$V_{cb}$ (and more) from $B \to D^{(*)} l\nu$ decays

Outlook:

- Role of $B \to D^{(*)} l\nu$ decays for theory validation
- Measurement of $V_{cb}$: status
- Measurement of $V_{cb}$: perspectives
- Conclusions

Belle
$B^0 \to D^+ l\nu$

DELPHI
$B^0 \to D^{*+} l\nu$
The Challenge

Measurement of inclusive $b \rightarrow clv$ decays + OPE :

$|V_{cb}| = (41.9 \pm 0.6) \times 10^{-3}$

- < 2% already achieved
- ~ 1% within reach

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Quests. for Exclusive Decays

Can achieve comparable precision?

- theoretical limits
- experimental limits

Can probe OPE predictions? (!)

and strengthen belief in OPE

("The Devil in the detail", Grinstein, Daegu, Oct 2004)

("The fly in the ointment" Bigi, SLAC. Dec 2004)
Probe OPE in $B \rightarrow D(*)l\nu$

Shape of Form Factors:

- the slope
- the curvature

Integrated Rates

- Saturation: $b \rightarrow cl\nu = B \rightarrow (D + D^* + D^{**}) l\nu$
- D** states: "3/2 > 1/2 Puzzle"
Partial Rates

\[
\frac{d\Gamma(B \to D\ell\bar{\nu})}{dw} = \frac{G_F^2 m_B^5}{48\pi^3} r^3 (1 + r)^2 (w^2 - 1)^{3/2} |V_{cb}|^2 \mathcal{F}^2(w)
\]

\[
\frac{d\Gamma(B \to D^*\ell\bar{\nu})}{dw} = \frac{G_F^2 m_B^5}{48\pi^3} r^3 (1 - r^*)^2 \sqrt{w^2 - 1} (w + 1)^2 \\
\times \left[ 1 + \frac{4w}{1+w} \frac{1 - 2wr^* + r^2}{(1 - r^*)^2} \right] |V_{cb}|^2 \mathcal{F}^*^2(w)
\]

\[
w = v_B \cdot v_D = \frac{M_B^2 + M_D^2 - q^2}{2 M_B M_D}
\]
Form Factors

Consider the following expansions: (hep-ph /0111392)

\[
\mathcal{F}(w) = \mathcal{F}(1) \left[ 1 - \rho_{\mathcal{F}}^2 (w - 1) + c_{\mathcal{F}} (w - 1)^2 + \cdots \right] \\
\mathcal{F}_*(w) = \mathcal{F}_*(1) \left[ 1 - \rho_{\mathcal{F}_*}^2 (w - 1) + c_{\mathcal{F}_*} (w - 1)^2 + \cdots \right] \\
h_{A_1}(w) = h_{A_1}(1) \cdot f( w | \rho_{A_1}^2, \ldots )
\]

QCD provides bounds on normalization and shape parameters

Most of these can be experimentally tested
QCD Bounds

Normalization (LQCD, next talk):

\[ F(1) = 1.04 \pm 0.01 \pm 0.01 \]

\[ h_A(1) \approx F_*(1) = 0.92 \pm 0.03 \]

Curvature:

expect \( c > 0 \)

\[ c_{F*} \approx 0.66 \rho_{F*}^2 - 0.11 \]

similar bounds for \( c_F, c_{A1} \)

Slope:

\[ \frac{3}{4} < \rho_{F*}^2 < 1 \]

\[ \rho_F^2 - \rho_{F*}^2 \approx 0.19 \]

\[ \rho_{A1}^2 - \rho_{F*}^2 \approx 0.17, \rho_{A1}^2 \approx \rho_F^2 \]

Fit \( d\Gamma/dw \), determine \( F_*(1)V_{cb}, \rho^2 \) using bounds on \( c \)

Byproduct:

test expectations for shape parameters

Phys.Rev. D56,6895,(97)
Nucl.Phys. B530,153 (98)
hep-ph/0111392
Status (before ICHEP04)

