Two themes:
1) Why Charm Physics allows B physics to reach its full Potential
2) Charm physics as a probe of New physics Beyond the Standard Model
Precision Quark Flavor Physics: charm’s role

The discovery potential of B physics is limited by systematic errors from QCD:

- Form factors in semileptonic ($\beta$) decay:
  - $u \to c V V$
  - $d \to s V V$

- D system: CKM matrix elements are tightly constrained to <1% by unitarity

- Work back from measurements of absolute rates for leptonic and semileptonic $D$ decays yielding decay constants and form factors to test QCD techniques that can then be applied to the B system.

- In addition as $\text{Br}(B \to D) \sim 100\%$ absolute $D$ branching ratios normalize B physics.

2005

Decay constants in B mixing:

$$|V_{ub}|, |V_{cb}|$$

$$|V_{ud}|, |V_{ts}|$$

$$B_d^{-} \rightarrow B_d^{-}$$

$$|V_{CKM}|^2$$

$$|f(q^2)|^2$$
Theoretical errors dominate width of bands

Precision theory + charm = large impact
Precision theory + charm = large impact

precision QCD calculations tested with precision charm data

→ theory errors of a few % on B system decay constants & semileptonic form factors

+ 500 fb⁻¹ @ BABAR/Belle
Outline of the Lectures

Overview: How Charm Physics Helps B Physics
   → Precision Quark Flavor Physics

Experiments That Contribute To Charm Physics

Lecture 1

Precision CKM Physics:
   Lifetimes
   Hadronic Decays
   Leptonic Decays and Decay constants
   Semileptonic Decays and CKM matrix elements
   Tests of Unitarity

Lecture 2

Charm as a Probe of New Physics:
   Mixing
   CP Violation & Rare Decays
   Summary & Outlook
Reviews for Lecture 2

Covers all of charm:

A Cicerone for the Physics of Charm
S Bianco, F.L. Fabbri, D. Benson & I. Bigi

Specific to lecture 2:

D0D0 Mixing and Rare Charm Decays
G. Burdman and I. Shipsey
arXivhep-ph/0310076
From the last lecture

Question: what could the additional semileptonic decay modes be?

\[ \sum B(D^+ \rightarrow Xe\nu)_{xcl} = (15.1 \pm 0.5 \pm 0.5)\% \]
\[ \sum B(D^0 \rightarrow Xe\nu)_{excl} = (6.1 \pm 0.2 \pm 0.2)\% \]

\[ B(D^+ \rightarrow Xe\nu) = (16.19 \pm 0.20 \pm 0.36)\% \]
\[ B(D^0 \rightarrow Xe\nu) = (6.45 \pm 0.17 \pm 0.15)\% \]
## Preliminary Results

Similar analysis by BES II

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>$B$ (%) (CLEO-c/57/pb)</th>
<th>$B$ (%) (PDG-04)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. $D^0 \rightarrow \pi^- e^+\nu$</td>
<td>$0.26 \pm 0.03 \pm 0.01$</td>
<td>$0.36 \pm 0.06$</td>
</tr>
<tr>
<td>2. $D^0 \rightarrow K^- e^+\nu$</td>
<td>$3.44 \pm 0.10 \pm 0.10$</td>
<td>$3.58 \pm 0.18$</td>
</tr>
<tr>
<td>3. $D^0 \rightarrow K^+(K^-\pi^0)e^+\nu$</td>
<td>$2.16 \pm 0.24 \pm 0.11$</td>
<td>$2.15 \pm 0.35$</td>
</tr>
<tr>
<td>4. $D^0 \rightarrow K^+(K_S^0\pi^-)e^+\nu$</td>
<td>$2.25 \pm 0.21 \pm 0.11$</td>
<td>$2.15 \pm 0.35$</td>
</tr>
<tr>
<td>5. $D^0 \rightarrow \rho^- e^+\nu$</td>
<td>$0.19 \pm 0.04 \pm 0.02$</td>
<td>—</td>
</tr>
<tr>
<td>6. $D^+ \rightarrow \pi^0 e^+\nu$</td>
<td>$0.44 \pm 0.06 \pm 0.03$</td>
<td>$0.31 \pm 0.15$</td>
</tr>
<tr>
<td>7. $D^+ \rightarrow \bar{K}^0 e^+\nu$</td>
<td>$8.71 \pm 0.38 \pm 0.37$</td>
<td>$6.7 \pm 0.9$</td>
</tr>
<tr>
<td>8. $D^+ \rightarrow \bar{K}^0(K^-\pi^+)e^+\nu$</td>
<td>$5.70 \pm 0.28 \pm 0.25$</td>
<td>$5.5 \pm 0.7$</td>
</tr>
<tr>
<td>9. $D^+ \rightarrow \rho^0(\pi^+\pi^-)e^+\nu$</td>
<td>$0.21 \pm 0.04 \pm 0.02$</td>
<td>$0.25 \pm 0.10$</td>
</tr>
<tr>
<td>10. $D^+ \rightarrow \omega(\pi^+\pi^-\pi^0)e^+\nu$</td>
<td>$0.17 \pm 0.06 \pm 0.01$</td>
<td>—</td>
</tr>
</tbody>
</table>

