CLEO Measurements of the CKM Elements $|V_{ub}|$ and $|V_{cb}|$

Thomas Meyer
CLEO Collaboration
(Cornell University)

Outline

- Current Situation
- How to Measure $|V_{q_1q_2}|$
- $B$’s at CLEO
- Getting $|V_{cb}|$ From $B \rightarrow D^* \ell \nu$
- Getting $|V_{ub}|$ From $B \rightarrow \pi/\rho/\omega/\eta \ell \nu$
- Summary and Outlook
STATUS OF $|V_{ub}|$ AND $|V_{cb}|$

Unitary CKM matrix describes mixing between quark mass eigenstates in (charged-current) weak interactions

$$V \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1 - \frac{1}{2} \lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2} \lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

• PDG 00 values:

  $$|V_{cb}| = 0.0402 \pm 0.0019 \quad \text{and} \quad |V_{ub}| = (3.6 \pm 1.0) \times 10^{-3}$$

• Note 4.7% error on $|V_{cb}|$
  
  - Third most accurately measured CKM element
    (After $|V_{ud}|$ and $|V_{us}|$)
  - From exclusive $B \to D(\ast)\ell\nu$, inclusive $b \to c$
    (CLEO, LEP)

• And 28% error on $|V_{ub}|$!
  
  - Based primarily on lepton endpoint measurements
  - Agrees with CLEO measurements of $B \to \pi/\rho \ell\nu$
    And values from LEP $b \to u \ell\nu$

• Branching fractions

  $${\cal B}(b \to c \ell\nu) = 10.5\% \quad \bigcirc$$

  $${\cal B}(b \to u \ell\nu) \sim 2 \times 10^{-3} \quad \bigotimes$$

Thomas Meyer

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Unitarity property (constraint) leads to famous triangle in complex plane when applied to $d$ and $b$ columns

Only this combination produces triangle with all sides of same order $O(\lambda^3)$

CKM elements define Standard Model (SM)

- $|V_{q_1q_2}|$ simply sets scale for all $q_2 \to q_1$ transitions
- Area of triangle measures CP violation within SM
  \[ \Rightarrow \text{Sides—and angles—probe } \mathcal{CP} \]
- $|V_{ub}|$ sets bound on apex $\rho^2 + \eta^2$, $|V_{cb}|$ sets scale of base

Also provide window for testing it

- Over-constrain triangle—stress-test the theory
- Tests of unitarity $\iff$ Sensitivity to new physics

Experimental measurement, however, is non-trivial . . .
Good place to study $b \to c, u$ transitions

- **Leptonic** physics understood and calculable
- **Hadronic** physics unknown—but can be parameterized with *form factors*
  - $\sqrt{\text{Constraints from HQET, other symmetries}}$
  - $\sqrt{\text{Universal to some extent}}$
  - $\times \text{Model-dependent}$
**Semileptonic $B$ Decay—Kinematics**

View as $b \rightarrow Wq$, $W \rightarrow \ell \nu$

\[
\begin{align*}
\text{Kinematic variables} & \\
\bullet \ w: \text{Lorentz boost } \gamma \text{ of } X \text{ in } B \text{ rest frame} & \quad w = v_B \cdot v_X \\
\bullet \ q^2: \text{Mass of virtual } W, \text{ 4-mom transfer to } \ell \nu \text{ pair} & \quad q^2 = (p_\nu + p_\ell)^2 = (p_B - p_X)^2
\end{align*}
\]

At $w = 1$ ($q_{\text{max}}^2$), daughter quark $q$ does not recoil

For heavy $q$, light degrees of freedom ($q' + \text{gluons}$) unaware of $b \rightarrow q$ transition (Heavy Quark Symmetry)

$\Rightarrow$ Theoretical calculation on sound footing
**B’s at CLEO**

- Symmetric $e^+ e^-$ machine
  - Operates on $\Upsilon(4S)$ resonance
  - $B\bar{B}$ pairs produced at threshold
    - Each $B$ has only $|\vec{p}_B| \approx 300$ MeV/c
  - Cross-sections
    - $\sigma(B\bar{B}) = 1.0$ nb
    - $\sigma(q\bar{q}) = 3.1$ nb

- Off-resonance (“continuum”) running 60 MeV below $\Upsilon(4S)$
  - Measure in data production of various “background” processes
    - $q\bar{q}$ ($q = u, d, s, c$), $\tau\bar{\tau}$, 2-photon, . . .
  - Simply *subtract* these from $B$-physics analyses
CLEO