- Linear fits as good as quadratic
- D* slope parameters larger than expected:
  \[ \rho^2_{F} - \rho^2_{A1} \approx -0.20 \text{ (Belle)} \]
  \[ \rho^2_{F} - \rho^2_{A1} \approx -0.37 \text{ (CLEO)} \]
  .... consistent with 0 due to large errors

<table>
<thead>
<tr>
<th>Fitted slope parameter</th>
<th>CLEO</th>
<th>BELLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B \rightarrow D^*\ell\bar{\nu} ), unitarity constrained fit to ( \rho^2_{A1} )</td>
<td>( 1.67 \pm 0.11 \pm 0.22 ) [10]</td>
<td>( 1.35 \pm 0.17 \pm 0.19 ) [11]</td>
</tr>
<tr>
<td>( B \rightarrow D^<em>\ell\bar{\nu} ), linear fit to ( \rho^2_{F^</em>} )</td>
<td>( 0.98 \pm 0.09 \pm 0.07 ) [12]</td>
<td>( 0.89 \pm 0.09 \pm 0.05 ) [13]</td>
</tr>
<tr>
<td>( B \rightarrow D\ell\bar{\nu} ), unitarity constrained fit to ( \rho^2_{F} )</td>
<td>( 1.30 \pm 0.27 \pm 0.14 ) [14]</td>
<td>( 1.16 \pm 0.25 \pm 0.15 ) [15]</td>
</tr>
<tr>
<td>( B \rightarrow D\ell\bar{\nu} ), linear fit to ( \rho^2_{F} )</td>
<td>( 0.76 \pm 0.16 \pm 0.08 ) [14]</td>
<td>( 0.69 \pm 0.14 \pm 0.09 ) [15]</td>
</tr>
</tbody>
</table>
ICHEP04 Update

- **BABAR**: \( B^0 \rightarrow D^* l^+ \nu \) with \( \sim 85 \text{ M BB} \) (\( \sim 60 \text{ K signal events} \))
- Get all prominent bckg (> few %) from data in each \( w \) bin
- Form Factor:
  - \( h_A(w) \): fit \( h_A(1)V_{cb} \) and \( \rho^2_{A1} \), +QCD bounds
  - \( F_*(w) \): 3rd order expansion, fit \( F_*(1)V_{cb} \), \( \rho^2_{F*} \) and \( c_{F*} \), without constraints

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**Figure:**

- Signal + BG
- Continuum D*1
- Fake leptons
- Combinatoric

---

**Graph:**

- \( \Delta M \text{ (MeV/c}^2) \)
- \( 0 \) to \( 30 \text{ Events/10}^7 / 0.5 \text{ MeV/c}^2 \)
- \( 0 \) to \( 30 \)
- \( 140 \) to \( 165 \)

**Legend:**

- **Total**: 7868.00, 88.70 / 7779.68
- **D*enu Signal**: 2800.41, 78.39 %
- **D*enu Signal**: 621.13, 7.98 %
- **Real D*enu**: 18.23, 6.24 %
- **Uncorrelated D*enu**: 432.82, 5.56 %
- **Correlated D*enu**: 104.58, 1.39 %
- **Continuum D*enu**: 178.55, 2.30 %
- **Fake D*enu**: 547.51, 7.04 %

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$B^0 \rightarrow D^* l^+ \nu$ BABAR Results

| $A_1(1)|V_{cb}| \times 10^3$ | $\rho^2$ | $c$ | $\chi^2/\text{ndf}$ |
|-----------------------------|---------|-----|------------------|
| $\mathcal{F}$              | 35.0 ± 0.9 | 0.95 ± 0.09 | 0.54 ± 0.17 | 67/57 |
| $A_1$                       | 35.5 ± 0.8  | 1.29 ± 0.03  |       -     | 69/58 |

- Linear FF excluded @ 3 $\sigma$
- $\rho^2_{F^*}$ and $c_{F^*}$ consistent with U-bounds
- $\rho^2_{F^*}$ within prediction
- $\rho^2_{A1} - \rho^2_{F^*} \approx 0.3$
- $\rho^2_{F^*}(\text{BABAR}) < \rho^2_{F}(\text{CLEO,Belle})$

\[ \text{need BABAR} \ B \rightarrow D l \nu \text{ for self-consistent, precise test} \]