Full CLEO-c data set (later BESIII) will make **significant** improvements in the precision with which each absolute charm semileptonic branching ratio is known.
Answer: anything with a d or s valence quark to couple to charm. Examples: excited $K^*$, additional pions, eta, etaprime etc.
Example of an additional mode

First Observation

\[ D^+ \rightarrow \eta e^+ \nu, \eta \rightarrow \gamma \gamma \]
Yield: \(32.3 \pm 6.6\) events

\[ U = E_{\text{miss}} - |P_{\text{miss}}| \ (\text{GeV}) \]

We find significant yields for \(D^+ \rightarrow \eta e^+ \nu\) with \(\eta\) reconstructed

In \(\gamma \gamma\) and \(\pi^+ \pi^- \pi^0\), the relative yields are consistent with expectation

This is the first time these plots have been shown outside CLEO

Preliminary

\[ D^+ \rightarrow \eta e^+ \nu, \eta \rightarrow \pi^+ \pi^- \pi^0 \]
Yield: \(8.6 \pm 3.0\) events

\[ U = E_{\text{miss}} - |P_{\text{miss}}| \ (\text{GeV}) \]
Charm As a Probe of Physics Beyond the Standard Model

Can we find violations of the Standard Model at low energies?
Example $\beta$ Decay $\Rightarrow$ missing energy $\Rightarrow$ W (100 GeV mass scale) from experiments at the MeV mass scale.

The existence of multiple fermion generations appears to originate at high mass scales $\Rightarrow$ can only be studied indirectly.

CP violation, mixing and rare decays $\Rightarrow$ may investigate the physics at these new scales through intermediate particles entering loops.

Why charm? in the charm sector the SM contributions to these effects are small $\Rightarrow$ large window to search for new physics

CP asymmetry $\leq 10^{-3}$
Rare decays $\leq 10^{-6}$
$D^0 - \bar{D}^0$ mixing $\leq 10^{-2}$

charm is the unique probe of the up-type quark sector (down quarks in the loop).

High statistics instead of High Energy
D Mixing

Mixing has been fertile ground for discoveries:

- CKM factors $\propto \Theta_c^2$ same order as $\tau_{\text{kaon}}$
- Mixing rate $\approx 1$
- Mixing rate (1958) used to bound c quark mass $\rightarrow$ discovery (1974).
- CPV part of transition, $\epsilon_K$ (1964), was a crucial clue top quark existed $\rightarrow$ discovery (1994).
- Dominated by top $\propto (m_t^2 - m_{c,u}^2)/m_W^2 \rightarrow$ Large
- B lifetime Cabibbo suppressed $\propto V_{cb}^2$
- Mixing also Cabibbo suppressed ($V_{td}^2$)
- Mixing rate $\rightarrow$ early indication $m_{\text{top}}$ large
- CKM factors $\propto \Theta_c^2 \sim 0.05$
- (b-quark $\propto V_{ub}V_{cb}$ negligible)
- But $\tau_D$ not Cabbibo suppressed ($V_{cs} \sim 1$)
- Additional suppression: Mixing $\propto (m_s^2 - m_d^2)/m_W^2 = 0$ SU(3) limit.
- SM mixing small $\propto \Theta_c^2 \times [\text{SU(3) breaking}]^2 < O(10^{-3})$

