Semileptonic $B_{(s)}$ Decays
IUPAP Young Scientist Award

Phillip Urquijo
ICHEP
July 10, 2012

Thank you to my colleagues who worked with me on many of the measurements in this talk, particularly from Belle, LHCb, Heavy Flavour Averaging Group
About me


THE UNIVERSITY OF MELBOURNE

Université de Genève

Syracuse University

universität bonn

Semileptonic B decays, \(|V_{ub}|, |V_{cb}|\)

CKM co-convenor, Rare B, & \(B_s\)

ATLAS EXPERIMENT

http://atlas.ch

e/\gamma trigger, SUSY

\(\tau\) trigger deputy coordinator

LHCb

\(\sigma(b\bar{b}), f_s\)

Analysis framework

Semileptonic B decays, IUPAP Prize, ICHEP 2012

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$|V_{cb}|$, $|V_{ub}|$ and the Unitarity Triangle

- New physics searches in the flavour sector require precise and over-constraining measurements of the sides and angles of the Unitarity Triangle.
- Must measure CKM matrix elements, fundamental parameters of the Standard Model and cannot be predicted.
- $|V_{cb}|$ and $|V_{ub}|$ have a special role in the UT
  - Accessible from Tree Level processes.
  - Free of New Physics in loops

\[ \Gamma_x \equiv \Gamma(b \rightarrow x\ell\nu) \propto |V_{xb}|^2 \]

<table>
<thead>
<tr>
<th>2004</th>
<th>PDG</th>
<th>Prec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>V_{td}/V_{ts}</td>
<td>$</td>
</tr>
<tr>
<td>$\Phi_1$</td>
<td>$(23.5 \pm 2.1)$</td>
<td>9%</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}/V_{cb}</td>
<td>$ inclusive</td>
</tr>
</tbody>
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$|V_{cb}|$, $|V_{ub}|$ and the Unitarity Triangle

- New physics searches in the flavour sector require precise and over-constraining measurements of the sides and angles of the Unitarity Triangle.
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<tr>
<td>$</td>
<td>V_{td}/V_{ts}</td>
<td>$</td>
</tr>
<tr>
<td>$\Phi_1$</td>
<td>(21.4±0.8)</td>
<td>3.7%</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}/V_{cb}</td>
<td>$ inclusive</td>
</tr>
</tbody>
</table>

Symplectic $B$ decays, IUPAP Prize, ICHEP 2012  
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Semileptonic B decays

**tree level, short distance:**

\[ b \rightarrow c e \nu \]

Decay properties depend directly on \(|V_{cb}| \) & \(|V_{ub}| \) and \( m_b \) in the **perturbative regime** \((\alpha_s^n)\).
Semileptonic B decays

**tree level, short distance:**

\[
B \rightarrow D e \nu
\]

Decay properties depend directly on \(|V_{cb}| \& |V_{ub}|\) and \(m_b\) in the perturbative regime \((\alpha_s^n)\).

But quarks are bound by soft gluons: non-perturbative long distance interactions of \(b\) quark with the light quark in the \(B\) meson.
Semileptonic B decays

Decay properties depend directly on $|V_{cb}|$ & $|V_{ub}|$ and $m_b$ in the perturbative regime ($\alpha_s^n$).

But quarks are bound by soft gluons: non-perturbative long distance interactions of $b$ quark with the light quark in the $B$ meson.

Heavy Quark Effective Theory: Precise tools to describe dynamics of the $b$ quark

Departure from the heavy quark symmetry can be expressed as $(\Lambda_{QCD}/m_Q)^n$ corrections
Inclusive versus Exclusive

Two Complementary approaches using different theoretical tools, and different experimental signatures.

→ Crucial independent consistency check.
\[ V_{cb} \]
Theoretical Tools for Inclusive Semileptonic $b$ Decays

**Operator Production Expansion** predicts the total rate as:

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

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

$m_b, m_c$: renormalisation scheme dependent quantities

Large error from $m_b^5$

<table>
<thead>
<tr>
<th>$\Lambda_{QCD}^2/m_b^2$</th>
<th>$\mu_\pi^2(-\lambda_1)$ - kinetic energy of $b$ quark, $\mu_G^2(\lambda_2)$ - chromomagnetic coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_{QCD}^3/m_b^3$</td>
<td>$\rho_D, \rho_{LS} (\rho_1, \tau_{1-3})$ (Spin-orbit, Darwin terms)</td>
</tr>
</tbody>
</table>

Measure **moments** integrated over large phase space to allow assumption of **quark-hadron** duality
\[ |V_{cb}| \text{ from Inclusive } B \rightarrow X_c l^+ \nu \]

- \( \lambda_l \) and \( m_b \), and thus \( |V_{cb}| \) from "moments" in semileptonic decays

- Need high resolution access to \( B \) rest frame, unfolded observables:
  - Hadronic invariant mass
  - Lepton momentum