- CLEO II (1989) \[3.3 \times 10^6 B\bar{B} \text{ decays}\]
  Drift chambers, crystal calorimeter, muon counters

- CLEO II.V—Upgraded version (1996) \[6.5 \times 10^6 B\bar{B} \text{ decays}\]
  - Silicon detector replaces inner wire chamber

- Nearly hermetic detector
  - Tracking coverage \(\approx 95\% \) of \(4\pi\)
  - Calorimeter coverage \(\approx 98\%\)
Analyzing $B \to D^* \ell \nu$

Differential decay rate:

$$\frac{d\Gamma}{dw} = \frac{G_F}{48\pi^3} |V_{cb}|^2 F(w)^2 G(w)$$

- $G(w)$ contains kinematics and is known
- $F(w)$ is form factor for $B \to D^*$
  - Parameterizes non-perturbative (unknown) physics
  - Absolutely normalized at zero recoil ($w = 1$)
    - i.e. $F(1)$ provided by theory
    - In $m_Q \to \infty$ limit: $F(1) \to 1$
    - For $B \to D^* \ell \nu$, corrections only at order $1/m_c^2$
      $\Rightarrow F(1) = 0.913 \pm 0.042$ $^a$

Basic analysis technique:

1. Fit for $B \to D^* \ell \nu$ signal in data, in (10) bins of $w$
2. Measure $d\Gamma/dw$ in each bin
3. Fit with functional form from phenomenology
4. Extrapolate to $w = 1$ and extract $F(1)|V_{cb}|$

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$^a$ (PLB264, 455; 338, 84; PRD47, 2965; 51, 2217; 53, 3149; PRL 76, 4124)
Reconstructing \( B \rightarrow D^* \ell \nu \)

Fully reconstruct \( D^* \) decay
\[
D^* \rightarrow D^0 \pi \rightarrow K^- \pi^+
\]

**Separate** analyses for \( \bar{B}^0 \rightarrow D^{*+} \ell \nu, B^- \rightarrow D^{*0} \ell \nu \)

- Backgrounds, \( B(D^* \rightarrow D \pi) \), \( \tau_B \) different
- Eff’y for charged \( \pi^\pm \) different than for neutral \( \pi^0 \)

\[ \Rightarrow \] \( D^{*+} \) analysis has preliminary results for \( B \) and \( F(1)|V_{cb}| \)
**FINDING $D^*$ ℓ’S**

**$D^*$ Finding**

- $D$ candidate from $K$ and $\pi$ tracks
- $D^*$ from addition of slow $\pi$

$$D^0 \rightarrow K^-\pi^+$$  
$$D^{*+} \rightarrow D^0 \pi^+$$

**$D^*\ell$ pairs can arise from more than just signal △**

- $B \rightarrow D^* X \ell \nu$
  - Non-resonant $B \rightarrow D^* \pi \ell \nu$ or higher resonant states, *e.g.*
    $$D^{**} \rightarrow D^* \pi$$
- Other backgrounds
  - Estimated *in data*, some input from Monte Carlo
Fitting for the $B \to D^* \ell \nu$ Yield

Separate signal $B \to D^* \ell \nu$ from $B \to D^* X \ell \nu$ with kinematics:

$$\cos \theta_{B-D^*\ell} = \frac{2E_B E_{D^*\ell} - m_B^2 - m_{D^*\ell}^2}{2|\vec{p}_B||\vec{p}_{D^*\ell}|}$$

Signal should have $\cos \theta \in [-1, 1]$

Background extends to unphysical values

Binned maximum-likelihood fit to $\cos \theta_{B-D^*\ell}$ distribution in data

- Backgrounds subtracted
- Signal shape in $\cos \theta_{B-D^*\ell}$ from Monte Carlo
- Normalizations (= yields) allowed to float

$\Rightarrow$ Result: $B \to D^* \ell \nu$ and $B \to D^* X \ell \nu$ yield in each $w$-bin
Representative Fits for $\bar{B}^0 \rightarrow D^{*+} \ell \nu$