$10^{-2}$ possible
Some Formalism

Time evolution of $D^0$ or $\bar{D}^0$ is determined by Schrödinger’s Equation

$$\frac{\partial}{\partial t} \begin{pmatrix} D^0 \\ \bar{D}^0 \end{pmatrix} = \left| M - \frac{i}{2} \Gamma \right| \begin{pmatrix} D^0 \\ \bar{D}^0 \end{pmatrix}$$

$$a(t) \mid D^0 > + b(t) \mid \bar{D}^0 >$$

- Diagonalizing $H$ gives mass eigenstates as linear combinations of $D^0$ and $\bar{D}^0$.
- $\Gamma_{12}$ describes $D^0 \rightarrow f \rightarrow \bar{D}^0$ via on-shell intermediate states.
- $M_{12}$ describes $D^0 \rightarrow f \rightarrow \bar{D}^0$ via off-shell intermediate states.
- CP violation in mixing can arise from interference between on-shell and off-shell amplitudes. This leads to $\Gamma(D^0 \rightarrow \bar{D}^0) \neq \Gamma(\bar{D}^0 \rightarrow D^0)$.
- Note in the $Bd$ system $\Gamma_{12}$ is very small; mixing is dominated by $\Delta M = 2M_{12}$. 

Beijing Charm L2 8/16/05 Ian Shipsey
Switching to $x$ and $y$

$$a(t) | D^0 > + b(t) | \bar{D}^0 >$$

$$i \frac{\partial}{\partial t} \begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} M - \frac{i}{2} \Gamma \\ 0 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 \\ M_{12}^* - \frac{i}{2} \Gamma_{12}^* \end{pmatrix}$$

$$= \begin{pmatrix} \frac{1}{\tau_{D^0}} \end{pmatrix}$$

C.P.T assumed

$$\text{CPV: } | M_{12}^* - \frac{i}{2} \Gamma_{12}^* \neq | M_{12} - \frac{i}{2} \Gamma_{12} |$$

But initially assume conservation here

$$\text{Measure time in units of } \tau_{D^0}$$

$$\frac{1}{2} \begin{pmatrix} 0 \\ -ix - y \end{pmatrix}$$

$$\begin{pmatrix} 0 \\ - \frac{i}{2} x \end{pmatrix}$$

$$\begin{pmatrix} 0 \\ - \frac{i}{2} y \end{pmatrix}$$

$D^0$ shifts energy of CP eigenstates

$\bar{D}^0$ shifts lifetimes of CP eigenstates
New Physics Alters x not y

Assume:
CP Conserved

\[ -iM_{12} \text{ or } -\frac{i}{2}x \]
off - shell

\[ x = M_{12} \tau_{D^0} \]

\[ \Delta \tau = 0 \]

\[ D_2 \propto D^0 - \bar{D}^0 \]

\[ D_1 \propto D^0 + \bar{D}^0 \]

Studying time evolution is a route to distinguishing new physics, i.e determining x and y separately but it is not the only way to achieve this.
Because $x$ is very small, $x$ is a window for new physics.
y in the Standard Model

\[ y : \Sigma A(D^0 \rightarrow \text{Common State}) \]

\[ \propto \sqrt{BR} \]

- In principle, a precision experimental determination \( O(1\%) \) of all branching ratios, and phases, "measures" \( y \) to 1%

**Common States**

\[ E_n = M_{D^0} \]

\[ y \leq 10^{-3} \]

**Short Distance predictions**
- Span wide range
- But major sources of SU(3) breaking exist: \( m_K \neq m_\pi \neq m_\eta \)
- \( f_K \neq f_\pi \) and relative phases between DCSD and CF amplitudes

Work by Falk, Grossman, Ligeti, Nir, Petrov indicate \( y \sim 1\% \) possible (see later)

**Hadronic Problem**
- \( \frac{\Gamma(D^0 \rightarrow K^+K^-)}{\Gamma(D^0 \rightarrow \pi^+\pi^-)} ; 3.0 \pm 0.2 \)

**Approximate cancellation**

**Probably not a window for new physics**
More on $x, y$ in SM

In fact the diagrams for $y$ may also be the best way to think about $x$ as well.

Both $x$ and $y$ are generated by $s, d$ contributions. The same diagram generates both the real part ($x$) and the imaginary part ($y$).

Same thing happens in $B$ mixing (the $c$ quark contribution takes place for both $x$ and $y$) but for $B$’s the real part ($x$) is dominated by top. If $m_{\text{top}} \sim m_{\text{charm}}$ then $B$ and $D$ mixing would be analogs.

For $y$, $SU(3)$ cancelation is broken by phase space.

For $x$, both $D \to 4\pi$ & $D \to 4K$ can contribute. For $x$ there is more effective $SU(3)$ cancellation than in $y$. Nobody knows how big the size of this effect. It is feasible that $y \gg x$ (SM).