- Use hadronic tag \( B_{\text{tag}} \rightarrow D^{(*)}Y \) (\( Y=n\pi, m\pi^0, pK_s, qK \)), to fully constrain the signal side \( B \) properties:
  - \( \rightarrow \text{tag - charge - momentum} \)

  New, improved hadronic tag method introduced by Belle in 2012 (see Y. Yook)

  Used for many neutrino mode analyses, even for rare \( B \rightarrow l^+ \nu \)!
$|V_{cb}|$ Determination

- Inclusive semileptonic decays recoiling against fully reconstructed hadronic tagged $B$s
- Unfold measured spectra & apply radiative corrections to obtain true distributions

\[ \frac{\Gamma(b \to u \ell \nu)}{\Gamma(b \to c \ell \nu)} \approx \frac{|V_{ub}|^2}{|V_{cb}|^2} \approx \frac{1}{50} \]

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$|V_{cb}|$ Global Fit to $B \rightarrow X_{cl} \ell \nu$ & $B \rightarrow X_{s} \gamma$

- First fit to multiple schemes, with consistent results!
- Tested OPE parameters used for $|V_{ub}|$
- Consistency between $X_{cl} \ell \nu$ and $X_{s} \gamma$ added confidence to the theory
- $\Delta |V_{cb}| / |V_{cb}| \sim 1-2\%$ dominated by theory uncertainties.

Measure moments as functions of Minimum lepton energy threshold, $E_{\text{min}}$

<table>
<thead>
<tr>
<th>Measure moments as functions of Minimum lepton energy threshold, $E_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta B$</td>
</tr>
<tr>
<td>$&lt;E_{\gamma}^2&gt;$ (GeV)</td>
</tr>
<tr>
<td>$\delta B$</td>
</tr>
</tbody>
</table>

Line: Fit
Band: Theory error

- $|V_{cb}| = (41.96 \pm 0.45 \pm 0.07) \times 10^{-3}$
- $m_b^{1S} = 4.691 \pm 0.037 \text{ GeV}$

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|V_{cb}| Summary

• Small but persistent discrepancy, up to $\sim 2.4\sigma$, between exclusive and inclusive.
• May not be (only) due to differences in theory/normalisation approaches.
• $\Delta$Exclusive$\sim 2\%$, $\Delta$Inclusive$\sim 1-2\%$ (↓from 4% in 2004)

Semileptonic B decays, IUPAP Prize, ICHEP 2012

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**Puzzle:**

- Measured sum of exclusive mode BR’s ≠ inclusive
- **What is it?** broad resonances, unmeasured $D^{**}$ decay modes (BR’s unknown!)
  neutral transitions ($\pi^0$, $\eta$), *Difficult to directly measure!*
- Affects exclusive $|V_{cb}|$ & $D(*)\tau^+\nu$! (S.Stone, Monday)
- Instead estimate cross feed into $|V_{cb}|$ & $D(*)\tau^+\nu$ measurements using $B \to D(*)l\nu X$ BRs, measured first at ICHEP. Should shed some light on the problems.

\[
\begin{array}{c|c|c|c|c}
  B^0 \to D' l\nu & \Rightarrow D l\nu & \Rightarrow D^{**} l\nu & \Rightarrow \text{???} \\
  5.\pm 0.1\% & 2.1\pm 0.1\% & 1.4\pm 0.1\% & 1.6\pm 0.3\% \\
\end{array}
\]

**Semileptonic $B$ decays, IUPAP Prize, ICHEP 2012**

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FIG. 2: Measured electron momentum spectra from $B^+$ and $B^0$ decays before background subtraction, overlaid with the various backgrounds and the MC signal. Secondaries also includes hadron fakes. The errors shown are statistical only.

TABLE I: Electron yields for $p^*B_e \geq 0.4 \text{ GeV/c}$. The errors are statistical only.

<table>
<thead>
<tr>
<th>Candidate</th>
<th>$B^+$</th>
<th>$B^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>On Resonance Data</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$6423 \pm 80$</td>
<td>$5403 \pm 74$</td>
<td></td>
</tr>
<tr>
<td><strong>Scaled Off Resonance</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$249 \pm 48$</td>
<td>$209 \pm 39$</td>
<td></td>
</tr>
<tr>
<td><strong>Combinatorial Background</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$1244 \pm 20$</td>
<td>$696 \pm 13$</td>
<td></td>
</tr>
<tr>
<td><strong>Secondary (Inc. Hadron Fakes)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$555 \pm 11$</td>
<td>$1843 \pm 22$</td>
<td></td>
</tr>
<tr>
<td><strong>Background Subtracted</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$4300 \pm 96$</td>
<td>$2597 \pm 87$</td>
<td></td>
</tr>
</tbody>
</table>

The unfolded spectrum is corrected for QED effects using the PHOTOS algorithm [34], as the OPE does not have $O(\alpha)_{\text{QED}}$ corrections. The unfolded electron energy spectrum and the bin-to-bin statistical covariance matrix calculated with the unfolding algorithm are shown in Fig. 3 (for illustrative purposes only, as the full error analysis is performed on a moment measurement basis).
\[ |V_{ub}| \text{ from Inclusive } B \rightarrow X_{ul}\nu \]

- Total rate can’t be measured! Too much \( B \rightarrow X_{c}\nu \) background.

