Measurement of $V_{cb}$ and Charmless Hadronic B Decays at CLEO

Xin Zhao
University of Kansas/CLEO
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- Introduction to CLEO
- Measurement of $|V_{cb}|$
- Charmless Hadronic B Decays
- CLEOIII Status
- Summary
A Brief History of CLEO

CLEO Integrated Luminosities


10^9

10^8

10^7

10^6

10^5

10^4

10^3

10^2

10^1

BB / Year

CLEO Related

CESR Related

CLEO I

CLEO I.5

CLEO II

CLEO II.5

CLEO III

Particle ID

New Tracking

2cm BP
Silicon
He-propane

Mixing
b → s γ
K, η'K,
π/ρν
Csl
3.5cm BP

b → u ν

New Tracking

Microbeta
7 Bunches

9X3 Bunches

SC IR Quads
SC RF

Crossing Angle

Xi n Z h ao, K a n s a s // C L E O R A D C O R /2/0/0/0
CLEO II/II.V Detector
- Integrated Luminosity of 13.5 $fb^{-1}$
- 9.1 $fb^{-1}$ on $\Upsilon(4S) : \sim 9.7 \times 10^6 B\bar{B}$ events
- 4.4 $fb^{-1}$ on continuum (60 MeV below the $\Upsilon(4S)$ resonance)
- 2/3 data taken in CLEO II.V configuration

**CLEO analysis covers wide topics in B meson decay, esp. the measurements of the CKM matrix elements and CP violation.**
The CKM matrix and Unitary Triangle

- The CKM matrix
  The CKM matrix must be unitary in the Standard Model

\[
V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0
\]
\[
V_{ub}V_{us}^* + V_{cb}V_{cs}^* + V_{ts}V_{ts}^* = 0
\]
\[
V_{us}V_{ud}^* + V_{cs}V_{cd}^* + V_{ts}V_{td}^* = 0
\]

- The Unitary Triangles

- Below I will focus on the new CLEO results of the measurement of $|V_{cb}|$ and charmless hadronic B decays
The partial width of $\bar{B}^0 \to D^{\ast+} \ell^- \bar{\nu}$ is proportional to $|V_{cb}|^2$:

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

- $w = v_B \cdot v_{D^\ast}$, the relativistic $\gamma$ of $D^\ast$ in the $B$ rest frame.
- $\mathcal{G}(w)$ contains kinematic factors and is known.
- $\mathcal{F}(w)$ is the form factor describing $B \to D^\ast$ transition.

At zero recoil of $D^\ast$ (i.e. $w = 1$), $\frac{d\Gamma}{dw} \propto (\mathcal{F}(1)|V_{cb}|)^2$, $\mathcal{F}(1)$ can be calculated by theory like HQET (Heavy Quark Effective Theory).
Analysis Technique

- The technique is to measure $d\Gamma/dw$ and extrapolate to $w = 1$ to extract $\mathcal{F}(1)|V_{cb}|$. For $D^*\ell\nu$, $w$ runs from 1 to 1.5. We divide it into ten bins.
  (use CLEO-II sample $\sim 3 \times 10^6 B\bar{B}$ events)

- Event full reconstruction: $\bar{B}^0 \rightarrow D^{*+}\ell^-\bar{\nu}$, $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^-\pi^+$

- The $\bar{B}^0 \rightarrow D^{*+}\ell^-\bar{\nu}$ yield in each $w$ bin is extracted from a likelihood fit to the $\cos \theta_{B-D^*} \ell$ distribution, which can well distinguish between $\bar{B}^0 \rightarrow D^{*+}\ell^-\bar{\nu}$ and $\bar{B}^0 \rightarrow D^{*+}X\ell^-\bar{\nu}$ ($\bar{B}^0 \rightarrow D^{**+}\ell^-\bar{\nu}$ and $\bar{B}^0 \rightarrow D^{*+}\pi\ell^-\bar{\nu}$, non-zero missing mass)

Representative fit plots

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$^a$the angle between the $D^*\ell$ combination and $B$
We then do a $\chi^2$ fit on the overall $w$ distribution taking into account backgrounds, reconstruction efficiency and the $w$ resolution ($\sigma_w \sim 0.03$).

