrow \pi \ell \bar{\nu}_\ell$ with hadronic tag at Belle consistent with untagged results.

- New measurement of $B \rightarrow \rho \ell \bar{\nu}_\ell$ decay with hadronic tag at Belle with precision comparable with world average.

- There is still tension at $2\sigma$ level between exclusive and inclusive measurements of $|V_{cb}|$ and $|V_{ub}|$. 
Backup
$B^+ \rightarrow \eta' \ell \bar{\nu}_\ell$ branching fraction comparison

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Branching Fraction (× 10^{-4})</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO</td>
<td>$2.66 \pm 0.80 \pm 0.56$</td>
</tr>
<tr>
<td>BABAR (SL)</td>
<td>$0.04 \pm 0.22 \pm 0.04$</td>
</tr>
<tr>
<td>BABAR (loose untagged)</td>
<td>$0.24 \pm 0.08 \pm 0.03$</td>
</tr>
<tr>
<td>Average</td>
<td>$0.23 \pm 0.08 \pm 0.03$</td>
</tr>
</tbody>
</table>

**New results**
- Belle had.tag: $< 0.57$ @ 90% CL

**HFAG**
- End Of 2011

$B(B^+ \rightarrow \eta' \ell \nu ) [\times 10^{-4}]$
Hadronic tag calibration at Belle

- Hadronic mode used as tags are not very well studied so we have big uncertainties in branching fractions as well as in decay dynamics which lead to big difference in tag efficiency between data and MC.
- Strategy is to use charm semileptonic decays as a tag and make correction for individual hadronic tag modes assuming factorizing reconstruction efficiencies.
- Charm semileptonic branching fractions were rescaled to recent PDG ones.
Hadronic tag calibration at Belle

The missing mass squared distribution was fitted separately for each hadronic tag mode and charmed semileptonic mode.

For each tag mode the average correction factor was calculated over all charmed semileptonic modes and used to reweight events in the MC.
Hadronic tag calibration at Belle

\[
\frac{N_{\text{Data}}}{N_{\text{MC}}} = 1.011 \pm 0.018_N \pm 0.025_B \pm 0.030_{\text{PID}} \\
= 1.011 \pm 0.045_{\text{tot}}, \\
\frac{N_{\text{Data}}}{N_{\text{MC}}} = 0.975 \pm 0.013_N \pm 0.030_B \pm 0.023_{\text{PID}} \\
= 0.975 \pm 0.042_{\text{tot}}
\]

For charmless semileptonic decays lepton ID systematic cancels out in ratio as well as decay rate of $\Upsilon(4S) \rightarrow B^0$ and $B^\pm$ mesons.