- Remove \( b \rightarrow c\ell\nu \): \textbf{BUT} lose a part of the \( b \rightarrow u\ell\nu \) signal.

\[
\Gamma(B \rightarrow X_u \ell\nu) \times f_C = |V_{ub}|^2 \xi_C
\]

Fraction of the signal that passes the cut → corrected for QCD, motion of \( b \)-quark

Problems:
Restriction of phase space \textbf{creates complication, need models, many debates over which to use}
\[
\Gamma \sim |V_{ub}|^2 \text{ mb}^5, \text{ but partial rates } \Delta\Gamma \sim |V_{ub}|^2 \text{ mb}^{10}
\]
Selecting $b \rightarrow u \nu$

- Need a large fraction of the rate, $f_c$, to control theory uncertainty.

Use hadronic $B_{\text{tag}} \rightarrow D(\ast)Y$ to reduce combinatorial and precisely reconstruct $m_X$, $q^2$.

- $E_\ell = \text{lepton energy}$
- $q^2 = \text{lepton-neutrino mass squared}$
- $m_X = \text{hadron system mass}$

**Experimental resolution leads to irreducible $c\nu\ell$ contamination**

- $E_{\text{lep}}>2 \text{ GeV}$
- $q^2>8 \text{ GeV}^2$
- $M_X<1.7 \text{ GeV}$

- $f_c \quad 25\%$
- $38\%$
- $65\%$
Hadron Mass in Recoil (method)

• My solution: exploit non-linear correlations between kinematic, background & event variables to separate $b\rightarrow u$ and $b\rightarrow c$.

• Optimise for maximal kinematic phase space coverage:~90%!

• BDT Efficiency: 22.2%.
  • first BDT in Belle

\[
\Delta BR(p^*_{lep}>1.0\text{GeV}) = 1.96 (1 \pm 0.09_{\text{stat}} \pm 0.08_{\text{sys}}) \times 10^{-3}
\]

\begin{table}[h]
<table>
<thead>
<tr>
<th>Errors</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Det. &amp; Comb.</td>
<td>4.8</td>
</tr>
<tr>
<td>$B \rightarrow Xu \ell \nu$ SF</td>
<td>3.6</td>
</tr>
<tr>
<td>$B \rightarrow h \ell \nu$ Excl</td>
<td>4.9</td>
</tr>
<tr>
<td>$B \rightarrow KK \ell \nu$</td>
<td>1.5</td>
</tr>
<tr>
<td>$B \rightarrow cl\ell \nu$ backgrd.</td>
<td>1.7</td>
</tr>
</tbody>
</table>
\end{table}
**Inclusive $|V_{ub}|$**

- **Use** $m_c, m_b, \mu_\pi^2$ from $B \to X_c l \nu$ and $B \to X_s \gamma$

- **Agreement between experiments!**

- **Theory:** Error (5-7%) dominated by $m_c, m_b, \mu_\pi^2$

- **Experiment:** Error from $B \to \rho/\omega/\eta$ $l \nu$, non-resonant. & high $X_u$ mass region (unmeasured)

- **4 approaches:**
  - BLNP, DGE, GGOU (above), ADFR

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$B \to (\pi, \rho, \omega, \eta, \eta') l^+ \nu$

- Moving towards a complete understanding of $X_u l^+ \nu$ semileptonic width, resonant & non-resonant
- In 2012, used new hadronic tag: $\sim 2.1 \times 10^6 B^+$ tags, $\sim 1.4 \times 10^6 B^0$ tags (2-3 x previous).
- Best $\pi^0$, $\rho^{0/+}$, $\omega$, measurements and best tagged $\eta$, $\eta'$ measurements.
- $m_{X_u} > 1$ GeV still a big challenge.