1.000 < $w$ < 1.051

Events vs. $\cos \Theta_{B-D^*\ell}$

1.306 < $w$ < 1.357

Events vs. $\cos \Theta_{B-D^*\ell}$
Fitting the Decay Rate

- Unfolds phase space, kinematic factors, and form factor $F(w)$
- Takes into account reconstruction eff’y, smearing in $w$
- $w$-dependence of $F(w)$ from dispersion relations $^a$
- Fit parameters essentially $F(1)|V_{cb}|$ and $\rho_{hA_1}^2$ (slope at $w = 1$)
  \[
  F(1)|V_{cb}| = (42.4 \pm 1.8 \pm 1.9) \times 10^{-3}
  \]
  \[
  \rho_{hA_1}^2 = 1.67 \pm 0.11 \pm 0.22
  \]
- Integrating over $w$,
  \[
  \mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\ell\nu) = (5.66 \pm 0.29 \pm 0.33)\%
  \]

$^a_{\text{NPB530,153}}$
Form factor at zero recoil known: $\mathcal{F}(1) = 0.913 \pm 0.042$

$\Rightarrow |V_{cb}| = 0.0464 \pm 0.0020 \pm 0.0021 \pm 0.0021$ [CLEO]

- Consistent with previous CLEO, LEP measurements—but slightly higher

Compare this result to previous ones
Swamped by Cabibbo-favored $b \to c \ell \nu$

- $|V_{ub}| > 0$ first verified only in 1990
- Hard cuts required experimentally to control $b \to c$ backgrounds—makes theoretical interpretation difficult
- Inclusive theoretical calculations only reliable when large part of phase space is sampled—experimental measurement hard!

Tradeoff

Exclusive analysis incurs large model dependence

but

Inclusive analysis suffers from large backgrounds
**B → X_u ℓν Analysis**

**Analysis Goals—In progress**

- Extract $|V_{ub}|$
- Measure $B_i$ and kinematics ($q^2$) of $\pi$, $\rho$ modes
- Consider/Evaluate range of models
- Reconstruct $B \to X_u \ell \nu$ candidates in seven channels
  
  $\pi^\pm \to \pi^\pm \pi^0$
  $\pi^0 \to \pi^+ \pi^-$
  $\eta \to \pi^+ \pi^- \pi^0$
  $\eta \to \gamma \gamma, \omega \to \pi^+ \pi^- \pi^0$

**Neutrino Reconstruction**

- Conservation laws dictate that what goes in must come out

$$p_\text{miss}^\mu = p_0^\mu - \sum_{\text{particles } i} p_i^\mu$$

- Hermetic detector “captures” all particles
  1. Charged particles—tracks + PID $\Rightarrow p_i^\mu$
  2. $\pi^0$, $\gamma$—unmatched showers + beamspot $\Rightarrow p_i^\mu$

- **Neutrino** must carry away any momentum-energy missing in final state

$$\Rightarrow p_\nu^\mu \equiv p_\text{miss}^\mu$$
Neutrino Reconstruction

Must **veto** events with more than one missing particle

- e.g. Add’l $\nu$, $K_L^0$, neutrons
- Lepton counting: $N_\ell > 1 \sim N_\nu > 1$
- *Test* neutrino hypothesis: $M_{\text{miss}}^2 = 0$
  Cuts out $b \rightarrow c \ell \nu$ that misreconstructs as signal

Measure tracks and showers, *not* particles

- Must be sure to account for each particle *exactly* once
- Examine net charge $\Delta Q$ of event
  - Easy way to detect missing tracks: $|\Delta Q| = 0$
  - Include $|\Delta Q| = 1$, increases signal eff’y more than bkgrd
    Ex: Slow $\pi$ missed, but little impact on $(E_{\text{miss}}, \vec{p}_{\text{miss}})$
Continuum suppression

- Need to avoid cuts that bias $q^2$ distribution
- $\theta_{\text{thrust}}$: angle between $X_u-\ell$ and thrust of rest of event
- Off-resonance data subtraction

$b \rightarrow c \ell \nu$ suppression

- Angle between $\ell$ in $W$ rest frame and $W$ in $B$ frame
  Reflects $V-A$ nature of charged current
- Apply cut on $\cos \theta_{\text{lep}}$ in vector modes only
- $|p_{\ell}| > 1.5$ GeV/c (vector), 1.0 GeV/c (pseudoscalar)
- Softer $\ell$ from $b \rightarrow c \ell \nu$ than $b \rightarrow u \ell \nu$
• Define variables for each $B$-candidate

\[
\Delta E \equiv (E_\nu + E_\ell + E_{\text{had}}) - E_{\text{beam}} \\
\tilde{M}_B \equiv \sqrt{E_{\text{beam}}^2 - |\alpha \vec{p}_\nu + \vec{p}_\ell + \vec{p}_{\text{had}}|^2} \\
\alpha = 1 - \frac{\Delta E}{E_\nu}
\]