Signatures:

: New physics will enhance $x$ but not $y$ we can consider $y$ as a SM background. CP violation in mixing would be a smoking gun for new physics.
Theoretical “Guidance”

**SM Mixing Predictions**

- $x = \frac{\Delta M}{\Gamma}$
- $y = \frac{\Delta \Gamma}{2\Gamma}$

**New Physics Mixing Predictions**

- $R_{mix} \equiv \frac{1}{2} (x^2 + y^2)$

New physics will enhance $x$ but not $y$.

SM mixing predictions ~ bounded by box diagram rate & expt. sensitivity. New Physics predictions span same large range \(\Rightarrow\) mixing is not a clear indication of New Physics.

No CP-violating effects expected in SM. CP violation in mixing would therefore be an unambiguous signal of New Physics.
\( \text{D}^0\overline{\text{D}}^0 \) Mixing \( x, y \), semileptonic Theoretically Cleanest

- Charge of the “soft pion” tags whether the initial state was \( \text{D}^0 \) or \( \overline{\text{D}}^0 \).
- Cabibbo favored decay: \( \text{D}^0 \rightarrow K^- l^+ \nu \) (7%) gives “right-sign” charge correlation
- Mixing is a source of “wrong-sign” decays: \( \text{D}^0 \rightarrow \overline{\text{D}}^0 \rightarrow K^+ l^+ \nu \)
- As there is only one diagram there is no direct decay route for a \( \text{D}^0 \rightarrow K^+ l^+ \nu \)
- This is what “clean” means, the wrong sign pair is unambiguously a mixing signature

\[
\begin{align*}
\text{time distribution} & \propto \frac{1}{4} \left( [x^2 + y^2] t^2 \right) e^{-t} \\
\text{but } x^2 + y^2 & \ll x \text{ or } y
\end{align*}
\]

Theoretically clean usually means experimentally challenging

\[
m(\pi_s K^+ l^-) - m(K^+ l^-) \rightarrow \text{Missing } \nu
\]
Measurement of $y_{CP}$ from

\[ D^0 \rightarrow K^+K^- \ \& \ D^0 \rightarrow \pi^+\pi^- \]

$y$ can be determined by measuring the lifetime difference between $D^0$ decays to $CP$-even and $CP$-odd final states:

\[ y = \frac{\Delta \Gamma}{2 \Gamma} = \frac{\Gamma_{CP^+} - \Gamma_{CP^-}}{\Gamma_{CP^+} + \Gamma_{CP^-}} \]

Experimentally, it is easier to measure the lifetime difference of a $CP$-even decay relative to the non-$CP$ final state $D^0 \rightarrow K^- \Box^+$ (assumes no $CP$ violation):

In the limit of no CP violation $\Gamma_+ = \Gamma + \delta$, $\Gamma_- = \Gamma - \delta$

\[ y_{cp} = \frac{\Gamma + \delta - (\Gamma + \delta)}{2 \Gamma} = \frac{\delta}{\Gamma} = \frac{\Gamma + \delta}{\Gamma} - 1 = \frac{\tau_{mixed}}{\tau_+} - 1 \]

$K^-K^+$ (or $\pi^+\pi^-$) pure $CP$ $D_+$

$K^-\pi^+$ $50\%$ $D_+$ $50\%$ $D_-$

\[ y_{CP} = \frac{\tau(D^0 \rightarrow K^-\pi^+)}{\tau(D^0 \rightarrow K^-K^+)} - 1 \]
Measurement of $y$

$$y = \frac{\Delta \Gamma}{2\Gamma} = \frac{\Gamma_{CP^+} - \Gamma_{CP^-}}{\Gamma_{CP^+} + \Gamma_{CP^-}}$$

Easier, measure CP-even decay relative to $D^0 \to K^-\pi^+$:
(1/2 CP even $\frac{1}{2}$ CP odd)

$$y_{CP} = \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to K^-K^+)} - 1$$

Early FOCUS measurement with non zero $y_{CP}$:

$$y = (3.4 \pm 1.4 \pm 0.7)\%$$
Status of $y$ (summer 2005)

$D^0$ and $\bar{D}^0$ have different lifetimes to CP even final states if CPV is present.

More recent analyses allow for CP violation, by comparing charge conjugate states rather than combining them.

No evidence for CPV is found.