<table>
<thead>
<tr>
<th>Approach</th>
<th>Efficiency</th>
<th>Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untagged</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Tagged by $B \to D^{(*)} l \nu$</td>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>Tagged by $B \to$ hadrons</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$m$ (MeV)</th>
<th>BR(ave.)</th>
<th>$\times 10^{-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^\pm/\pi^0$</td>
<td>139</td>
<td>1.4</td>
</tr>
<tr>
<td>$\eta$</td>
<td>547</td>
<td>0.4</td>
</tr>
<tr>
<td>$\rho^\pm/\rho^0$</td>
<td>775</td>
<td>2.3</td>
</tr>
<tr>
<td>$\omega$</td>
<td>783</td>
<td>1.2</td>
</tr>
<tr>
<td>$\eta'$</td>
<td>958</td>
<td>0.2</td>
</tr>
<tr>
<td>Inc-$\Sigma$(Excl)</td>
<td>14.5</td>
<td></td>
</tr>
</tbody>
</table>

**Belle Preliminary**

- $B^+ \to \rho^0 l \bar{\nu}_l$
- $B^+ \to \pi^0 l \bar{\nu}_l$
- Data - Unfolded
- High purity
- Full likelihood fit
- Yield extracted by binned background

**Stat. errors only**

Semileptonic $B$ decays, IUPAP Prize, ICHEP 2012

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\[ |V_{ub}| \text{ Summary} \]

- \( \Delta \text{Incl.} \sim 6\% \) (↓ from 18\% in 2004)
  \( \Delta \text{Excl.} \sim 10\% \)
  Up to 2-3 \( \sigma \) difference between Excl.-Incl.

- Variation on WA in inclusive is substantial, but theory agrees very well for \( p > 1.0 \) measurements (pure OPE)

**Inclusive**

- Babar: \( 4.33 \pm 0.27^{+0.10}_{-0.11} \)
- GGOU: \( p > 1.3 \text{ GeV} \)
- Babar: \( 4.54 \pm 0.27^{+0.10}_{-0.11} \)
- GGOU: \( p > 1.0 \text{ GeV} \)
- WA: \( 4.39 \pm 0.15^{+0.12}_{-0.14} \)
- HFAG EOF2011

**Exclusive**

- Babar: \( 3.44 \pm 0.10^{+0.37}_{-0.32} \)
- GGOU: \( 3.44 \pm 0.10^{+0.37}_{-0.31} \)
- Belle: \( 3.38 \pm 0.14^{+0.37}_{-0.31} \)
- tagged, LCSR
  - WA: \( 3.40 \pm 0.07^{+0.37}_{-0.32} \)
  - HFAG EOF2011 LCSR
  - WA: \( 3.30 \pm 0.30 \)
  - HFAG EOF2011 Global Fit

**ICHEP exclusive**

- CKM Fitters: \( 3.41^{+0.21}_{-0.10} \)
- CKMFitter: \( 3.41^{+0.21}_{-0.10} \)
- Winter 2012
- UTFIT: \( 3.69 \pm 0.10 \)
- Summer 2012

- LCSR: Khodjamirian et al. \( q^2 < 12 \) PRD 83:094031 (2011)

Semileptonic \( B \) decays, IUPAP Prize, ICHEP 2012  Phillip URQUIJO
**$|V_{ub}|$ Summary**

- **$\Delta$Incl.** ~6% (\(\downarrow\) from 18% in 2004)
- **$\Delta$Excl.** ~10%
  - Up to 2-3 $\sigma$ difference between Excl.-Incl.

- Variation on WA in inclusive is substantial, but theory agrees very well for $p>1.0$ measurements (pure OPE)

- **New** Belle results on $B \to \tau \nu$ @ICHEP 2012 in agreement with both methods. (See M.Nakao’s talk).

  - **$\Delta$Leptonic.** ~10%!!

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**HFAG Incl. Range**
- BABAR: $4.33 \pm 0.27^{+0.10}_{-0.11}$
- GGOU: $p > 1.3$ GeV
- BELLE: $4.54 \pm 0.27^{+0.10}_{-0.11}$
- GGOU: $p > 1.0$ GeV
- WA: $4.39 \pm 0.15^{+0.12}_{-0.14}$
- HFAG EOF2011

**HFAG Excl. Range**
- BABAR: $3.44 \pm 0.10^{+0.37}_{-0.32}$
- Un-tag, LCSR
- BELLE: $3.44 \pm 0.10^{+0.37}_{-0.31}$
- Un-tag, LCSR
- BELLE: $3.38 \pm 0.14^{+0.37}_{-0.31}$
- Tagged, LCSR
- WA: $3.40 \pm 0.07^{+0.37}_{-0.32}$
- HFAG EOF2011 LCSR
- WA: $3.30 \pm 0.30$
- HFAG EOF2011 Global Fit

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**B$\to\tau\nu$**
- BABAR: $3.87 \pm 0.53 \pm 0.09$
- BELLE, Lat.Ave. ICHEP 2012
- WA: $4.21 \pm 0.42 \pm 0.10$
- WA (private), Lat.Ave. ICHEP 2012

**CKM Fitters**
- CKMfitter: $3.41^{+0.21}_{-0.10}$
- Winter 2012
- UTFIT: $3.69 \pm 0.10$
- Summer 2012

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**Semileptonic $B$ decays, IUPAP Prize, ICHEP 2012**

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**Phillip URQUIJO**

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**References**
- LCSR: Khodjamirian et al. $q^2 < 12$
- GGOU: Gambino et al.
  - PRD 83:094031 (2011)
LHC Era: $B_s$, $\Lambda_b$ and $b$-production
The LHC Era

- Vast quantity of $b$-mesons: they can be precisely reconstructed in modes with one neutrino!
  - Clean separation from large IP!
  - Used as a calibration tool (rely on well understood decay properties).
  - $\sigma_{bb}$ and $f_s/f_d$ - key to many measurements at the LHC!

