Charmless semileptonic B-decays

\[ B \rightarrow X_u \ l \ \nu \]
Outline

- Motivation
- Recent inclusive measurements
- Recent exclusive measurements
- Modelling related issues
- Summary
Motivation: the Flavour Sector and charmless semileptonic decays

- Charmless semileptonic decay rates and BR measurements allow the determination of $|V_{ub}|$

- $|V_{ub}|$ related to fundamental questions:
  - Test the weak coupling between the charged current and a $b$-$u$ quark pair
  - Consistency of the CKM paradigm in the Standard Model (SM)
  - $|V_{ub}|$ important parameter in global CKM fits

- **Inclusive & Exclusive** measurements
  - Independent experimental and theoretical methods and uncertainties
  - Rely upon calculation of form factors and partial decay rates for excl./incl.
Input from theory for $|V_{ub}|$

- **Exclusive:**
  - QCD absorbed in form factors

  $$
  \frac{d\Gamma(B \to \pi l\nu)}{dq^2} = \frac{G_F^2}{24\pi^3} p_\pi^3 |V_{ub}|^2 \times |f(q^2)|^2
  $$

  (2-1) form factors for pseudo-scalar
  3 form factors for vector ...

- **Inclusive: OPE**

  Operator Production Expansion predicts the total rate as:

  $$
  \Gamma_{SL} = |V_{cb}|^2 \frac{G_F^2 m_b^5}{192\pi^3} (1 + A_{EW}) A_{pert} \times \left[ c_0(r) + \frac{0}{m_b} + c_2(r, \frac{\mu_\pi^2}{m_b^2}, \frac{\mu_\rho^2}{m_b^2}) + c_3(r, \frac{\rho_D^3}{m_b^3}, \frac{\rho_{LS}^3}{m_b^3}) + \ldots \right]
  $$

  Free quark decay
  QCD Pert.
  Non-perturbative suppressed by $1/m_b^2$

  Quark masses: renorm. scheme dependent
Motivation: Charmless, semileptonic decays

- Charmless, semileptonic decays described by:
  1. Kinematic variables: \( q^2 = (p_{lep} + p_\nu)^2, \ p_{lep} \)
  2. Invariant hadronic mass \( M_X \)

- Complications:
  1. Small signal yields
  2. Drowned in 50 times more abundant \( b \to c \) transitions:
     - removing charm bkg \( \to \) tight kinematic cuts \( \to \) phase space regions with high theory uncertainties
     - exclusive decays provide more kinematic constraints
Experimental intro: tag and recoil method

- Experimental methods:
  1. Tagging techniques: known charge, flavour and kinematics

- Hadronic tagging at Belle: multivariate method (neural net) used for tag side selection
Presented Belle and BABAR measurements

- Inclusive and exclusive measurements in this talk:
  - Two most recent inclusive $X_u$ measurements at Belle 2010 and BABAR 2012
  - Untagged $\omega$ measurement (BABAR 2013)
  - SL tagged $\omega$ measurement (BABAR 2013)
  - Untagged $\pi, \eta, \eta', \omega$ (BABAR 2012)
  - Hadronically tagged $\pi, \rho, \omega$ (Belle 2013)
### Latest two inclusive measurements

<table>
<thead>
<tr>
<th></th>
<th>Belle</th>
<th>BABAR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dataset</strong></td>
<td>605 fb(^{-1})</td>
<td>426 fb(^{-1})</td>
</tr>
<tr>
<td><strong>Tag side selection</strong></td>
<td>Cut-based, hadronic</td>
<td>Cut-based, hadronic</td>
</tr>
<tr>
<td><strong>Signal side selection</strong></td>
<td>BDT trained using kinematic variables</td>
<td>Cut-based signal selection</td>
</tr>
<tr>
<td><strong>Purity</strong></td>
<td>(\approx 22%)</td>
<td>(\approx 18%)</td>
</tr>
<tr>
<td><strong>Lepton momentum selection</strong></td>
<td>(p_{lep}^* &gt; 1) GeV</td>
<td>(p_{lep}^* &gt; 1) GeV</td>
</tr>
<tr>
<td><strong>Signal extraction method</strong></td>
<td>2D fit in ((m_x, q^2))</td>
<td>1D fits using (p_l, m_x, q^2, P_+)</td>
</tr>
<tr>
<td><strong>Considered phase space regions</strong></td>
<td>-</td>
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</table>
Inclusive measurements