The observables become: $Y = y \cos \phi$, $\Delta Y = x \sin \phi$  

I take $\phi = 0$ in the average:

<table>
<thead>
<tr>
<th></th>
<th>$y_{CP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>E791</td>
<td>$(0.8 \pm 2.9 \pm 1.0)%$</td>
</tr>
<tr>
<td>FOCUS</td>
<td>$(3.4 \pm 1.4 \pm 0.7)%$</td>
</tr>
<tr>
<td>CLEO</td>
<td>$(-1.1 \pm 2.5 \pm 1.4)%$</td>
</tr>
<tr>
<td>Belle 01</td>
<td>$(-0.5 \pm 1.0 \pm 0.8)%$</td>
</tr>
<tr>
<td>BABAR</td>
<td>$(0.8 \pm 0.4 ^{+0.5}_{-0.4})%$</td>
</tr>
<tr>
<td>Belle 03</td>
<td>$(1.15 \pm 0.69 \pm 0.38)%$</td>
</tr>
</tbody>
</table>

![Graph showing the values of $y_{CP}$ for different experiments.](image)

$$\langle y_{CP} \rangle = (0.9 \pm 0.4)\%$$
$y = \Delta \Gamma / 2 \Gamma_D$ (Average)

$\langle y_{CP} \rangle = (0.9 \pm 0.4)\%$
Search for D Mixing in Semileptonic Decays

\[ \Delta m = m(\pi_s K^+ l^-) - m(K^+ l^-) \]

\[ N_{unmix} = 40198 \pm 329 \]

\[ N_{mix} = 19 \pm 67 \]

\[ R_{mix} = \frac{N_{unmix}}{N_{mix}} \cdot \frac{\varepsilon_{unmix}}{\varepsilon_{mix}} = (0.20 \pm 0.70) \times 10^{-3} \text{ (stat)} \]

\[ R_{mix} < 1.4 \times 10^{-3} \text{ at 90% CL (stat + sys)} \quad \text{(ICHEP, 2004)} \]

In a new analysis (2005) Belle fit the WS time dependence

\[ t^2 e^{-t} \]

\[ R_{mix} < 1.0 \times 10^{-3} \text{ at 90% CL (stat + sys)} \]
D Mixing Semileptonic Summary

<table>
<thead>
<tr>
<th>Year</th>
<th>Expt.</th>
<th>$R_{\text{mix}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>Belle</td>
<td>$&lt;1.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>2004</td>
<td>Belle</td>
<td>$&lt;1.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>2004</td>
<td>BABAR</td>
<td>$&lt;4.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>2002</td>
<td>FOCUS</td>
<td>$&lt;1.31 \times 10^{-3}$</td>
</tr>
<tr>
<td>2002</td>
<td>CLEO</td>
<td>$&lt;8.6 \times 10^{-3}$</td>
</tr>
<tr>
<td>1996</td>
<td>E791</td>
<td>$&lt;5.0 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

$R_{\text{mix}} \equiv \frac{1}{2} \left( x^2 + y^2 \right)$

FOCUS result is unpublished
M. Hosack Fermilab Thesis 2002-25.

BABAR & Belle are adding more data and expect to publish improved upper limits soon.

$\chi = \frac{\Delta M}{\Gamma_D}$
D^0\overline{D^0} Mixing II from hadronic decays

- Production: e^+e^- → cc; c → D^*+ → D^0\pi^+_s.
- Charge of the “soft pion” tags whether the initial state was D^0 or D^0 (as before)
- Cabibbo favored decay: D^0 → K^-π^+ (4%) gives “right-sign” charge correlation
- Mixing is a potential source of wrong-sign decays: D^0 → D^0 → K^+\pi^-
- Doubly Cabibbo suppressed decay D^0 → K^+\pi^- also gives wrong-sign (\pi^+_sK^+) charge correlation with strong phase δ
- Use time dependence to distinguish:

\[ r_{ws}(t) = \left( \left[ \frac{B}{A} - \frac{1}{2}(ix + y)t \right] e^{-t/2} \right)^2 \]

\[ R_D = \left| \frac{B}{A} \right|^2 \]

\[ R_D + \sqrt{R_D} (y\cos\delta - x\sin\delta)t + \frac{1}{4}(x^2 + y^2)t^2 \right] e^{-t} \]

\[ r_{ws}(t) = (R_D + \sqrt{R_D} y't + \frac{1}{4}[x't^2 + y' t^2]t^2) e^{-t} \]
The Wrong Sign Rate

90 fb$^{-1}$

$D^{*+} \rightarrow D^0 \pi^+$ 3σ cut on $Q$

Right sign: $D^0 \rightarrow K^- \pi^+$ 228K

Wrong sign

$D^0 \rightarrow K^+ \pi^-$

$845 \pm 40$

S/B~1

x2 statistics of previous measurements.