- Semileptonic $B_s/\Lambda_b$ decays teach us more about $|V_{ub}|/|V_{cb}|$, and for search for NP.

- To achieve this required new, precise measurements of the $B_s/\Lambda_b$ systems.

Generally charm mesons tag the $b$-hadron species, and the lepton charge tags the $b$ flavour, except for cross feed.

$B^+/B^0/B_s/\Lambda_b \rightarrow D^0 X \mu^- \nu$
$\rightarrow D^+ X \mu^- \nu$
$\rightarrow D_s X \mu^- \nu$
$\rightarrow \Lambda_c X \mu^- \nu$

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First Cross section measured with $b \to D^0 X \mu \nu$

$\sigma_{bb} (7 \text{ TeV}: 2>\eta>6) = 75.3 \pm 5.4 \pm 13.0 \text{ pb}$

- As clean as a B-factory
- First $b$ paper at the LHC (3 pb$^{-1}$)

First Production fraction:

$B/B_s/\Lambda_b \to D^0/D^+/D_s/\Lambda_c \mu \nu$

- $B_s$ showed no $p_T$ dependence, not flat for $\Lambda_b$.
- Solved a long standing puzzle in b-fragmentation!
  - PU in PRD.85.032008 (2011)

\[
\frac{f_s}{f_u + f_d} = 0.134 \pm 0.004 \pm 0.011 \text{ (LHCb)} \quad 3 \text{ pb}^{-1}
\]

\[
\frac{f_s}{f_u + f_d} = 0.128 \pm 0.012 \text{ (LEP)}
\]

\[
\frac{f_s}{f_u + f_d} = 0.164 \pm 0.026 \text{ (Tevatron HFAG 2012)}
\]
B_s Semileptonic Width Components

- Most precise measurements of D_{s}^{*+} \ell^- \nu modes.
- BR(D_s/D_s^*) modes determined using neutrino reconstruction!
- 8.3\sigma significance discovery of B_s \rightarrow D_{s2} \mu^- \nu.

\[
\frac{\mathcal{B}(B_s^0 \rightarrow D_{s2}^+ X \mu^- \nu)}{\mathcal{B}(B_s^0 \rightarrow X \mu^- \nu)} = (3.3 \pm 1.0 \pm 0.4)\% \\
\frac{\mathcal{B}(\overline{B}_s^0 \rightarrow D_{s1}^+ X \mu^- \nu)}{\mathcal{B}(\overline{B}_s^0 \rightarrow X \mu^- \nu)} = (5.4 \pm 1.2 \pm 0.5)\% ,
\]

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Inclusive Semileptonic $B_s$ Decay Width, $Y(5S)@Belle$

- $B_s$ inclusive width
- $B_s \rightarrow Xl\nu$
- Assumed from theory (that SU3 symmetry is kept), to measure the production fraction.
  \[ \Gamma_{SL}(B_s) = \Gamma_{SL}(B_d) = \Gamma_{SL}(B_u) \]
- $\Gamma_{SL}(B_s)$ only precisely measured by Belle at $Y(5S)$ with 121 fb$^{-1}$.

- Method:
  **Inclusive:**
  $B_s \rightarrow Xl\nu$ with $B_s(\rightarrow D_s)$ tagging
  - See C. Oswald@ ICHEP2012

\[ x(D_s) = \frac{p(D_s)}{p_{\text{max}}(D_s)} < 0.5 \]

$BR(B_s \rightarrow Xl\nu):l=e,\mu$ $10.61 \pm 0.46_{\text{stat}} \pm 0.37_{\text{sys}} \pm 0.67_{\text{param}}$

121 fb$^{-1}$ $Y(5S)$
63 fb$^{-1}$ off. res.