- **Belle selection**
  - Cut on BDT classifier (wrt/ total uncertainty)
  - Fit on $M_{BC}$ to estimate continuum and combinatorial backgrounds
  - Remaining $b \to c$ and secondaries background from 2dim fit in $M_X, q^2$

- **BABAR selection**
  - Cut-based
  - $M_{ES}$ fit for combinatorial bkg
  - $b \to u$ and “other bkg” yields from 2dim fit in $M_X, q^2$

\[ p_{lep}^* > 1\text{GeV} \]
Kaon veto, D* veto, missing mass, total charge

Projections of $m_X$ and $q^2$ after fit
components: $X_u, X_c$, fake, secondaries

components: $X_u$, bkg
Inclusive results

- **Leading uncertainties:** modelling, PID, tracking

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>ΔB/B BABAR</th>
<th>ΔB/B Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape function</td>
<td>5.6</td>
<td>3.6</td>
</tr>
<tr>
<td>Gluon popping</td>
<td>2.7</td>
<td>1.5</td>
</tr>
<tr>
<td>Resonances modelling</td>
<td>1.9</td>
<td>4.0</td>
</tr>
<tr>
<td>Unmeasured states</td>
<td>-</td>
<td>2.9</td>
</tr>
<tr>
<td><strong>Modelling total</strong></td>
<td><strong>6.5</strong></td>
<td><strong>5.8</strong></td>
</tr>
<tr>
<td>B → c</td>
<td>2.7</td>
<td>1.7</td>
</tr>
<tr>
<td><strong>PID and reconstruction</strong></td>
<td><strong>3.4</strong></td>
<td><strong>3.1</strong></td>
</tr>
<tr>
<td>other</td>
<td>2.1</td>
<td>2</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td><strong>8.4</strong></td>
<td><strong>8.1</strong></td>
</tr>
</tbody>
</table>

- **Good agreement between Belle and BABAR**

| Measurement | BLNP $|V_{ub}| \times 10^3$ | GGOU $|V_{ub}| \times 10^3$ | DGE $|V_{ub}| \times 10^3$ |
|-------------|-------------------|-----------------|-----------------|
| **BABAR**   | $4.28 \pm 0.23^{+0.18}_{-0.20}$ | $4.35 \pm 0.24^{+0.09}_{-0.10}$ | $4.40 \pm 0.24^{+0.12}_{-0.13}$ |
| Phys.Rev.D86,032004 |                |                 |                 |
| **Belle**   | $4.47 \pm 0.27^{+0.19}_{-0.21}$ | $4.54 \pm 0.27^{+0.10}_{-0.11}$ | $4.60 \pm 0.27^{+0.11}_{-0.13}$ |
| Phys.Rev.Lett.104:021801 |                |                 |                 |
| **Average all** | $4.40 \pm 0.15^{+0.19}_{-0.21}$ | $4.39 \pm 0.15^{+0.12}_{-0.14}$ | $4.45 \pm 0.15^{+0.15}_{-0.16}$ |

- **Belle:** minimized theory uncertainty on b-quark mass

- **Measurement over full phase space region due to 2dim fit → theory error minimized**

- **Current precision ~ 5%**
Untagged measurement of $B \to \omega \ell \nu$

- Relatively narrow vector resonance, more complicated FF structure
- Neural net selection, suppressing cont./charm bkg
- Estimation of combinatorial $B\bar{B}$ bkg with $\omega$-mass sideband fit
- Signal extraction via fit in $\Delta E, M_{ES}$
- Bins of $q^2 = (p_l + p_{miss})^2$