We use the dispersion relations\(^a\) to constrain the shapes of the form factor $\mathcal{F}(w)$ and fit for $\mathcal{F}(1)|V_{cb}|$ and a “slope”, $\rho^2 (w = 1)$.

\(^a\)Caprini, Lellouch and Neubert (NPB530, 153)
## Systematic Errors

| Source                                | $|V_{cb}|F(1)|$ (%) | $\rho^2$ (%) | $\Gamma(B \rightarrow D^{*}\ell\nu)$ (%) |
|---------------------------------------|-----------------|--------|--------------|----------------------------------|
| 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          |
| $B(D \rightarrow K\pi)$              | 1.2             | 0.0    | 2.3          |
| $\tau_B$                              | 1.0             | 0.0    | 2.1          |
| $B(D^{*} \rightarrow D\pi)$          | 0.4             | 0.0    | 0.7          |
| **Subtotal**                          | **2.2**         | **12.0**| **3.7**      |
| **Total**                             | **4.4**         | **13** | **6.2**      |
We find

\[ \mathcal{F}(1)|V_{cb}| = (42.4 \pm 1.8 \pm 1.9) \times 10^{-3} \]
\[ \mathcal{B}(\tilde{B}^0 \rightarrow D^{*+}\ell^{-}\bar{\nu}) = (5.66 \pm 0.29 \pm 0.33)\% \]

Using \( \mathcal{F}(1) = 0.913 \pm 0.042 \), we calculate

\[ |V_{cb}| = (46.4 \pm 2.0 \pm 2.1 \pm 2.1) \times 10^{-3} \]

- This result is comparable to LEP’s but somewhat larger
- A measurement using \( D^{*0}\ell\nu \) will come soon. Combining these two channels will give the best single measurement of \( |V_{cb}| \) using the exclusive technique.
Charmless Hadronic Two-Body B Decays

Two main types of diagrams:

- $b \to u$ spectator (tree) diagrams (suppressed by $V_{ub}$)
- $b \to s$ penguin diagrams (suppressed by loops)
- Usually, there is more than one contribution to one decay
Analysis Technique

**Signal:** \( e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B} \quad (\sigma \sim 1 \text{ nb}) \)

**Background:** \( e^+e^- \rightarrow q\bar{q}, \ q = u, d, s, c \quad (\sigma \sim 3 \text{ nb}) \)

**Initial selection constraints:**

- \( m_B \equiv \sqrt{E_{\text{beam}}^2 - |\sum_i p_i|^2} \quad (\sigma_{m_B} \approx 2.5 \text{ MeV}) \)
- \( \Delta E \equiv \sum_i E_i - E_{\text{beam}} \quad (\sigma_{\Delta E} \approx 20-30 \text{ MeV}) \)
- Continuum suppression via event shape
  (continuum “jetty”, \( B\bar{B} \) “spherical”)

**Yields determined from unbinned maximum likelihood fits.**

Variables used to distinguish *signal* from *background*:

- Mass and energy of B candidates: \( m_B \) and \( \Delta E \).
- Fisher discriminant - *linear combination of 11 shape variables*.
- \( B \) candidate flight direction.
- Resonance masses and helicity angle for \( VP \) decays.
- \( dE/dx \) and \( \Delta E \) for particle ID.
  - At high \( p \), weak separation of \( K^\pm \) and \( \pi^\pm \) ⇒
    Simultaneously fit for both components
    \((e.g. \ B \rightarrow K^\pm\pi^\mp/\pi^\pm\pi^\mp)\).
Illustration of Fit Results for $B \rightarrow K^{\pm}\pi^{\mp}, \pi^{\pm}\pi^{\mp}$
\[ B \rightarrow K\pi, \pi\pi \]

