Measurement of exclusive semileptonic B to D decays and the determination of exclusive $|V_{cb}|$

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HQL Melbourne June 2008
The Significance of $|V_{cb}|$ Measurements

CKM are fundamental SM parameters, size not theoretically predicted.

Constrain one side of the Unitarity Triangle

The precise determination of $|V_{ub}|/|V_{cb}|$ provides a benchmark for testing new physics in other processes.

- Current precision
  - $\sin^2\varphi_1 < 4\%$
  - $|V_{cb}| \sim 1-2\%$ inclusive
  - $|V_{ub}| \sim 3-4\%$ exclusive
- $|V_{ub}| \sim 7\%$ inclusive
  - $>10\%$ exclusive

Precise exclusive determinations used to check inclusive results, and probe our understanding of HQET.
Semileptonic $B$ decays

tree level, short distance:

$$b \rightarrow c e \nu$$

decay properties depend directly on $|V_{cb}|$ & $|V_{ub}|$ and $m_b$

perturbative regime ($\alpha_s^n$)
Semileptonic $B$ decays

tree level, short distance:

\[ B \rightarrow D e \nu \]

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

decay properties depend directly on $|V_{cb}|$ & $|V_{ub}|$ and $m_b$

perturbative regime ($\alpha_s^n$)
Exclusive Semileptonic Decays

One hadronic current.

Matrix element for semileptonic decays:

\[
(M_{Q\bar{q}} \to X_{q'\bar{q}} \to X_{q'\bar{q}} \ell^- \bar{\nu}_\ell) = -i \frac{G_F}{\sqrt{2}} V_{q'Q} L^\mu H_\mu
\]

Leptonic current exactly known.

Hadronic current described by Form Factors (FF), functions of squared momentum transfer \(q^2\).

Exclusive rates are determined by \(|V_{cb}|\) and Form Factors (FF)

FF are calculated using non-perturbative methods.

- Theoretically calculable at kinematic limits.
- Lattice QCD works if \(D^*\) is at rest relative to the \(B\).

Empirical extrapolation is necessary to extract \(|V_{cb}|\) from measurements.

Measure differential rates to constrain the FF shape, then use FF normalization from the theory for \(|V_{cb}|\).
|V_{cb}| and Form factors from $B \rightarrow D^* \ell \nu$

Differential decay rate
\[ \frac{d\Gamma(B^0 \rightarrow D^* \ell^+ \nu_\ell)}{dwd \cos \theta_\ell \cos \theta_V d\chi} = \frac{G_F^2 |V_{cb}|^2}{48\pi^3} F(w, \theta_\ell, \theta_V, \chi) G(w) \]

Incorporates 3 non-trivial form factors $A_1(w), A_2(w),$ and $V(w).$

HQ symmetry (b and c mass infinite) predicts a single universal FF, normalised to 1 at zero recoil.

HQET relates the 3 FF's to each other through Heavy Quark Symmetry, leaving 3 free parameters that are determined experimentally.

Amplitude ratios:
\[ R_1(w) = \frac{V}{A_1} \]
\[ R_2(w) = \frac{A_2}{A_1} \]

Curvature:
\[ \rho^2(w) = -\frac{dF}{dw}|_{w=1} \]

Using parameterisation to extract 3 parameters from 4 observables in the data: $w, \theta_V, \theta_\ell, \chi$


Experimentally clean, a check of inclusive methods.

Heavy Quarks and Leptons Melbourne 2008  Phillip Urquijo

\[ w \equiv \frac{M_B^2 + M_{D^*}^2 - q^2}{2M_B M_{D^*}} \]
The **Xc** system

In addition to the well measured $\Delta$-like $D^{(*)}$ components are the $D^{**}$, P-wave excitations of $D$-mesons.

⇒ HQET predicts **four $D^{**}$ mesons**: 2 narrow and 2 wide, all observed in hadronic B decays.

(hep-ex/0307021, hep-ex/0611054)

$$\text{BR}(B \rightarrow X_{c} \ell \nu) \sim 10.5\%$$

**D**

- $D^*$ 54%
- $D$ 21%
- $D^{**}$ ~25%

BUT, Heavy Quark Symmetry also predicts $\Gamma(B \rightarrow \text{Narrow} \ell \nu) >> \Gamma(B \rightarrow \text{Broad} \ell \nu)$

New BaBar and Belle measurements seem to defy this, eluding to a non-negligible contribution from non-resonant decay.