$R_{WS} = \frac{\Gamma(D^0 \rightarrow K^+ \pi^-)}{\Gamma(D^0 \rightarrow K^- \pi^+)} = (0.371 \pm 0.0)$

$B(D^0 \rightarrow K^+ \pi^-) \sim 1.4 \times 10^{-4}$
The Wrong Sign Rate

<table>
<thead>
<tr>
<th></th>
<th>$K^-\pi^+$</th>
<th>$K^-\pi^-$</th>
<th>$R_{WS}$ [%]</th>
<th>$A_D$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>E791 (66)</td>
<td>5.6K</td>
<td>not quoted</td>
<td>$0.68^{+0.34}_{-0.33} \pm 0.07$</td>
<td>–</td>
</tr>
<tr>
<td>ALEPH (67)</td>
<td>1038</td>
<td>19</td>
<td>$1.84 \pm 0.59 \pm 0.07$</td>
<td>–</td>
</tr>
<tr>
<td>FOCUS (68)</td>
<td>37K</td>
<td>150</td>
<td>$0.404 \pm 0.085 \pm 0.025$</td>
<td>–</td>
</tr>
<tr>
<td>CLEO (61)</td>
<td>13.5K</td>
<td>45</td>
<td>$0.332^{+0.063}_{-0.065} \pm 0.040$</td>
<td>$-2^{+19}_{-20} \pm 1$</td>
</tr>
<tr>
<td>Belle (63)</td>
<td>83K</td>
<td>845</td>
<td>$0.371 \pm 0.018$</td>
<td>$-8.0 \pm 7.7$</td>
</tr>
<tr>
<td>BaBar (62)</td>
<td>120K</td>
<td>430</td>
<td>$0.357 \pm 0.022 \pm 0.027$</td>
<td>$9.5 \pm 6.1 \pm 8.3$</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>0.368 ± 0.021</td>
<td></td>
</tr>
</tbody>
</table>

$$\langle R_{WS} \rangle = (0.368 \pm 0.021)\%$$
\[ r_{WS}(t) = (R_D + \sqrt{R_D} y't + \frac{1}{4} [x'^2 + y'^2] t^2) e^{-t} \]

DCSD interference mix

Simulation

![Graph showing data and fit to WS](image-url)

- **Data**
- **Fit to WS**

**Graph Details:**
- **Events**
- **Proper time (fs)**
- **Categories:**
  - \( D^0 \rightarrow K^+ \pi^- \)
  - Interference
  - Mixing
  - D0 & D3body
  - Combinatoric

**Courtesy:** Ji Lin

Beijing Charm L2 8/16/05 Ian Shipsey
This is a substantial improvement on previous results.

<table>
<thead>
<tr>
<th>Fit case</th>
<th>Parameter</th>
<th>95% C.L. interval $(\times 10^{-3})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(decay)</td>
<td>$A_D$</td>
<td>$-250 &lt; A_D &lt; 110$</td>
</tr>
<tr>
<td>CPV(Mixing)</td>
<td>$A_M$</td>
<td>$-991 &lt; A_M &lt; 1000$</td>
</tr>
<tr>
<td></td>
<td>$x'^2$</td>
<td>$x'^2 &lt; 0.89$</td>
</tr>
<tr>
<td></td>
<td>$y'$</td>
<td>$-30 &lt; y' &lt; 27$</td>
</tr>
<tr>
<td>no CPV</td>
<td>$x'^2$</td>
<td>$x'^2 &lt; 0.81$</td>
</tr>
<tr>
<td></td>
<td>$y'$</td>
<td>$-8.2 &lt; y' &lt; 16$</td>
</tr>
<tr>
<td></td>
<td>$R_D$</td>
<td>$2.7 &lt; R_D &lt; 4.0$</td>
</tr>
</tbody>
</table>
Mixing Summary

Combining all results:

CP conservation is assumed.

No statistically significant evidence for mixing has yet been found.

CDF expect a mixing result using $D \rightarrow K\pi$ soon.

Important to measure $\delta$ can be done at a charm factory.