$\chi^2/\text{ndf} = 6.4/7$

Electrons

15% $B$
85% $B_s$
Summary

- Measurements of $|V_{ub}|$ and $|V_{cb}|$ via Semileptonic decays have been a great challenge for both theory and experiment, particularly in controlling hadronic physics.
- "Tension" between inclusive and exclusive analyses persists, while uncertainties are being reduced.
- Will they improve?
  - Next generation B-factories will produce hadronic tagged, high statistics, high purity samples and fully measure the charmless semileptonic spectra.
  - LHCb will provide competitive results in exclusive modes, already starting to dominate in $B_s$ and $\Lambda_b$ semileptonic decays.
  - Still a big challenge for theory
    - Precision data can inspire and validate theory advances.
  - Semileptonic decays prove to be important in new physics flavour measurements!

\[
\begin{align*}
|V_{cb}| & \text{ Exclusive (D*lv)} & |V_{ub}| & \text{ Exclusive (πlv)} & |V_{ub}| & \text{ Inclusive} \\
\uparrow & 1-2 \, \sigma & \uparrow & 2-3 \, \sigma & & \\
|V_{cb}| & \text{ Inclusive} & |V_{ub}| & \text{ Inclusive} & \\
\end{align*}
\]

\[
\left| \frac{V_{ub}}{V_{cb}} \right| = \begin{cases} 
0.0846 \pm 0.0035 \, \text{fit} \\
0.089 \pm 0.010 \, \text{exclusive} \\
0.0969 \pm 0.0068 \, \text{inclusive} 
\end{cases}
\]

Ratios are compatible

V. INTERPRETATION AS NEW PHYSICS

In this section we assume that physics beyond the Standard Model does not affect tree-level processes at the current level of precision, and that any sign of new physics must arise due to higher-order loop effects. Given these assumptions, it is well known [3–6] that the $\sim 2$ tension in the fit to the unitarity triangle can be interpreted as a manifestation of new physics effects in $K$ and/or $B_d$ mixing. In order to test the consistency of these two possibilities with the current measurements, we describe the two new physics possibilities.
Backup
Summary of $|V_{ub}|$ and $|V_{cb}|$

$|V_{cb}|$ Exclusive ($D^*\nu l$)
- Exp. error 1.4%
- LQCD norm. 1.9%

$|V_{cb}| = (39.04 \pm 0.55 \pm 0.73) \cdot 10^{-3}$

$|V_{cb}|$ Inclusive
- Exp. error 1.1%
- Theory error 1.4%

$|V_{cb}| = (41.88 \pm 0.44 \pm 0.59) \cdot 10^{-3}$

$|V_{ub}|$ Exclusive ($\pi \nu l$)
- Exp. error 5.5%
- LQCD norm. 7.5%

$|V_{ub}| = (3.23 \pm 0.18 \pm 0.24) \cdot 10^{-3}$

$|V_{ub}|$ Inclusive
- Exp. error 3.6%
- Theory error 3.9%

$|V_{ub}| = (4.41 \pm 0.15 \pm 0.17) \cdot 10^{-3}$
Exclusive $|V_{ub}|$

- Exclusive rates determined by $|V_{ub}|$ and Form Factors
  - Calculable at kinematical limits with LightConeSumRules or LatticeQCD
  - Empirical extrapolation necessary to extract $|V_{xb}|$ from measurements

\[
q^2=(m_B^2+m_\pi^2-2m_BE_\pi)^2
\]

\[
\Delta \zeta(0, q_{max}^2) = \frac{G_F^2}{24\pi^3} \int_0^{q_{max}^2} dq^2 p_\pi^3 |f(q)|^2
\]

One FF for $B \rightarrow \pi \ell \nu$ with massless lepton

\[
= \frac{1}{|V_{ub}|^2 \tau_B} \int_0^{q_{max}^2} dq^2 \frac{d\mathcal{B}(B \rightarrow \pi \ell \nu)}{dq^2}
\]

<table>
<thead>
<tr>
<th>Approach</th>
<th>Efficiency</th>
<th>Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untagged</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Tagged by $B \rightarrow D^{(*)}\ell\nu$</td>
<td>$\uparrow$</td>
<td>$\downarrow$</td>
</tr>
<tr>
<td>Tagged by $B \rightarrow$ hadrons</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

Semileptonic $B$ decays, IUPAP Prize, ICHEP 2012

Phillip URQUIJO
1. $|V_{ub}|$ from partial $q^2$ integral with FF (from theory/lattice).

2. **Fit** data and lattice calculations in $q^2$ (2-3 shape pars + $|V_{ub}|$, data & LQCD correlations)

**Error budget:**
- 2% from total rate
- 4% from $q^2$ shape
- 8% from FF normalisation
\[ |V_{ub}| \] **Exclusive-Inclusive Puzzle**

- **Inclusive:**
  - \[ |V_{ub}| \] varies depending upon theoretical framework and is highly sensitive to the input **b-quark** mass.
  - High mass components, and fragmentation will be measured constrained.

- **Exclusive:**
  - Rely on normalisation from theory or Lattice, but stat limited tests of those predictions. Rely on precision tests from \( D \to \pi/K \nu \), and \( q^2 \) shape comparisons in B decays.
  - \[ |V_{ub}| \] can be obtained from other exclusive decay channels such as \( B_s \to K \mu \nu \)

- **Right handed current?**
How to determine $|V_{qb}|$

2 Complementary approaches using different theoretical tools, and different experimental signatures.

→ Crucial independent consistency check.