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CKM2005 UCSD
Present World Average

- **HFAG average:**

  \[ h_A \left( 1 \right) \left| V_{cb} \right| = \left( 37.7 \pm 0.9 \right) \times 10^{-3} \]
  
  \[ \left| V_{cb} \right| = \left( 41.4 \pm 1.0 \pm 1.8 \right) \times 10^{-3} \]

  2.4% exp., 4% th. error

  ☺ Consistent with inclusive

  ☺ Exp. error soon decrease

  ❗ What about th. error?

  next slide

- Loose internal consistency: \( \chi^2/ndof = 27/14 \)

- Consistency not bound to improve in the future

- Scale exp. error according to PDG recipe?

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Error Budget

- Even without $\mathcal{L}$ increase many correlated errors will soon decrease due to ongoing measurements of:
  - $R_1, R_2$ (BABAR, next slide)
  - $f_{00}$ (BABAR, ICHEP04)
  - $\tau(B)$ (BB & Belle, ICHEP04)
  - $D B.R.$ (CLEO-C)

- Other errors (tracking, PID) not expected to improve with $\mathcal{L}$, but are reduced in the world average

| Source of Uncertainty | $\delta(A_1 | V_{cb})$ (%) | $\delta \rho_{A_1}^{\rho}$ | $\delta B$ (%) |
|-----------------------|-----------------------------|-----------------------------|----------------|
| Data and MC statistics| 0.7                         | 0.03                        | 1.4            |
| $B(D^0 \rightarrow K^- \pi^+)$ | 0.4                         | 1.1                         | -              | 2.2 0.8 |
| $B(D^0 \rightarrow K^- \pi^+ \pi^- \pi^+)$ | 0.4                         | -                           | 0.8            |
| $B(D^0 \rightarrow K^- \pi^+ \pi^0)$ | 0.5                         | -                           | 1.0            |
| Particles identification | 1.1                         | -                           | 2.2            |
| Tracking & $\pi^0$ reconstr. | 1.3                         | -                           | 2.6            |
| Partial Sum | 2.2                         | 0.03                        | 4.5            |

- $B^0$ lifetime | 0.3                         | 0.5                         | -              | -         |
- Number of $B \overline{B}$ | 0.6                         | -                           | 1.2            |
- $B(D^{*+} \rightarrow D^0 \pi^+)$ | 0.4                         | -                           | 0.7            |
- $B(\Upsilon(4S) \rightarrow B^0 \overline{B}^0)$ | 0.8                         | 1.2                         | -              | 2.5 1.5 |
- $D^{*+} \ell^- $ vertex efficiency | 0.5                         | -                           | 1.0            |
- $\pi^0$ efficiency | 1.1                         | 0.01                        | 1.9            |
- $D^{*} \pi \ell \nu$ sample composition | 1.8                         | 0.06                        | 2.0            |
- $B$ momentum | 0.3                         | -                           | 0.7            |
- Radiative corrections | 0.2                         | 0.01                        | 0.4            |
- $\cos \theta_{B^0, D^{*+}} & \tilde{w}$ fit method | 0.8                         | 0.02                        | 1.6            |
- $R_1(1)$ and $R_2(1)$ | 0.6                         | $^{+2.9}_{-2.6}$            | 0.05 0.26      | $^{+3.9}_{-3.3}$ 0.7 |

Total Error

My guess for BABAR $\pm 3% \pm 0.09 \pm 6%$

My guess for w.a.: $\sigma(h_A(1) V_{cb}) \sim 1.5%$

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$R_1, R_2$

- Ratio of Axial to Axial and Vector to Axial FF
- Affect $V_{cb}$:
  - correlation with $\rho^2$
  - acceptance correction
- Measured with a fit to helicity-related quantities
- BABAR (ICHEP04), still based on linear shape, improves by ~ 5 times wrt CLEO (PRL76,3898,1996)

$$ R_1 \hspace{1cm} R_2 $$

**BABAR**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.33\pm0.06$</td>
<td>$0.92\pm0.04$</td>
</tr>
</tbody>
</table>

**CLEO**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.18\pm0.30$</td>
<td>$0.71\pm0.22$</td>
</tr>
</tbody>
</table>

error : stat. $\oplus$ syst.