The components of the $X_c$ system are not yet fully understood.

<table>
<thead>
<tr>
<th>BR[%] HFAG ave.</th>
<th>$B^0$</th>
<th>$B^+$</th>
</tr>
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<tbody>
<tr>
<td>Inclusive - $\Sigma$ Exclusive</td>
<td>$2.08 \pm 0.34$</td>
<td>$1.62 \pm 0.42$</td>
</tr>
</tbody>
</table>
**Measurement methods/samples**

**Untagged**

⇒ ( |V_{cb}| and FF analyses )

- Initial 4-momentum known.
- Missing 4-momentum = ν.
- Reconstruct $B \rightarrow D^{(*)} l \nu$ using $m_B$ (beam-constrained) and $\Delta E = E_B - E_{beam}$.

**Full Reconstruction Tag ("B Beam")**

⇒ ( BR( $D^{(*)}(\pi) l \nu$ ) analyses )

- One $B$ reconstructed completely in known $b \rightarrow c$ mode.
- Many modes used.

---

`Full Reconstruction Tag ("B Beam")` and `Untagged` methods are illustrated in the diagram.
$|V_{cb}|$ and FF from $D^{(*)}$
$B^0 \to D^{*+} \ell \nu$ selection

Select $B^0 \to D^{*+} \ell \nu$ ($D^{*+} \to D^0 \pi$) events with $p^* > 1.2$ GeV.

Estimate backgrounds (comb., $D^{**}$) from

$$\Delta M = M(D^*) - M(D) \text{ and } \cos \theta_{BY}.$$  

\[
\cos \theta_{BY} = \frac{2E_B E_T - m_B^2 - m_Y^2}{2 |\vec{p}_B| |\vec{p}_Y|} \quad Y \equiv D^0 e
\]

**BaBar analyses:**

1. Three $D$ modes: $D \to K\pi, K\pi\pi, K\pi\pi\pi$, $\chi^2$ fit to 1D projections.
2. One $D$ mode: $D \to K\pi$, 4D maximum likelihood fit
Simultaneous $\chi^2$ fit fit 1D projections in \( w, \cos\theta_l, \cos\theta_V \) (integrated over angle \( \chi \)).

First simultaneous measurement of form factors and \( |V_{cb}| \), fully accounting for all correlations.

Final results combined with Phys. Rev. D74 092004 (which uses a full 4D fit) to give:

\[
\begin{align*}
\rho^2 &= 1.191 \pm 0.048 \pm 0.028 \\
R_1(1) &= 1.429 \pm 0.061 \pm 0.044 \\
R_2(1) &= 0.827 \pm 0.038 \pm 0.022 \\
F(1)|V_{cb}| &= (34.4 \pm 0.3 \pm 1.1) \times 10^{-3}
\end{align*}
\]
|Vcb| and form factors from $B^- \to D^*^0 \ e \ \nu$


- Look at: $D^{*0} \to \pi^0 D^0$ and $D^0 \to K^- \pi^+$
- Binned maximum likelihood fit in $\Delta m$, $\cos \theta_{BY}$ and $\omega^2$
- Main background: mis-reconstructed $B^{\pm 0} \to D^{*0\pm} \ e \ \nu$

$$F(1)|V_{cb}| = (35.9 \pm 0.6 \pm 1.4) \cdot 10^{-3}$$
$$\rho^2 = 1.16 \pm 0.06 \pm 0.08$$
$$\mathcal{B}(B \to D^{*0}) = (5.56 \pm 0.08 \pm 0.41)\%$$

- Main systematic uncertainties:
  - $\pi^0$ reconstruction efficiency, $BR(D^{*0} \to \pi^0 D^0)$
  - $R_1(l)$ and $R_2(l)$ for $\rho^2$
- Complementary to $D^{*+} \ \nu$ analyses
|Vcb| World average: from $B^0 \rightarrow D^{*-} e^+ \nu$

Lattice

|                   | F(1)**            | |Vcb| exclusive                  | incl.* Vs excl. |
|-------------------|-------------------|-------------------------|----------------|
| Hashimoto et al. PRD66 104503, 2002 | $0.919 \pm 0.033$ | $(39.37 \pm 0.60_{\text{exp.}} \pm 1.37_{\text{theo}}) \times 10^{-3}$ | $\sim 1.6 \sigma$ |
| Laiho et al. PoS LATTICE2007:358, 2006 | $0.930 \pm 0.022$ | $(38.90 \pm 0.59_{\text{exp.}} \pm 0.90_{\text{theo}}) \times 10^{-3}$ | $\sim 2.7 \sigma$ |

*Discrepancy observed w.r.t HFAG 1S scheme inclusive result $|Vcb|=(41.78 \pm 0.30_{\text{fit}} \pm 0.08_{\tau_B}) \times 10^{-3}$.