\[ \begin{array}{|c|c|c|c|c|} \hline \text{Mode} & \epsilon(\%) & \text{Yield} & \text{Signif.} & B(10^{-6}) \\ \hline K^{\pm}\pi^{\mp} & 48 & 80.2^{+11.8}_{-11.0} & 11.7\sigma & 17.2^{+2.5}_{-2.4}\pm1.2 \\ K^{0}\pi^{\pm} & 14 & 25.2^{+6.4}_{-5.6} & 7.6\sigma & 18.2^{+4.6}_{-4.0}\pm1.6 \\ K^{\pm}\pi^{0} & 38 & 42.1^{+10.9}_{-9.9} & 6.1\sigma & 11.6^{+3.0}_{-2.7}+1.4 \\ K^{0}\pi^{0} & 11 & 16.1^{+5.9}_{-5.0} & 4.9\sigma & 14.6^{+5.9}_{-5.1}+2.4 \\ \hline \pi^{\pm}\pi^{\mp} & 48 & 20.0^{+7.6}_{-6.5} & 4.2\sigma & 4.3^{+1.6}_{-1.4}\pm0.5 \\ \pi^{\pm}\pi^{0} & 39 & 21.3^{+9.7}_{-8.5} & 3.2\sigma & <12.7 \\ \pi^{0}\pi^{0} & 29 & 6.2^{+4.8}_{-3.7} & 2.0\sigma & <5.7 \\ \hline K^{\pm}K^{\mp} & 48 & 0.7^{+3.4}_{-0.7} & 0.0\sigma & <1.9 \\ K^{\pm}K^{0} & 14 & 1.4^{+2.4}_{-1.3} & 1.1\sigma & <5.1 \\ K^{0}\tilde{K}^{0} & 5 & 0 & 0.0\sigma & <17 \\ \hline \end{array} \]

(All upper limits at 90% C.L.)

- All four $K\pi$ modes are observed
  \rightarrow bound on the angle $\gamma$ of the unitary triangle.

- $B \rightarrow \pi^{0}\pi^{0}$ is a new result.

- Gluonic penguin contribution is large.
**Modes with \( \eta' \) and \( \eta \)**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Signif.</th>
<th>( B ) ((10^{-6}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^+ \to \eta'K^+ )</td>
<td>16.8( \sigma )</td>
<td>( 80^{+10}_{-9} \pm 7 )</td>
</tr>
<tr>
<td>( B^0 \to \eta'K^0 )</td>
<td>11.7( \sigma )</td>
<td>( 89^{+18}_{-16} \pm 9 )</td>
</tr>
<tr>
<td>( B^+ \to \eta K^{*+} )</td>
<td>4.8( \sigma )</td>
<td>( 26.4^{+9.6}_{-8.2} \pm 3.3 )</td>
</tr>
<tr>
<td>( B^0 \to \eta K^{*-0} )</td>
<td>5.1( \sigma )</td>
<td>( 13.8^{+5.5}_{-4.6} \pm 1.6 )</td>
</tr>
</tbody>
</table>

- No significant signals in other \( \eta' \) and \( \eta \) modes (we set upper limits instead)

- Confirmed large \( \eta'K \) signal

- Intrinsic charm content of \( \eta' \) has been proposed

*New CLEO results on \( B \to \eta_c K \):*

\[
BR(B^0 \to \eta_c K^0) = (1.09^{+0.55}_{-0.42} \pm 0.12 \pm 0.31) \times 10^{-3}
\]

\[
BR(B^+ \to \eta_c K^+) = (0.69^{+0.26}_{-0.21} \pm 0.08 \pm 0.20) \times 10^{-3}
\]

No enhancement has been seen compared to the \( B \to J/\psi K \) channel
**$B \rightarrow PV$ Modes**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield</th>
<th>Signif.</th>
<th>$B \times 10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^- \rightarrow \pi^- \rho^0$</td>
<td>$29.8_{-9.6}^{+9.3}$</td>
<td>5.4$\sigma$</td>
<td>$10.4_{-3.4}^{+3.3} \pm 2.1$</td>
</tr>
<tr>
<td>$B^- \rightarrow \pi^- \omega$</td>
<td>$28.5_{-7.3}^{+8.2}$</td>
<td>6.2$\sigma$</td>
<td>$11.3_{-2.9}^{+3.3} \pm 1.4$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \pi^\pm \rho^\mp$</td>
<td>$31.0_{-8.3}^{+0.4}$</td>
<td>5.6$\sigma$</td>
<td>$27.6_{-7.4}^{+8.4} \pm 4.2$</td>
</tr>
</tbody>
</table>