**Result:**

$$B(B^+ \to \omega \ell \nu) = (1.21 \pm 0.14 \pm 0.08) \times 10^{-4}$$

**Table:**

| $q^2$(GeV$^2$) | $|V_{ub}| \times 10^3$ |
|----------------|-----------------------|
| 0 – 12         | 3.37 ± 0.23 ± 0.38    |
| 12 – 21        | 3.04 ± 0.32 ± 0.37    |
| 0 – 21         | 3.23 ± 0.22 ± 0.38    |
SL tagged $B \to \omega l \nu$

- Tag-side tagged with semileptonic $D(\ast)$ decays
- Kinematics of $B$ from beam information and $\omega l$, $D^* l$ candidates
- $q^2 = (p_B - p_\omega)^2$
- Binned likelihood fit in $\cos \Phi_B, q^2$

Results:

$$B(B^+ \to \omega l \nu) = (1.35 \pm 0.21 \pm 0.11) \times 10^{-4}$$

LCSR  
|\text{Phys. Rev. D 71, 014029 (2005)}

$$|V_{ub}| = 3.41 \pm 0.31 \pm \text{theo.err.}$$
Untagged measurement of $B \rightarrow (\pi, \eta, \eta', \omega)l \nu$

- Making use of full BABAR dataset of $467.8 \cdot 10^6 B \bar{B}$
- Selection $\rightarrow$ momentum transfer sensitive
- Untagged, w/ loose neutrino reconstruction
  - Neutrino momentum $\rightarrow p_{miss}$
  - High signal and background yields
- Fit in $M_{ES}, \Delta E$, in $q^2$ bins
  - $q^2 = (p_B - p_{had})^2$
\[ B \rightarrow (\pi, \eta, \eta', \omega) l \bar{\nu} : \text{results} \]

\[ \Delta B(B \rightarrow \pi \ell \bar{\nu}_\ell)/\Delta q^2, \quad \Delta B(B \rightarrow \omega \ell \bar{\nu}_\ell)/\Delta q^2, \quad \Delta B(B \rightarrow \eta \ell \bar{\nu}_\ell)/\Delta q^2 \]

- For \( \pi \) two methods used to extract \( |V_{ub}| \): using lattice and LCSR calculations

| \( q^2 \) (GeV\(^2\)) | \( |V_{ub}| \times 10^3 \) |
|--------------------------|-----------------|
| LQCD                     | \( > 16 \)       | \( 3.47 \pm 0.13^{+0.60}_{-0.39} \) |
| LCSR                     | \( < 12 \)       | \( 3.46 \pm 0.10^{+0.37}_{-0.32} \) |
Hadronically tagged $B \rightarrow (\pi, \rho, \omega) l \nu$

- First hadronically tagged, exclusive charmless measurement at Belle \cite{PhysRevD.88.032005}
- Loose cuts on lepton momenta $0.3, \ 0.6 \ \text{GeV} \rightarrow e, \ \mu$
- New, multivariate NeuroBayes algorithm used, gain in statistics by factor of more than two
- Signal extracted in extended, binned likelihood fit in $M_{miss}^2$
Hadronically tagged $|V_{ub}|$ results

- Extraction of $|V_{ub}|$ from $\pi$, $\rho$, $\omega$ modes:

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

<table>
<thead>
<tr>
<th>$X_{ll}$</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0$</td>
<td>Khodjamirian et al.</td>
</tr>
<tr>
<td></td>
<td>Ball/Zwicky</td>
</tr>
<tr>
<td></td>
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<td>FNAL/MILC</td>
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<td>$\pi^+$</td>
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<tr>
<td>$\omega$</td>
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</tr>
<tr>
<td></td>
<td>ISGW2</td>
</tr>
</tbody>
</table>