Errors dominated by systematic errors in the lattice calculation of F(1).
BR(B → D^{(*)} (π) l ν)
$B \to D^{**} l \nu$ : A test of HQET

Although not directly used for $|V_{cb}|$, measurements of $B \to D^{**} l \nu$ are important for systematics in almost all semileptonic B analyses.

They also provide an essential test of HQET, relied upon for exclusive $|V_{cb}|$ determination.

- In the heavy quark limit ($m_b$ and $m_c \to \infty$), only two independent form factors:
  
  $\tau_{1/2}$ and $\tau_{3/2}$ for $j_l = 1/2, 3/2$

  $\Gamma(B \to D^{*}_2 l \nu ; D_1 l \nu) \propto |\tau_{3/2}(w)|^2$

  $\Gamma(B \to D^{*}_0 l \nu ; D^{*}_1 l \nu) \propto |\tau_{1/2}(w)|^2$

Theorists consistently predict the same result:

$\Gamma(B \to D^{*}_2 l \nu ; D_1 l \nu) \sim 10 \times \Gamma(B \to D^{*}_0 l \nu ; D^{*}_1 l \nu)$

A. Le Yaouanc, hep-ph/0003087,
Branching Fractions of $B \rightarrow D^{(*)}\pi \ell^+ \nu$

657M B/Bbar pairs
D. Liventsev et al., PRD 77, 091503 (2008)

- Reconstruct $e$, $\mu$ and $D^{(*)}(0)\pm$ in the recoil side of a B Beam event.
  $p_{\text{lepton}} >$ (0.6 GeV BaBar, 1.0 GeV Belle).

- Fitting missing mass squared:
  $M_{\nu}^2 = (P_{\text{beam}} - P_{\text{Btag}} - P_{B_{\text{sl}}})^2$

- Backgrounds are subtracted using data:
  $\Delta E \equiv E_{\text{tag}} - E_{\text{beam}}$ $M(D_{\text{sl}})$ sidebands
  $D^{(*)}\pi h^+$ fakes

- Feed-down subtracted using MC

- Branching ratios are calculated relative to the normalization modes to cancel out the Btag reconstruction efficiency

$|M_{\nu}^2| < 0.1 \text{ GeV}^2$
**Branching Fractions of**

\[ B \rightarrow D^{(*)}\pi \nu \]

657M B/Bbar pairs

D. Liventsev et al., PRD 77, 091503 (2008)

- Very clear peaks for narrow D1 and D2 states
- Large BR for D^*\_0, but no evidence for D_1^*

\[ B(\text{mode}) \equiv B(B \rightarrow D^{**}\ell\nu) \times B(D^{**} \rightarrow D^{(*)}\pi^+) \]

**D_\pi** invariant mass study

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield</th>
<th>(B, %)</th>
<th>Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B^+ \rightarrow D^*_0^{0}\ell^+\nu)</td>
<td>102 ± 19</td>
<td>0.24 ± 0.04 ± 0.06</td>
<td>5.4</td>
</tr>
<tr>
<td>(B^+ \rightarrow D^*_2^{0}\ell^+\nu)</td>
<td>94 ± 13</td>
<td>0.22 ± 0.03 ± 0.04</td>
<td>8.0</td>
</tr>
<tr>
<td>(B^0 \rightarrow D^*_0^-\ell^+\nu)</td>
<td>61 ± 22</td>
<td>0.20 ± 0.07 ± 0.05</td>
<td>2.6</td>
</tr>
<tr>
<td>(B^0 \rightarrow D^*_2^-\ell^+\nu)</td>
<td>68 ± 13</td>
<td>0.22 ± 0.04 ± 0.04</td>
<td>5.5</td>
</tr>
</tbody>
</table>