• Carve up $\Delta E - M_B$ plane into signal box (#1) and sidebands
  ▶ Backgrounds, cross-feeds constrained by data outside signal box, too

• Perform binned $\chi^2$ fit in $\Delta E - M_B$ to extract signal yields, background amounts in each box for each mode
SAMPLE π-MODE FITS

- Simultaneous fit for all $X_u$ modes accounts for cross-feed and common backgrounds
  1. $b \to c \ell \nu$ backgrounds from Monte Carlo
  2. $b \to u \ell \nu$ “other”, i.e. not in signal modes
  3. Cross-feed from other signal modes into this one, from MC
  4. Fakes ($h \to \ell$), from non-leptonic data
  5. Continuum backgrounds, as measured in OFF data
  6. Signal from Monte Carlo

- Use ISGW2 model here for signal and background shapes

Charged and Neutral π

$M_B$ vs. $\Delta E$ for $\Delta Q = 0$ only
SUMMARY

• CKM elements offer special opportunity to investigate and test Standard Model

• CLEO has preliminary measurement of $|V_{cb}|$ from $\bar{B}^0 \to D^{*+}\ell\nu$
  $|V_{cb}| = 0.0464 \pm 0.0020 \pm 0.0021 \pm 0.0021$
  ▶ Charged and neutral $D^*$ modes to be combined
  ▶ Systematics understood; analyses nearing completion
  ▶ Promises world’s most precise measurement from $B \to D^{*}\ell\nu$
  ▶ New analyses using CLEO II.V dataset underway as well

• CLEO has analyses in progress on $|V_{ub}|$ using full dataset
  ▶ Exclusive $B \to \pi/\rho/\omega/\eta\ell\nu$
    ▶ Promises $B_i$ and $q^2$ information
    ▶ Model discrimination
  ▶ Lepton-energy endpoint
    ▶ Window into essential non-perturbative physics
  ▶ $|V_{ub}|$ from $b \to s\gamma + E_\ell$-endpoint
  ▶ Several inclusive $b \to X \ell\nu$ analyses in the works

Will the Standard Model hold up . . . ?
$B \to D^* \ell \nu$ Backgrounds

$D^* \ell$ pairs can arise from more than just signal △

- **$B \to D^* X \ell \nu$**
  - Non-resonant $D^* \pi \ell \nu$ production
  - Higher resonant states, generically called $D^{**} \ell \nu$
  - Model with latest phenomenology
- **Combinatoric**—Events with $D^*$ resulting from mis-reconstruction (fakes)
  - Estimate magnitude from events in $\Delta m = M_{D^*} - M_D$ sideband
  - Shape from Monte Carlo
- **Continuum**—$e^+ e^- \to q\bar{q}$ with real $D^*$ and $\ell$
  - Subtracted using data taken slightly below $B\bar{B}$ threshold
- **Uncorrelated**—$D^*$ and $\ell$ come from different $B$’s
  - Estimate from inclusive $D^*$ and $\ell$ yields
- **Correlated**—Real $D^*$ and $\ell$ from same $B$, but not signal mode
  - Ex: $B \to D^* D_s$, with $D_s \to X\ell$
  - Estimated from Monte Carlo
- **Fake lepton**—Mis-ID hadrons as $\ell$, combine with real $D^*$

\[ a \] Estimate for $D^{*+}$ modes only
Estimating $w$

- $w \in (1, 1.51)$ is Lorentz boost of the $D^*$ in the $B$ rest frame.
- At CESR/CLEO, $B$’s nearly at rest: $|\vec{p}_B| \approx 300\text{ MeV}/c$.
- Know the magnitude but not the direction of $B$ momentum. Determined only up to azimuthal ambiguity.
- Compute estimate for $w$ using two extreme possibilities for $B$ direction.

\begin{itemize}
  \item Resolution good: $\sigma_w \approx 0.03$
\end{itemize}
CHECKING THE FIT

Projections of fit results into signal region, all $w$-bins combined
Cut on $\cos \theta_{B^{-D^*\ell}}$ applied