Inclusive: $\Gamma(\mathcal{B} \to X_c \ell \nu) = \frac{G_F^2 m_b^5}{192 \pi^3} |V_{cb}|^2 [1 + A_{\text{ew}}] A_{\text{nonpert}} A_{\text{pert}}$

sum over all hadron final states (heavy quark symmetry)

Exclusive: $\frac{d\Gamma(\mathcal{B} \to \pi \ell \nu)}{dq^2} = \frac{G_F^2}{24 \pi^2} |V_{ub}|^2 p_\pi^3 |f + (q^2)|^2$

$\mathcal{B} \to \pi$ form factor (lattice QCD)

Study weak interaction $|V_{cb}|, |V_{ub}|$

Study strong interaction “Structure of the B meson”

Semileptonic $\mathcal{B}$ decays, IUPAP Prize, ICHEP 2012

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Outlook for SL B decay measurements

- **LHCb**: Neutrino/q^2 reconstruction. For exclusive measurements.
  - |V_{ub}| : B_s \to K^{(*)}\mu\nu, B \to \rho\mu\nu

- **Belle II/SuperB**:  
  - High statistics hadronic tag reconstruction. 
  - Full exploration of SL charmless (and charmed) mass spectra: up to higher mass. 
  - Decay differentials to fully test models

- **Lattice** errors expected to **halve** in the next 2 years

---

Semileptonic B decays, IUPAP Prize, ICHEP 2012

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Exclusive $|V_{cb}|$

The $B \rightarrow D^{(*)}\nu$ differential decay rates are proportional to $|V_{cb}|^2$ and form factors.

$$d\Gamma(B \rightarrow D^{(*)}\nu)/dw=(G_F^2/48\pi^3) \ m_D^3 (m_B + m_D) (w^2 - 1)^{3/2} \ |V_{cb}|^2 \ |F_{B\rightarrow D^{(*)}}(w)|^2$$

$$w \equiv v_B \cdot v_{D^{(*)}} = \frac{p_B \cdot p_{D^{(*)}}}{m_B \cdot m_{D^{(*)}}} : D^{(*)} \ \text{boost}$$

Take 1 normalisation point from lattice-QCD at 0-recoil $(w=1) \sim 2\%$ errors

From experiment

$$|V_{cb}| \times \text{F.F. @} w=1$$

$\rho_D, \rho_{D^*}$ (F.F. slopes)

$F_{B\rightarrow D}(1)=1.074(18)_{\text{stat}}(16)_{\text{sys}}$  
$F_{B\rightarrow D^*}(1)=0.9077(51)_{\text{stat}}(158)_{\text{sys}}$

[Fermilab/MILC NPPS 140, 461(2005)]  
[Fermilab/MILC, arXiv:1011.2166]
\[|V_{cb}|, \ |V_{ub}| \text{ and New physics}\]

- **Indirect** constraints on NP
- Some UT constraints strongly affected:
  - \(B(B \to \tau \nu) \propto f_B^2 \cdot |V_{ub}|^2\)
  - \(\varepsilon_K\) dependent on \(|V_{cb}|\)
  - \(B(K^+ \to \pi^+ \nu \nu) \propto |V_{cb}|^4\)
  - \(B(K_L \to \pi^0 \nu \nu) \propto |V_{cb}|^4\)

- **Direct?**
  - LR models could affect the \(b \to u \ell \nu\) transitions
  - Charged Higgs can affect Cabibbo Favoured decays \(B \to D^{(*)}\tau \nu\)

\[
(\hat{B}_K)_{\text{fit}} = \begin{cases} 
1.09 \pm 0.12 & |V_{cb}|_{\text{excl}} \\
0.903 \pm 0.086 & |V_{cb}|_{\text{incl}} \\
0.98 \pm 0.10 & |V_{cb}|_{\text{excl+incl}} 
\end{cases}
\]

\[|V_{cb}|_{\text{excl}}: \chi^2/d.o.f. = 6.1 \quad \text{C.L.} = 0.2\%\]

\[|V_{cb}|_{\text{incl}}: \chi^2/d.o.f. = 2.6 \quad \text{C.L.} = 7.4\%\]
A word on tauonic modes: $B \to D^{(*)}\tau^+\nu_l$

- Higher values than expected from the SM

But, no indications in favour of a Type II charged Higgs.