Publish soon with HQET inspired FF

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Status & Perspectives

From D* decays:

\[ \sigma^{\text{exp}} \left( h_A(1) \vert V_{cb} \right) \sim 2\% \]

\[ h_A(1) = 0.92 \pm 0.04 \ (LQCD) \]

\[ \sigma(\vert V_{cb} \vert) = 2\% \text{ (exp.) } \oplus 4\% \text{ (th.)} \]

Ways to proceed:

- theory: improve computation of \( h_A(1) \)
- recall \( B \rightarrow Dl^+\nu \) case:
  \[ \mathcal{F}(1) = 1.074 \pm 0.018 \pm 0.015, \ 1\% \text{ in few years} \]
- experiments:

Reconsider long-time-neglected \( B \rightarrow Dl^+\nu \) decays

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next talk?
$B \rightarrow D l^+ \nu$ : status

- HFAG average with new LQCD results:

$$F(1) \mid V_{cb} \mid = (42.0 \pm 3.7) \times 10^{-3}$$
$$\mid V_{cb} \mid = (39.1 \pm 3.6 \pm 1.3) \times 10^{-3}$$

9% exp., 3.5% th. error

- ☑ Consistent with $D^*$, inclusive

- ☺ Very good internal consistency

- 😞 Large experimental error!

- 🗓 Bound to improve?

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$B \to Dl^+\nu$ : exp.overview

- **Background issues:**
  - downfeed from $D^*(*)$
  - uncorrelated $lD$
  - combinatoric

- **Reconstruct $\nu$ from $E_{miss}, P_{miss}$, compute $B$ mass**
  - large detector-related errors
  - efficiency depends also on decay properties of the other $B$ ($K_L$, additional $\nu, ...$)

Not needed in $D^*l\nu$ analysis

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Error Budget

- Large systematic error (10%) due to $\nu$ reconstruction
- Unlikely to reduce below 5% (see also new $|V_{ub}|$ meas.)

| Source of uncertainty                     | $\Delta |V_{ub}| F_D(1)$ (%) | $\Delta r_D^2$ (%) | $\Delta \Gamma$ (%) |
|-------------------------------------------|------------------------|--------------------|---------------------|
| $\nu$ reconstruction simulation           | 10.6                   | 9.7                | 15.5               |
| Correlated background normalization       | 2.4                    | 4.4                | 1.9                |
| $D^*$ form factor                         | 1.5                    | 2.8                | 0.9                |
| Other background normalization            | 0.6                    | 1.8                | 0.4                |
| $D^+$ vertexing efficiency                | 4.7                    | 5.8                | 5.3                |
| Lepton finding efficiency                 | 1.5                    | -                  | 3.0                |
| $N_{BB}$                                  | 0.5                    | -                  | 1.0                |
| $Br(D^+ \rightarrow K^+\pi^+\pi^+)$      | 3.3                    | -                  | 6.7                |
| $\tau_{CP}$                               | 1.0                    | -                  | 2.1                |
| **Total**                                 | **12.5**               | **12.6**           | **18.2**           |

- Need other methods. Consider tagged samples!
Tagged samples

- Fully reconstruct the B to several hadronic modes (~ 2500/1500 B⁺/B⁰ fb⁻¹) (tag side)
- Use the remnant (recoil) for the measurement

**BABAR**

*generic events*

**Belle,** $p_{lep} > 1$ GeV
Tagged $B \rightarrow Dl^+\nu$ samples: pros

- fully reconstructed hadron plus flavor constraints reduce background at start
- precise $\nu$ reconstruction using constraints from tag-$B$ enhances bckg rejection and improves determination of $w$

Background not an issue here!

