Experimental $|V_{ub}|$ review
Motivation: the Flavour Sector and charmless semileptonic decays

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

- Determining $|V_{ub}|$:
  - Test the weak coupling between the charged current and a b-u quark pair
  - Consistency of the CKM paradigm in the Standard Model
  - $|V_{ub}|$ constrains side opposite to $\phi_1$

- Inclusive & Exclusive measurements
  - Two experimental methods: tagged versus untagged
    - Give stat. Independent samples
  - Two different theoretical approaches:
    - inclusive versus exclusive final states
    - Complementary, independent theory uncertainties.
Inclusive measurements

**Belle** [Phys.Rev.Lett 104:021801]
- Hadronic tag, multivariate selection
- Fit on $M_{BC}$ to estimate continuum and combinatorial backgrounds
- Remaining $b \rightarrow c$ and secondaries background from 2dim fit in $M_X, q^2$

**BABAR** [Phys.Rev.D86,032004]
- Hadronic tag, cut-based selection
- $M_{ES}$ fit for combinatorial bkg.
- $b \rightarrow u$ and “other bkg” yields from 2dim fit in $M_X, q^2$

\[
\Gamma(b \rightarrow u\ell^+\nu) = \frac{G_F^2}{192\pi^2} |V_{ub}|^2 m_b^5 (1 + \text{補正項})
\]
in detail: talk by P.Gambino
### Latest Belle measurement

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

- Current precision ~ 5%

### Latest BABAR, different PS regions w/ consistent results

- BABAR
  - Phys. Rev. D86, 032004
  - 4.28 ± 0.23 +0.18
  - 4.35 ± 0.24 +0.09
  - 4.40 ± 0.24 +0.12

- Belle
  - Phys. Rev. Lett. 104:021801
  - 4.47 ± 0.27 +0.19
  - 4.54 ± 0.27 +0.10
  - 4.60 ± 0.27 +0.11

- Average all
  - 4.40 ± 0.15 +0.19
  - 4.39 ± 0.15 +0.12
  - 4.45 ± 0.15 +0.15

### Everything consistent for different experiments and different theory approaches + PS regions
Main sources: PID, tracking, **modelling**

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\Delta B/B$ BABAR</th>
<th>$\Delta B/B$ Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shape function</strong></td>
<td>5.6</td>
<td>3.6</td>
</tr>
<tr>
<td>Gluon popping</td>
<td>2.7</td>
<td>1.5</td>
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<tr>
<td><strong>Resonances modelling</strong></td>
<td>1.9</td>
<td>4.0</td>
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<tr>
<td>Unmeasured states</td>
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<td>2.9</td>
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<tr>
<td><strong>Modelling total</strong></td>
<td>6.5</td>
<td>5.8</td>
</tr>
<tr>
<td>$B \to c$</td>
<td>2.7</td>
<td>1.7</td>
</tr>
<tr>
<td>PID and reconstruction</td>
<td>3.4</td>
<td>3.1</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>
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</table>

Hints at inconsistencies in decay modelling in latest Belle exclusive analysis
Better SF determination: SIMBA

- Desirable to determine (LO) SF
  - in a data-driven manner
  - reducing the SF modelling dependency

\[ |V_{ub}| = \sqrt{\frac{\Delta B}{\tau_B \Delta \Gamma_{theo}}}. \]

[Toy SuperB]

\[ B \to X_u \gamma + X_u \ell \nu \quad 75 \text{ab}^{-1} \]

Preliminary

(exp. uncertainties only)

[Bernlochner, CKM 2012]
Exclusive measurements

- Pion final state most precise, both theoretically and experimentally
- Selection and reconstruction & theory → momentum transfer sensitive
- Untagged measurements with best statistics
- For higher resonances latest Belle hadronic tag measurement: promising

\[ \frac{d \Gamma(B \rightarrow h \ell \bar{\nu}_\ell)}{dq^2} \sim G_F^2 |V_{ub}|^2 L^{\mu\nu} H_{\mu\nu} \]

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

Khodjamirian et al. \( q^2 < 12 \text{ GeV}^2 \)
\( 3.41 \pm 0.06 + 0.37 - 0.32 \)

Ball-Zwicky \( q^2 < 16 \text{ GeV}^2 \)
\( 3.58 \pm 0.06 + 0.59 - 0.40 \)

HPQCD \( q^2 > 16 \text{ GeV}^2 \)
\( 3.52 \pm 0.08 + 0.61 - 0.40 \)