**D^*_\pi** invariant mass study

<table>
<thead>
<tr>
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<th>Yield</th>
<th>(B, %)</th>
<th>Signif.</th>
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</thead>
<tbody>
<tr>
<td>(B^+ \rightarrow D^*_1^{0}\ell^+\nu)</td>
<td>-5 ± 11</td>
<td>&lt; 0.07 @ 90% C.L.</td>
<td></td>
</tr>
<tr>
<td>(B^+ \rightarrow \bar{D}^*_0^{0}\ell^+\nu)</td>
<td>81 ± 13</td>
<td>0.42 ± 0.07 ± 0.07</td>
<td>6.7</td>
</tr>
<tr>
<td>(B^+ \rightarrow \bar{D}^*_2^{0}\ell^+\nu)</td>
<td>35 ± 11</td>
<td>0.18 ± 0.06 ± 0.03</td>
<td>3.2</td>
</tr>
<tr>
<td>(B^0 \rightarrow D^*_1^-\ell^+\nu)</td>
<td>4 ± 8</td>
<td>&lt; 0.5 @ 90% C.L.</td>
<td></td>
</tr>
<tr>
<td>(B^0 \rightarrow D^*_1^-\ell^+\nu)</td>
<td>20 ± 7</td>
<td>0.54 ± 0.19 ± 0.09</td>
<td>2.9</td>
</tr>
<tr>
<td>(B^0 \rightarrow D^*_2^-\ell^+\nu)</td>
<td>1 ± 6</td>
<td>&lt; 0.3 @ 90% C.L.</td>
<td></td>
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</tbody>
</table>

**dominant syst due to Breco Br(D^{(*)}(90(2))) and track reconstruction.**

Heavy Quarks and Leptons Melbourne 2008

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Helicity distributions of $(B \to D_0^{*}, D_2^{*} \pi \ell \nu)$

D. Liventsev et al., PRD 77, 091503 (2008)

- $D\pi$ invariant mass fit in bins of helicity.
- $\theta$ angle between
  - $\pi$ in $D^{**}$ rest frame and $D^{**}$ boost vector
- Helicity distributions for $D^{*}0$ and $D^{*}2$ fit with
  - $J= 0$ ($\chi^2/\text{ndf} = 6.0/4$)
  - $J= 2$ ($\chi^2/\text{ndf} = 2.0/3$)
Branching Fractions of 
$B \rightarrow D^{(*)}(\pi\pi) \ell \nu$

341M $B$/$B^{\ast}$ pairs
B. Aubert et al., PRL 100, 151802 (2008)

Results consistent with isospin symmetry

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\mathcal{B}(B^-)$ [%]</th>
<th>$\mathcal{B}(B^0)$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D\ell^-\bar{\nu}_\ell$</td>
<td>$2.33 \pm 0.09 \pm 0.09$</td>
<td>$2.21 \pm 0.11 \pm 0.12$</td>
</tr>
<tr>
<td>$D^{*}\ell^-\bar{\nu}_\ell$</td>
<td>$5.83 \pm 0.15 \pm 0.30$</td>
<td>$5.49 \pm 0.16 \pm 0.25$</td>
</tr>
<tr>
<td>$D\pi^\pm \ell^-\bar{\nu}_\ell$</td>
<td>$0.42 \pm 0.06 \pm 0.03$</td>
<td>$0.43 \pm 0.08 \pm 0.03$</td>
</tr>
<tr>
<td>$D^{*}\pi^\pm \ell^-\bar{\nu}_\ell$</td>
<td>$0.59 \pm 0.05 \pm 0.04$</td>
<td>$0.48 \pm 0.08 \pm 0.04$</td>
</tr>
</tbody>
</table>

$\mathcal{B}(B^- \rightarrow D^{(*)}(\pi^\pm)\ell^-\bar{\nu}_\ell) = (1.52 \pm 0.12_{\text{stat.}} \pm 0.10_{\text{syst.}})\%$

$\mathcal{B}(B^0 \rightarrow D^{(*)}(\pi^\pm)\ell^-\bar{\nu}_\ell) = (1.37 \pm 0.17_{\text{stat.}} \pm 0.10_{\text{syst.}})\%$
Fit to $B \rightarrow D^{**} l \nu$ components

- Simultaneous fit to all 4 channels, including crossfeeds.
- BG normalised from fits to $B_{tag}$ mass.
- Large BR for wide states - in disagreement with HQET.