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Tagged $B \rightarrow Dl^+\nu$ samples: **cons**

- No free lunch!
- Low event yield:
  - $\sim 200 \, D(e+\mu)\nu / 100 \, \text{fb}^{-1} / \exp$
  - $\sim 2000$ events (BABAR+Belle) by summer 2006
  - $\sim 5000$ by end 2008

- Already on tape ~ as many events as in published results
Tagged $B \to D l^+ \nu$ samples: expectation

- Rescale untagged Belle results, accounting for improved S/N
- Ignore bonus from improved $\omega$ reconstruction

| year | # evts | $\sigma |V_{cb}|$ (%) | $\sigma$(BR) % |
|------|--------|----------------|----------------|
| 2006 | 2000   | 3.5            | 2.2            |
| 2008 | 5000   | 2.2            | 1.5            |

- Assuming similar systematic error as for $D^*$, would expect

$\sigma^{(exp.)} V_{cb} \sim 2.5\%$

by end of 2008

- Could be improved with theory bounds on $\rho_F^2$
Total Rates & D**

- BR \( (B^0 \rightarrow lvX) = (10.5 \pm 0.8)\% \)
- BR \( (B^0 \rightarrow lvD) = (2.1 \pm 0.2)\% \)
- BR \( (B^0 \rightarrow lvD^*) = (5.4 \pm 0.2)\% \)

Other semileptonic decays (excited D states) must account for ~ 3% of the total B decay rate.

- BR \( (B \rightarrow lvD^{**}) = (2.7 \pm 0.7)\% \) \( \text{ARGUS, missing mass} \)
- BR \( (B \rightarrow lv(D\pi+D^*\pi) = (2.6 \pm 0.5)\% \) \( \text{ALEPH, DELPHI topological analysis} \)

Unitarity of Quantum Mechanics is preserved! Is OPE as well?
The $\frac{1}{2} > \frac{3}{2}$ Puzzle

- $\text{BR}(B \rightarrow l\nu D^*_1) = (0.7 \pm 0.2 \%)$
- $\text{BR}(B \rightarrow l\nu D^*_2) < 0.5\%$
- $B \rightarrow l\nu(D^*_2 + D^*_1)/B \rightarrow l\nu D^{**} < 30\%$

Contradicts OPE + sum rules predicting narrow states to prevail!


Diagrams show experiments do not distinguish broad states from “open” $B \rightarrow l\nu DX$ decays

“Old” results: B-factories?

D0 2005 (prel.):
- narrow states account for ~ 50%
- $B \rightarrow l\nu D^* X$ decays!
Conclusions

- QCD+OPE is in good shape as for exclusive B decays

- Error on $|V_{cb}| (~4\%)$ is dominated now by theory:
  - deal with poor consistency of experimental results!

- Without progress in theory, future is in tagged measurements of $B \rightarrow D\ell^+\nu$ decays

- Combining D (3% , exp. dominated) and D* (4% th. dominated) could go down to $\sim 2.5\%$ (my estimate)
  
  \[
  \text{do better only if theory improves on } F^*
  \]

*many thanks to Kolja for useful suggestions*

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BACKUP material
Definition of $D^*$ \textit{ff}

\[ F(w)^2(1+4\frac{w}{w+1}\frac{1-2wr+r^2}{(1-r)^2}) = \]

\[ = h_{AI}(w)^2\left[2\frac{1-2wr+r^2}{(1-r)^2}\right](1+R_1(w)^2\frac{w-1}{w+1})+\left[1+(1-R_2(w))\frac{w-1}{w_1}\right]^2 \]

\[ h_{AI}(w)=h_{AI}(1)(1-8\rho_{AI}^2+(53\rho_{AI}^2-15)z^2-(231\rho_{AI}^2-91)z^2) \]

\[ z = \frac{(\sqrt{(w-1)}-\sqrt{2})}{(\sqrt{(w+1)}+\sqrt{2})} \]