FNAL/MILC \( q^2 > 16 \text{ GeV}^2 \)
\( 3.36 \pm 0.08 + 0.37 - 0.31 \)
Hadronically tagged $B \rightarrow (\pi, \rho, \omega) l \nu$

First published hadronically tagged, exclusive charmless measurement at Belle

Multivariate algorithm for tagging

Loose cuts on lepton momenta

Signal extracted in extended, binned likelihood fit in $M_{miss}^2$

Total signal yields → $104 \pm 19$

$\pi^0$

964 ± 63.3

$\rho^0$

658 ± 50.3

$\omega$

$\rho^+$

$\pi^+$

Theory

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

$\chi^2$

Table:

<table>
<thead>
<tr>
<th>$\pi^0$</th>
<th>Khodjamirian et al.</th>
<th>Ball/Zwicky</th>
<th>HPQCD</th>
<th>FNAL/MILC</th>
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<td>$\pi^+$</td>
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<td>FNAL/MILC</td>
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<td>$\rho^0$</td>
<td>Ball/Zwicky</td>
<td>UKQCD</td>
<td>ISGW2</td>
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<tr>
<td>$\rho^+$</td>
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</tr>
<tr>
<td>$\omega$</td>
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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
PLE 416, 392 (1998)

ISGW2
PRD 52, 2783 (1995)

Theory error is not available.
Hadronically tagged $B \rightarrow (\pi, \rho, \omega) \ l \ \nu$

[Phys. Rev. D 88, 032005 (2013)]

- Enhancement seen at mass of $f_2(1270)$, 3 times the MC predictions (ISGW2 & Pythia 6.2)
- $B \rightarrow (\pi\pi) \ l \ \nu$ expect 334.9, observe $45.9 \pm 45.4$

- Tensions in description of final state yields and fragmentation
Non-parametric uncertainties

- HYBRID-models at Babar and Belle: exclusive & inclusive $\rightarrow$ resonant & non-resonant
  - 1. Resonances + “inclusive rest”

- Modelling “inconsistent & incomplete”

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

Hints: $b \rightarrow s$ gamma, sum of exclusives

\[ B \rightarrow \rho(\rightarrow \pi\pi)l\nu \]

Important for future analyses, e.g RH currents, helicity studies...

Dispersion relations + $\chi_{PT} \rightarrow$ spectral function

 Originally from CLEO
 Further developed by BABAR
$B \rightarrow (\pi, \eta, \eta', \omega) l \nu$ untagged results

- For $\pi$ two regions of PS to extract $|V_{ub}|$ using lattice and LCSR calculations

Untagged full BABAR dataset $467.8 \cdot 10^6 B \bar{B}$

| Method  | $q^2$ (GeV$^2$) | $|V_{ub}| \times 10^3$  |
|---------|-----------------|-------------------------|
| LQCD    | $> 16$          | $3.47 \pm 0.13^{+0.60}_{-0.39}$  |
| LCSR    | $< 12$          | $3.46 \pm 0.10^{+0.37}_{-0.32}$  |
recent $B \to \omega \ell \nu$

- 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 $\Delta E, M_{ES}$


- Tag-side tagged with semileptonic $D^{(*)}\ell\nu\bar{c}$ candidates
- Kinematics of $B$ from beam information and $\omega\ell, D^{(*)}\ell$ candidates
- Binned likelihood fit in $\cos\Phi_B, q^2$

Two intersecting cones

\[ B(B^+ \to \omega\ell\nu) = (1.21 \pm 0.14 \pm 0.08) \times 10^{-4} \]
\[ B(B^+ \to \omega\ell\nu) = (1.19 \pm 0.16 \pm 0.09) \times 10^{-4} \]

previous $B(B^+ \to \omega\ell\nu) = (1.35 \pm 0.21 \pm 0.11) \times 10^{-4}$
Recent paper estimated baryon-antibaryon form factors, predicted BR of $(1.04 \pm 0.38) \times 10^{-4}$ in Phys. Lett. B 704, 495 (2011).

Full Belle data set, hadronic tag.