$D^{*+}$ Energy $E_{D^*}$

Lepton Energy $E_\ell$

(Error bars on data are for data sample, and do not include statistical errors on combinatoric and continuum bkgrds)
**Fitting $d\Gamma/dw$**

Binned $\chi^2$ fit: $(B \to D^*\ell\nu$ yield)$_i \mapsto (d\Gamma/dw)_i$

$$\chi^2 = \sum_{i=1}^{10} \frac{\left[ N_{i,\text{obs}} - \sum_{j=1}^{10} \epsilon_{ij} N_j \right]^2}{\sigma_{N_{i,\text{obs}}}^2}$$

- $N_{i,\text{obs}}$: Yield in $i$th $w$-bin
- $\epsilon_{ij}$: Accounts for reconstruction eff’y, $w$-smearing
- $N_j$: number of signal decays in $j$th $w$-bin

$$N_j = 4f N_{\Upsilon(4S)} \mathcal{B}(D^* \to D\pi) \mathcal{B}(D \to K\pi) \tau_B \int_{w_j} dw \frac{d\Gamma}{dw}$$

![Graph showing events vs. $w$ with fit and data points]
\( \bar{B}^0 \rightarrow D^{*+}\ell\nu \) **SYSTEMATICS**

| Source                        | \(|V_{cb}|\mathcal{F}(1)(\%)| \rho^2(\%)| \Gamma(\%) |
|-------------------------------|------------------------|---------|----------|
| Slow \( \pi \) finding       | 3.1                    | 3.7     | 2.9      |
| Combinatoric Bkgd             | 1.4                    | 1.8     | 1.2      |
| Lepton ID                     | 1.1                    | 0.0     | 2.1      |
| \( K, \pi \) & \( \ell \) finding | 1.0             | 0.0     | 1.9      |
| Number of \( B\bar{B} \) events | 0.9              | 0.0     | 1.8      |
| Uncorrelated Bkgd             | 0.7                    | 0.9     | 0.7      |
| Correlated Bkgd               | 0.4                    | 0.3     | 0.5      |
| \( B \) momentum & mass      | 0.3                    | 0.5     | 0.4      |
| \( D^*X \ell\nu \) model     | 0.2                    | 1.9     | 1.9      |
| Subtotal                      | 3.8                    | 4.7     | 5.0      |
| \( R_1(1) \) and \( R_2(1) \) | 1.4                    | 12.0    | 1.8      |
| \( \text{B}(D \rightarrow K\pi) \) | 1.2                | 0.0     | 2.3      |
| \( \tau_B \)                  | 1.0                    | 0.0     | 2.1      |
| \( \text{B}(D^{*} \rightarrow D\pi) \) | 0.4                | 0.0     | 0.7      |
| Subtotal                      | 2.2                    | 12.0    | 3.7      |
| **Total**                     | **4.4**                | **13**  | **6.2**  |
History

• First observation of $|V_{ub}| > 0$ made in 1990
  Found $B \rightarrow X\ell\nu$ beyond kinematic endpoint for charm

• Measurement of $\mathcal{B}(B \rightarrow \pi/\rho \ell\nu)$ and $|V_{ub}|$ published early 1996
  ▶ Successful debut of $\nu$–reconstruction
  ▶ Data sample of 4 fb$^{-1}$
  ▶ 20% error on $|V_{ub}|$—model-dependence of form factors

$$|V_{ub}| = (3.3 \pm 0.2^{+0.3}_{-0.4} \pm 0.7) \times 10^{-3}$$

• Update of $\mathcal{B}(B \rightarrow \rho \ell\nu)$ in 1999

$$|V_{ub}| = (3.25 \pm 0.14^{+0.21}_{-0.29} \pm 0.55) \times 10^{-3}$$

First examination of partial rate in (3) bins of $q^2$
High $|p_\ell|$ cut selects region where most models agree
Another round at CLEO continues . . .

- $|V_{cb}|$ from $B \to D^* \ell \nu$ with CLEO II.V dataset
  - SVX improves slow $\pi$ efficiency
- $|V_{ub}|$ from endpoint of lepton energy spectrum with full CLEO dataset
- $|V_{ub}|$ from measurements of non-perturbative physics from $b \to s \gamma$ combined with endpoint spectrum
- Inclusive $b \to u \ell \nu$ analysis
  - Use other kinematic variables to cut out charm
    - Hadronic mass, $q^2$
  - But retain larger fraction of phase space