G. Burdman and I. Shipsey
Unique opportunities at Threshold

\[ \Psi'' \rightarrow D^0 \bar{D}^0, \ D^+ D^- \]

\[ \Psi'' \rightarrow L = 1 \]

\[ |D^0 \bar{D}^0\rangle_L = \frac{1}{\sqrt{2}} \left[ |D^0(k_1)\bar{D}^0(k_2)\rangle + (-1)^L |D^0(k_2)\bar{D}^0(k_1)\rangle \right] \]

Angular momentum
(L=1 for \(\psi(3770)\))
Mixing: $\psi(3770) \to DD(C = -1)$
Coherence simplifies study DCSD interfere away so not a background
Unmixed: $D^0 \to K^{-}\pi^+$ $D^0 \to K^+\pi^-$
mixing: $D^0 \to K^{-}\pi^+$ $D^0 \to D^0 \to K^{-}\pi^+
Can add lepton final states (Klv Klv)
Sensitivity: $\sim 10^{-4}$ (CLEO-c) $\sim 2 \times 10^{-5}$ (BES III) current limit: $10^{-3}$
CPV in D Decays
I’ll ignore CP violation in mixing (as it is negligible).

CPV via interference between mixing & decay (D⁰ only)

\[
\Gamma(D^0) \neq \Gamma(D^-)
\]

Very small in charm since mixing is suppressed (i.e. good hunting ground for New Physics).

Time dependent since mixing is involved

Direct CPV:

\[
\Gamma(D) \neq \Gamma(D^-)
\]

Experiment concentrates on this

\[
A_{CP} = \frac{\Gamma(f) - \Gamma(f^-)}{\Gamma(f) + \Gamma(f^-)} = \frac{2 \text{Im} A_1 A_2 \sin(\delta_1 - \delta_2)}{|A_1|^2 + |A_2|^2 + 2 \text{Re} A_1 A_2^* \cos(\delta_1 - \delta_2)} < 10^{-3}
\]

2 weak amplitudes with phase difference \quad strong phase-shift
Direct CP Violation

\[ A_{CP} \approx \frac{\text{Im}\left[V_{cd} V_{ud}^{*} V_{cs} V_{us}^{*}\right]}{\lambda^2} \sin \delta_{PT} \frac{P}{T} ; \quad A^2 \eta \lambda^4 \sin \delta_{PT} \frac{P}{T} \leq 10^{-3} \]

In Standard Model Direct CPV only for Singly Cabibbo suppressed decays.

1) Consider \( D^0 \to \pi^+\pi^- \) (same for \( K^+K^-\pi^+, \phi\pi^+, K^*K \), \( K^+K^-\pi^0, \pi^+\pi^-\pi^+, \pi^+\pi^-\pi^0 \), etc...)

Since this decay is Singly Cabibbo Suppressed...

\[ \Delta I = \frac{1}{2}, \frac{3}{2} \]

…we can modify its topology in a simple way to get a penguin.

Standard Model Contribution \( A_{CP} \sim 10^{-3} \)

New Physics up to \(~1\%\)

If CP\(~1\%\) observed: is it NP or hadronic enhancement of SM? Strategy: analyze many channels to elucidate source of CPV.
Search for Direct CP Violation in $D^+ \rightarrow K^-K^+\pi^-$

Three $A_{CP}$ measurements: (1) KK$\pi$ (2) $\phi\pi$, (3) $K^*K$ ~43,000 events relative to $D_s^+ \rightarrow KK\pi$ as control [Cabibbo favored hence no CP].

$$A_{CP} \equiv \frac{\Gamma(D^0 \rightarrow f) - \Gamma(D^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(D^0 \rightarrow f)}$$

$D^+ / D_s^+ \rightarrow K^-K^+\pi^-$

$D^- / D_s^- \rightarrow K^+K^-\pi^+$

For $\phi\pi$ & $K^*K$ significant improvement over previous measurements.
Search for Direct CP Violation in $D^0 \rightarrow \pi^+\pi^-, K^+K^-$

D* to tag $D^0$ flavor. Measure relative to $D^0 \rightarrow K\pi$ 123pb$^{-1}$ Cabibbo allowed mode ($A_{CP}=0$) as control.

Time integrated $A_{CP} = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(D^0 \rightarrow \bar{f})}{\Gamma(D^0 \rightarrow f) + \Gamma(D^0 \rightarrow \bar{f})}$

Most recent (& precise) result.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$D^0$</th>
<th>$D^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$KK$</td>
<td>$8190 \pm 140$</td>
<td>$8030 \pm 140$</td>
</tr>
<tr>
<td>$\pi\pi$</td>
<td>$3660 \pm 69$</td>
<td>$3674 \pm 68$</td>
</tr>
</tbody>
</table>

Time dependent measurements can distinguish direct & indirect CPV.