Fit in $M_{miss}^2$

Result: BF $(5.8^{+2.4}_{-2.1} \pm 0.9) \times 10^{-6}$, upper limit at 90% C.L. of $9.6 \times 10^{-6}$

Summary of exclusive $|V_{ub}|$

- BCL: combined fit to data and theory prediction
  
  \[ \text{Phys. Rev.} \text{D79, 054507 (2009)} \]

- 4 params $\propto V_{ub}$

- 4 theory points used

HFAG Eo2013

\[ |V_{ub}^{excl}| = (3.28 \pm 0.29) \cdot 10^{-3} \]
• Inclusive $|V_{ub}|$ “larger” than exclusive one

• Persistent tension of $\approx 3\sigma$

• BABAR and Belle agree

• Reasons:
  • Theory
  • Experiment
  • Modelling
  • NP

Most recent $|V_{ub}|$ measurements

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

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

- Persistent tension in $|V_{ub}|$ between inclusive and exclusive measurements $\approx 3\sigma$
- Wishes and points to be understood better:
  - Composition of invariant hadronic mass spectrum & fragmentation in light quark
  - SF modelling → SIMBA: data-driven + reduced model dependence
  - UNQUENCHED lattice calculations for FF of higher mass states ($\rho, \omega, \eta$) desirable

Thanks!
Untagged $B \rightarrow \omega l \nu$

- Untagged measurement of $B \rightarrow \omega l \nu$
- 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:**

$$B(B^+ \rightarrow \omega l \nu) = (1.21 \pm 0.14 \pm 0.08) \times 10^{-4}$$
Tag-side tagged with semileptonic $D^{(*)}$ 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  

$|V_{ub}| = 3.41 \pm 0.31 \pm \text{theo.err.}$
**EXCLUSIVE**

SL tagged $B \rightarrow \omega \ l \ \nu$

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

**Results:**

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

**LCSR**  

$|V_{ub}| = 3.41 \pm 0.31 \pm \text{theo.err.?}$

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**Two intersecting cones**

- Data
- Ball & Zwicky
- ISGW2

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LCSR  

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 $b \rightarrow c$ transitions:
     - removing charm bkg → tight kinematic cuts → 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
## Latest two inclusive measurements

<table>
<thead>
<tr>
<th></th>
<th>Belle</th>
<th>BABAR</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dataset</td>
<td>$605 \text{ fb}^{-1}$</td>
<td>$426 \text{ fb}^{-1}$</td>
</tr>
<tr>
<td>Tag side selection</td>
<td>Cut-based, hadronic</td>
<td>Cut-based, hadronic</td>
</tr>
<tr>
<td>Signal side selection</td>
<td>BDT trained using kinematic variables</td>
<td>Cut-based signal selection</td>
</tr>
<tr>
<td>Purity</td>
<td>$\approx 22%$</td>
<td>$\approx 18%$</td>
</tr>
<tr>
<td>Lepton momentum selection</td>
<td>$p_{lep}^* &gt; 1 \text{ GeV}$</td>
<td></td>
</tr>
<tr>
<td>Signal extraction method</td>
<td>2D fit in $(m_x, q^2)$</td>
<td></td>
</tr>
<tr>
<td>Specific phase space regions</td>
<td>1D fits using $p_l, m_x, q^2, P_+$</td>
<td></td>
</tr>
</tbody>
</table>
Untagged measurement of $B \to (\pi, \eta, \eta', \omega) l \nu$

- 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 $\rightarrow p_{\text{miss}}$
  - High signal and background yields
- Fit in $M_{ES}, \Delta E$, in $q^2$ bins
- $q^2 = (p_B - p_{\text{had}})^2$
**Inclusive results**

**Good agreement between Belle and BABAR**

- **Measurement**
  - **BLNP** $|V_{ub}| \times 10^3$
    - BABAR
      - Phys. Rev. D 72, 073006 (2005)
      - 4.28 ± 0.23$^{+0.18}_{-0.20}$
    - Belle
      - Phys. Rev. Lett. 104:021801
      - 4.47 ± 0.27$^{+0.19}_{-0.21}$
    - Average all
      - 4.40 ± 0.15$^{+0.19}_{-0.21}$
  - **GGOU** $|V_{ub}| \times 10^3$
    - BABAR
      - JHEP 0710, 058 (2007)
      - 4.35 ± 0.24$^{+0.09}_{-0.10}$
    - Belle
      - JHEP 0710, 058 (2007)
      - 4.54 ± 0.27$^{+0.10}_{-0.11}$
    - Average all
      - 4.39 ± 0.15$^{+0.12}_{-0.14}$
  - **DGE** $|V_{ub}| \times 10^3$
    - BABAR
      - 4.40 ± 0.24$^{+0.12}_{-0.13}$
    - Belle
      - 4.60 ± 0.27$^{+0.11}_{-0.13}$
    - Average all
      - 4.45 ± 0.15$^{+0.15}_{-0.16}$

- **Measurement over full phase space region → theory error minimized**
- **Current precision ~ 5%**