- First observation of the above $\Delta S=0$ decay modes.
- We see no significant yields in any of the $\Delta S=1$ transitions, which indicates that gluonic penguin decays play less of a role in $B \to PV$ decays than in $B \to PP$ decays. (as expected in factorization based models)
Pure gluonic penguin, simple final state, sensitive to $\sin 2\beta$

Combine the $B^- \to \phi K^-$ and $BR(B^0 \to \phi K^0)$ measurements, we observe

$$BR(B \to \phi K) = (6.2^{+2.0+0.7}_{-1.8-1.7}) \times 10^{-6}$$
CP Asymmetry Measurements

Direct CP asymmetry can result from interference of two amplitudes with different strong and weak phases.

- **Definition**
  \[
  A_{CP} \equiv \frac{\mathcal{B}(\bar{B} \to f) - \mathcal{B}(B \to \bar{f})}{\mathcal{B}(\bar{B} \to f) + \mathcal{B}(B \to \bar{f})}
  \]

- Parent $B$ flavor self-tagged by high-$p$ charged particle.
- $A_{CP}$ included as free parameter in ML fits.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield</th>
<th>$A_{CP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^\pm \pi^\mp$</td>
<td>80.2$^{+11.8}_{-11.0}$</td>
<td>$-0.04 \pm 0.16$</td>
</tr>
<tr>
<td>$K^\pm \pi^0$</td>
<td>42.1$^{+10.9}_{-9.9}$</td>
<td>$-0.29 \pm 0.23$</td>
</tr>
<tr>
<td>$K^0 \pi^\pm$</td>
<td>25.2$^{+6.4}_{-5.6}$</td>
<td>$+0.18 \pm 0.24$</td>
</tr>
<tr>
<td>$K^\pm \eta'$</td>
<td>100$^{+13}_{-12}$</td>
<td>$+0.03 \pm 0.12$</td>
</tr>
<tr>
<td>$\omega \pi^\pm$</td>
<td>28.5$^{+8.2}_{-7.3}$</td>
<td>$-0.34 \pm 0.25$</td>
</tr>
</tbody>
</table>

- No $A_{CP}$ observed, but allowed range significantly reduced.
- All measurements are statistics-limited.
CLEO III had a successful engineering run this spring and began data taking in mid-July.

**CESR upgrades**

- $I_{\text{per beam}} =$ up to 500 mA
- $L \sim 1.6 - 2.2 \times 10^{33} cm^{-2}s^{-1}$
- 20-30 $fb^{-1}$/year

**New detectors in CLEO**

- 4-layer Silicon vertex detector
- Drift Chamber
- Ring Imaging CHernkov (RICH)
**CLEO III Status**

Drift Chamber has shown very good momentum and tracking resolution

- Residuals summed over 47 DR anode layers
- Average $\sigma = 100\text{ um}$ for core 80%
- Wide $\sigma = 2 \times$ narrow $\sigma$
- Total rms = 123\text{ um}

RICH is very effective in PID

Fit to Gaussian + quadratic
- mean $5.2848 \pm 0.0032 \text{ GeV}$
- sigma $0.0855 \pm 0.0035 \text{ GeV}$
Conclusion

- CLEO continues to mine our data for new results, very wide and deep program
- Good measurement of $|V_{cb}|$
- Comprehensive measurement on exclusive charmless hadronic B decays
  - Due to statistics limit and theoretical uncertainties, the measurements can’t be precisely converted into CKM elements. But very useful to test various phenomenological models.
  - Data indicate existence of many contributing and interfering diagrams.
    The gluonic penguin contribution is large.
- Many other physics results.
- CLEO III detector works very well, we are exploring the best place to run the beautiful detector.