Preliminary BaBar result.
### $B \rightarrow D^{**} l \nu$ Branching fraction results

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>$B (\bar{B} \rightarrow D^{<strong>} l^{-} \bar{\nu}_l ) \times B (D^{</strong>} \rightarrow D^{(*)}\pi) % (Belle)$</th>
<th>$\text{BABAR Branching Fraction}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^- \rightarrow D_0^{*0} l^{-} \bar{\nu}_l$</td>
<td>$0.24 \pm 0.04 \pm 0.06$</td>
<td>$0.28 \pm 0.05 \pm 0.04$</td>
</tr>
<tr>
<td>$B^- \rightarrow D_2^{*0} l^{-} \bar{\nu}_l$</td>
<td>$0.22 \pm 0.03 \pm 0.04$</td>
<td>$0.16 \pm 0.03 \pm 0.01$</td>
</tr>
<tr>
<td>$\bar{B}^0 \rightarrow D_0^{*+} l^{-} \bar{\nu}_l$</td>
<td>$0.20 \pm 0.07 \pm 0.05$</td>
<td>$0.47 \pm 0.09 \pm 0.07$</td>
</tr>
<tr>
<td>$\bar{B}^0 \rightarrow D_2^{*+} l^{-} \bar{\nu}_l$</td>
<td>$0.22 \pm 0.04 \pm 0.04$</td>
<td>$0.08 \pm 0.04 \pm 0.02$</td>
</tr>
</tbody>
</table>

#### $D_\pi$ invariant mass fit

<table>
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<tr>
<th>Decay Mode</th>
<th>$B (\bar{B} \rightarrow D^{<strong>} l^{-} \bar{\nu}_l ) \times B (D^{</strong>} \rightarrow D^{(*)}\pi) % (Belle)$</th>
<th>$\text{BABAR Branching Fraction}$</th>
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<tbody>
<tr>
<td>$B^- \rightarrow D_1^{0} l^{-} \bar{\nu}_l$</td>
<td>$&lt; 0.07 @ 90\text{CL}$</td>
<td>$0.27 \pm 0.05 \pm 0.05$</td>
</tr>
<tr>
<td>$B^- \rightarrow D_1^{1} l^{-} \bar{\nu}_l$</td>
<td>$0.42 \pm 0.07 \pm 0.07$</td>
<td>$0.29 \pm 0.03 \pm 0.03$</td>
</tr>
<tr>
<td>$B^- \rightarrow D_2^{*0} l^{-} \bar{\nu}_l$</td>
<td>$0.18 \pm 0.06 \pm 0.03$</td>
<td>$0.07 \pm 0.01 \pm 0.01$</td>
</tr>
<tr>
<td>$\bar{B}^0 \rightarrow D_1^{1} l^{-} \bar{\nu}_l$</td>
<td>$&lt; 0.5 @ 90\text{CL}$</td>
<td>$0.37 \pm 0.07 \pm 0.05$</td>
</tr>
<tr>
<td>$\bar{B}^0 \rightarrow D_1^{+} l^{-} \bar{\nu}_l$</td>
<td>$0.54 \pm 0.19 \pm 0.09$</td>
<td>$0.25 \pm 0.05 \pm 0.03$</td>
</tr>
<tr>
<td>$\bar{B}^0 \rightarrow D_2^{*+} l^{-} \bar{\nu}_l$</td>
<td>$&lt; 0.3 @ 90\text{CL}$</td>
<td>$0.04 \pm 0.02 \pm 0.01$</td>
</tr>
</tbody>
</table>

Belle: non-resonant $D^{(*)}\pi l\nu$ consistent with zero.

BaBar: non-resonant fixed to zero in fit.

#### $D_1$ $BR > 6$ sigma significance in BaBar; not found in Belle.
World averages of $D^{**} \rightarrow \text{nu}$ measurements

- Many measurements of narrow states, with the common assumptions:

\[
\begin{align*}
\mathcal{B}(b \to B) &= 37.8 - 39.7\% \\
\mathcal{B}(D_1 \to D^* \pi^+) &= 66.7\% \\
\mathcal{B}(D^*_2 \to D^* \pi^+) &= 20\%
\end{align*}
\]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\mathcal{B}(B \to D_1 \ell \nu)$</th>
<th>$\mathcal{B}(B \to D^*_2 \ell \nu)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>$0.43 \pm 0.10 \pm 0.07$</td>
<td></td>
</tr>
<tr>
<td>OPAL</td>
<td>$0.69 \pm 0.21 \pm 0.10$</td>
<td></td>
</tr>
<tr>
<td>CLEO</td>
<td>$0.35 \pm 0.08 \pm 0.06$</td>
<td></td>
</tr>
<tr>
<td>DO</td>
<td>$0.22 \pm 0.02 \pm 0.04$</td>
<td></td>
</tr>
<tr>
<td>BELLE</td>
<td>$0.44 \pm 0.07 \pm 0.06$</td>
<td></td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>$0.24 \pm 0.04$</td>
<td></td>
</tr>
</tbody>
</table>

$\chi^2$/dof = 12/4 (CL = 0.02)

$\chi^2$/dof = 2.8/2 (CL = 0.25)
Inconsistency with HQET

2 big questions...