Khodjamirian et al.  
PRD 83, 094031 (2011)

Ball/Zwicky  
PRD 71, 014015 (2005)  
PRD 71, 014029 (2005)

HPQCD  
PRD 73, 074502 (2006)

FNAL/MILC  
PRD 79, 054507 (2009)

UKQCD  
PLB 416, 392 (1998)

ISGW2  
PRD 52, 2783 (1995)

Theory error is not available.
Modelling of (non-)resonant decays

- HYBRID-models at Babar and Belle exclusive-inclusive $\rightarrow$ resonant-non-resonant
  1. Resonances: ISGW2 or SLPOLE.
  2. Non-resonant: “inclusive $V_{ub}$” with Defazio-Neubert model, with JETSET/Pythia for hadronisation

- Modelling “incomplete”

- Tensions: $\rho \rightarrow (\pi\pi), f_2(1270) \rightarrow \pi\pi$
  - Enhancement seen at mass of $f_2(1270)$ 3 times the model
  - $B \rightarrow (\pi\pi) l \nu$
    expect 334.9, observe $45.9 \pm 45.4$

- Challenge:
  - Understand high-mass regions
  - Study fragmentation

Hints: $b \rightarrow s$ gamma, sum of exclusives
Physical Review D 86 (2012) 052012
Modelling of (non-)resonant decays

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    expect 334.9, observe $45.9 \pm 45.4$

- Dispersion relations + ChPT:
  $M_x^{B \rightarrow (\pi \pi) l \nu}$ spectral function
Summary of exclusive $|V_{ub}|$

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield</th>
<th>Branching fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi$</td>
<td>12448 ± 361</td>
<td>1.45 ± 0.04 ± 0.06</td>
</tr>
<tr>
<td>$\omega$</td>
<td>1861 ± 233</td>
<td>1.21 ± 0.14 ± 0.10</td>
</tr>
<tr>
<td>$\eta$</td>
<td>867 ± 101</td>
<td>0.36 ± 0.03 ± 0.04</td>
</tr>
<tr>
<td>$\eta'$</td>
<td>141 ± 49</td>
<td>0.24 ± 0.08 ± 0.03</td>
</tr>
<tr>
<td>$\pi$</td>
<td>658 ± 50.3</td>
<td>1.49 ± 0.08 ± 0.07</td>
</tr>
<tr>
<td>$\rho$</td>
<td>964 ± 63.3</td>
<td>3.34 ± 0.15 ± 0.17</td>
</tr>
<tr>
<td>$\omega$</td>
<td>104 ± 19</td>
<td>1.07 ± 0.47 ± 0.07</td>
</tr>
<tr>
<td>$\omega$</td>
<td>SL tagged</td>
<td>103 ± 16</td>
</tr>
<tr>
<td>$\omega$</td>
<td>untagged</td>
<td>1125 ± 131</td>
</tr>
</tbody>
</table>

- 4 params $\rightarrow$ normalization $\propto V_{ub}$
- Only 4 theory points used

**Figure:**

- $\chi^2 = 60.2/44$, Fit prob 0.053

- $|V_{ub}^{excl}| = (3.28 \pm 0.29) \cdot 10^{-3}$
Tension in inclusive vs. exclusive $|V_{ub}|$

- Inclusive $|V_{ub}|$ “larger” than exclusive one
- Tension of $\approx 3\sigma$
- Reasons?
  - experimental?
  - theoretical?
  - Inbetween: modelling-related?
  - New Physics? Right-handed currents?
- New exclusive-inclusive Belle analysis on the way