Isospin invariance assumed
Exclusive \(|V_{cb}|\) Averages

\(B \to D^{*}l\nu\)

\[|V_{cb}| = (39.54 \pm 0.50_{\text{EXP}} \pm 0.74_{\text{LQCD}}) \times 10^{-3}\]

\(B \to Dl\nu\)

\[|V_{cb}| = (39.70 \pm 1.42_{\text{EXP}} \pm 0.89_{\text{LQCD}}) \times 10^{-3}\]
Exclusive $|V_{ub}|$ Averages

HFAG EOF2011 Average

| Theory | $q^2$, GeV/c$^2$ | $|V_{ub}| \times 10^3$ |
|--------|------------------|-----------------|
| LCSR1  | $< 12$           | $3.40 \pm 0.07_{-0.32}^{+0.37}$ |
| LCSR2  | $< 16$           | $3.57 \pm 0.06_{-0.39}^{+0.59}$ |
| HPQCD  | $> 16$           | $3.45 \pm 0.09_{-0.39}^{+0.37}$ |
| FNAL/MILC | $> 16$ | $3.30 \pm 0.09_{-0.30}^{+0.37}$ |

New results

Semileptonic $B$ decays, IUPAP Prize, ICHEP 2012
Inclusive $|V_{ub}|$ Averages

CLEO ($E_1$)
\[ 3.93 \pm 0.46 + 0.22 - 0.29 \]
BELLE sim. ann. ($m_X$, $q^2$)
\[ 4.37 \pm 0.46 + 0.23 - 0.26 \]
BELLE ($E_2$)
\[ 4.75 \pm 0.44 + 0.17 - 0.22 \]
BABAR ($E_2$)
\[ 4.29 \pm 0.24 + 0.18 - 0.24 \]
BELLE multivariate ($p^*$)
\[ 4.54 \pm 0.27 + 0.10 - 0.11 \]
BABAR ($m_X < 1.55$)
\[ 4.08 \pm 0.19 + 0.20 - 0.21 \]
BABAR ($m_X < 1.7$)
\[ 3.94 \pm 0.22 + 0.16 - 0.17 \]
BABAR ($m_X < 1.7$, $q^2 > 8$)
\[ 4.17 \pm 0.22 + 0.22 - 0.25 \]
BABAR ($P^* < 0.66$)
\[ 3.75 \pm 0.23 + 0.30 - 0.32 \]
BABAR ($m_X$, $q^2$ fit, $p^* > 1$GeV)
\[ 4.35 \pm 0.24 + 0.09 - 0.10 \]
BABAR ($p^* > 1.3$GeV)
\[ 4.33 \pm 0.27 + 0.10 - 0.11 \]

Average +/- exp + theory - theory
\[ 4.39 \pm 0.15 + 0.12 - 0.14 \]

$\chi^2$/dof = 11.2/10 (CL = 34.00 %)

P. Gambino, P. Giordano, G. Ossola, N. Uraltsev
JHEP 0710:058, 2007 (GGOU)

HFAG Ave. (BLNP)
\[ 4.40 \pm 0.15 + 0.19 - 0.21 \]
HFAG Ave. (DGE)
\[ 4.45 \pm 0.15 + 0.15 - 0.16 \]
HFAG Ave. (GGOU)
\[ 4.39 \pm 0.15 + 0.12 - 0.20 \]
HFAG Ave. (ADFR)
\[ 4.03 \pm 0.13 + 0.18 - 0.12 \]
HFAG Ave. (BLL)
\[ 4.62 \pm 0.20 + 0.29 \]
BABAR (LLR)
\[ 4.43 \pm 0.45 + 0.29 \]
BABAR endpoint (LLR)
\[ 4.28 \pm 0.29 + 0.48 \]
BABAR endpoint (LNP)
\[ 4.40 \pm 0.30 + 0.47 \]

Average +/- exp + theory - theory
\[ 4.39 \pm 0.15 + 0.12 - 0.14 \]

$\chi^2$/dof = 11.2/10 (CL = 34.00 %)

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Semileptonic $B$ decays, IUPAP Prize, ICHEP 2012

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Normalising the production rates

- Key ingredient - the inclusive charm+lepton final states measured for the first time at ICHEP 2012!
  - \( B^{+/0} \to D^{(*)} l \nu X / B^{+/0} \to l \nu X \) using Belle’s hadronic tagging method.

- Also sheds some light on nature of exclusive-inclusive saturation problem.

Semileptonic \( B \) decays, IUPAP Prize, ICHEP 2012

Phillip URQUIJO
## Semileptonic B decays

**Untagged**
- Initial 4-momentum known
- Missing 4-momentum = one ν
- Reconstruct $B \rightarrow X_q \ell \nu$
- Using $m_B$ (beam-constrained)
  and $\Delta E = E_B - E_{\text{beam}}$

**Semileptonic Tag**
- One $B$ reconstructed in $D^{(*)} \ell \nu$ modes.
- **Two missing ν in event.**

**Full Reconstruction Tag**
- One $B$ reconstructed completely in a known $b \rightarrow c$ mode without ν.

---

**Eff.**

<table>
<thead>
<tr>
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<tr>
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<td>Low</td>
</tr>
<tr>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

< 0.5 ab$^{-1}$

< 1 ab$^{-1}$

> 1 ab$^{-1}$