Experiment:
There’s a big hole in the measurement of the exclusive $X_c$ components. What’s missing?

Theory:
Why is there such a discrepancy between HQET prediction and measurement for the narrow and wide state BR?

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<tr>
<td>$D^*$</td>
<td>5.16 ± 0.11</td>
<td>6.07 ± 0.29</td>
</tr>
<tr>
<td>$D$</td>
<td>2.17 ± 0.12</td>
<td>2.27 ± 0.11</td>
</tr>
<tr>
<td>$D\pi$</td>
<td>0.43 ± 0.06</td>
<td>0.42 ± 0.05</td>
</tr>
<tr>
<td>$D^*\pi$</td>
<td>0.49 ± 0.08</td>
<td>0.61 ± 0.05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\Sigma$ Exclusive (measured)</th>
<th>$B^0$</th>
<th>$B^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>inclusive</td>
<td>8.25 ± 0.19</td>
<td>9.37 ± 0.32</td>
</tr>
<tr>
<td>Inclusive - $\Sigma$ Exclusive</td>
<td>10.33 ± 0.28</td>
<td>10.99 ± 0.28</td>
</tr>
</tbody>
</table>

$\tau_{1/2} (1) = 0.41(5) < \tau_{3/2} (1) = 0.57(10)$

BPS symmetry (N. Uraltsev, hep-ph/0312001)
Use an approximate non-pertrubative symmetry for heavy mesons, predicting $|\tau_{1/2} (w)|^2=0$.

Jugeau et al., hep-ph/0407176
HQET rules apply at $w=1$ (zero recoil) and infinite mass. Extensions have been performed to first order in $1/m_c$ and all $w$.

N. Isgur, hep-ph/9811377
Isgur predicted a non-negligible non-resonant contribution 10 years ago!

Quenched lattice computations of using static heavy quarks (infinitely massive b and c) give:

There’s a big hole in the measurement of the exclusive $X_c$ components. What’s missing?
Conclusions

D(*) and exclusive |V_{cb}|

\[ B^- \rightarrow D^{0*} \ell \nu \]

New measurement with simultaneous extraction of form factor parameters.

\[ |V_{cb}| = (39.37 \pm 0.60 \pm 1.37) \times 10^{-3} \sim 1.5 \sigma \text{ difference to inclusive results.} \]

\[ \Rightarrow \text{uncertainty from } F(1) \text{ is dominant, requiring more input from Lattice!} \]

\[ \text{BR ( } B^- \rightarrow D^{0*} \ell \nu \text{ )} \]

no different to expectation from \[ \text{BR ( } B^0 \rightarrow D^{+*} \ell \nu \text{ )} \]

D**

Narrow, \[ B \rightarrow D_1/D_2 \ell \nu \] decays observed and properties studied.

Large BR for wide \[ B \rightarrow D_0^* \ell \nu \] observed by BaBar and Belle, contradicting HQET predictions.

BaBar has found the \[ D_1' \] state, not yet seen by Belle.

But, If \( j=1/2 \) states dominate there is a problem with HQET!

15-20 % of the semileptonic decay rate is not allocated.

Experiment

Heavier states or non-resonant contributions?

Need further analysis of broad states and what saturates the inclusive sum.

Theory

Missing \( 1/m_c \) corrections in theoretical predictions.

Need unquenched lattice calculations.

If we do not control \( B \rightarrow D^{**} \ell \nu \) can we fully trust the HQET based extraction of exclusive \( |V_{cb}| \)?
backup
BaBar $B \rightarrow D^{**} l \bar{\nu}$ systematics.

<table>
<thead>
<tr>
<th></th>
<th>$B \rightarrow D_1 \ell^- \bar{\nu}_\ell$</th>
<th>$B \rightarrow D'<em>1 \ell^- \bar{\nu}</em>\ell$</th>
<th>$B \rightarrow D_2^* \ell^- \bar{\nu}_\ell$</th>
<th>$B \rightarrow D_0^* \ell^- \bar{\nu}_\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking efficiency</td>
<td>1.5</td>
<td>1.9</td>
<td>1.2</td>
<td>1.6</td>
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