Presented measurements

<table>
<thead>
<tr>
<th>Had tagged Belle</th>
<th>$B \rightarrow X_u l\nu$</th>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Had tagged BABAR</th>
<th>$B \rightarrow X_u l\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phys. Rev. Lett. 104, 021801</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Had tagged Belle</th>
<th>$B \rightarrow \pi l\nu$</th>
</tr>
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<tbody>
<tr>
<td>PHYS. REV. D88, 88.032005 (2013)</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Untagged BABAR</th>
<th>$B \rightarrow \pi l\nu$</th>
</tr>
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<tr>
<td>PHYS. REV. D86, 86, 092004(2012)</td>
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<tr>
<th>SL tagged BABAR</th>
<th>$B \rightarrow \omega l\nu$</th>
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<td>PHYS. REV. D88, 072006 (2013)</td>
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</table>

<table>
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<tr>
<th>Untagged BABAR</th>
<th>$B \rightarrow \omega l\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYS. REV. D 87, 032004 (2013)</td>
<td></td>
</tr>
</tbody>
</table>

$V_{ub} \times 10^{-3}$

Events

$M_X$ (GeV/c$^2$)

FPCP 2014 Marseille

Alexander Ermakov  Uni Bonn
Tension in inclusive vs. exclusive $|V_{ub}|$

- Inclusive $|V_{ub}|$ “larger” than exclusive one
- Tension of $\approx 3\sigma$
- Reasons?
  - experimental?
  - theoretical?
  - Inbetween: modelling-related?
  - New Physics? Right-handed currents?
- New exclusive-inclusive Belle analysis on the way

**HFAG2013**

**BCL**

$$|V_{ub}^{incl}| = (3.28 \pm 0.29) \cdot 10^{-3}$$

**BNLP**

$$|V_{ub}^{incl}| = (4.40 \pm 0.20 \pm 0.15) \cdot 10^{-3}$$
Summary and Outlook

- Consistent tagged and untagged exclusive measurements at BABAR and Belle
- New $V_{ub}$ measurements using higher mass states (omega) consistent
- Consistent inclusive measurements at BABAR and Belle using full respective datasets
- Tension of $\approx 3\sigma$ between inclusive and exclusive measurements
- Future:
  - Better and more complete understanding of mass spectrum composition
  - Measurement of fragmentation in light quark needs improvement
  - Lattice calculations for FF of higher mass states ($\rho, \omega, \eta$) desirable
  - New Physics? Right-handed currents?

Thanks!
Backup: right-handed currents

New physics observable via right-handed currents? \( |V_{ub}| = |V_{ub}^L| f(\epsilon'_R = \epsilon_R R \frac{V_{ub}^R}{V_{ub}^L}) \)

- \( B \to \rho \ell \nu \)
- \( B \to \omega \ell \nu \)
- \( B \to X_u \ell \nu \)
- \( B \to \tau \nu \)
- \( B \to \pi \ell \nu \)

**prel. Belle tagged**
**BaBar untagged**
**HFAG GGOU**
**HFAG + new Belle**
**HFAG Avg. with Lattice**

- \( f(\epsilon'_R): \)
  - \( B \to \pi \ell \bar{\nu}_\ell: 1 + \epsilon'_R \)
  - \( B \to \tau \bar{\nu}_\tau: 1 - \epsilon'_R \)
  - \( B \to X_u \ell \bar{\nu}_\ell: 1 + \epsilon'^2_R \)

Proposed by

**Private Fit**
- Solid: All
- Dashed: w/o \( \rho \) & \( \omega \)
- Input: see Backup

| Fit Scenario                      | \( |V_{ub}^L| \)  | \( \epsilon'_R \) | Tension wrt SM | \( \chi^2 \)/ndf | P-Value |
|----------------------------------|----------------|----------------|----------------|-----------------|---------|
| \( B \to \pi, X_u, \tau \) (dashed) | 4.07 ± 0.16    | −0.17 ± 0.06   | 2.8σ           | 2.8/1           | 0.09    |
| \( B \to \pi, X_u, \tau + \omega, \rho \) (solid) | 3.94 ± 0.15    | −0.12 ± 0.06   | 1.9σ           | 9.0/3           | 0.03    |