CDF plan this. BABAR/Belle (2003) found no evidence for indirect CP at the 1% level (see y status slide).
At the $\psi''(3770)$

$e^+e^- \rightarrow \psi'' \rightarrow D^0\bar{D}^0$

$J^{PC} = 1^{--}$ i.e. CP+$^+$

Suppose a $D^0$ is observed to decay to a CP eigenstate $f_1$ which is CP even:

Then in the limit of CP conservation, the state recoiling against the tag has a definite CP as well and it must be of opposite sign:

$CP(f_1f_2) = CP(f_1) \ CP(f_2) \ (-1)^l = CP^+$

• Example Two

CP eigenstates of $\pi^+\pi^-)(K^0\pi^0)(-1)^l$

Opposite sign

$\pi^+ \ - \ - = CP^+$
• CP violating asymmetries can be measured by searching for events with two CP odd or two CP even final states ex:

\[(\pi^+\pi^-)(\pi^+\pi^-)\]

• Sensitivity (two body final states)
  • \[A_{cp} < 0.01\] (CLEO-c)
  • \(< 2 \times 10^{-3}\) (BESIII)

• CP tagging allows searches for CPV in multi body decays using Dalitz plots. These searches are sensitive to amplitudes, rather than rates
More on CP Eigenstates at $\psi(3770)$

- In BFac/Tevatron: searches for D mixing, large DCSD rate interferes with signal with an unknown phase $\delta$

\[
y' = y\cos\delta - x\sin\delta \\
x' = x\cos\delta + y\sin\delta
\]

(CLEO-c /BESIII can measure $\delta$ by using CP tagging)

- **CP eigenstate tag $X$ flavor mode**

  $K^+K^- \leftrightarrow D_{CP} \leftrightarrow \psi(3770) \rightarrow D_{CP} \rightarrow K^+\pi^- (-1)^I$

  $+$ $-$ $-$ $\quad =\quad$ $\text{CP}^+$

(same phase is important in ADS method of determining $\phi_3/\gamma$)
Measurement of Strong Phase

- If CP violation in charm is neglected: mass eigenstates = CP eigenstates

$$|D_{CP}^{\pm}\rangle = \frac{1}{\sqrt{2}} \left[ |D^0\rangle^{\pm} |\bar{D}^0\rangle \right]$$

$$\sqrt{2} A(D_{CP^z} \rightarrow K^-\pi^+) = A(D^0 \rightarrow K^-\pi^+) \pm A(\bar{D}^0 \rightarrow K^-\pi^+)$$

Flavor mode

$$D_{CP}^{(+)} \rightarrow f_1 f_2$$

CP Eigenstate (·)

Eigenstate (-)

$$\sqrt{2} A(D_{CP^z} \rightarrow K^-\pi^+)$$

$$A(\bar{D}^0 \rightarrow K^-\pi^+)$$

$$A(D^0 \rightarrow K^-\pi^+)$$

$$\delta_D$$

In the limit of CP-invariance

$$A(D^0 \rightarrow K^-\pi^-) = A(\bar{D}^0 \rightarrow K^-\pi^+)$$

$$\cos \delta_D = \frac{Br(D_{CP^+} \rightarrow K^-\pi^+) - Br(D_{CP^-} \rightarrow K^-\pi^+)}{2\sqrt{r_D} Br(D^0 \rightarrow K^-\pi^+)}$$

$$-\cos \delta_D \sim \pm 10\%$$
Rare Charm Decays

FCNC modes are suppressed by the GIM mechanism:

\[ D^0 \rightarrow e^+ e^- \quad (B : 10^{-23}) \]

\[ D^0 \rightarrow \mu^+ \mu^- \quad (B : 3 \times 10^{-13}) \]

The lepton flavor violating mode \( D^0 \rightarrow e^\pm \mu^m \) is strictly forbidden.

Beyond the Standard Model, New Physics may enhance these, e.g.,

R-parity violating SUSY:

\[ \text{B}(D^0 \rightarrow e^+ e^-) \text{ up to } 10^{-10} \]

\[ \text{B}(D^0 \rightarrow \mu^+ \mu^-) \text{ up to } 10^{-6} \]

\[ \text{B}(D^0 \rightarrow e^\pm \mu^m) \text{ up to } 10^{-6} \]

Search for \( D^0 \rightarrow e^+e^-, \mu^+\mu^- \)

Normalizing mode:

\[ D^{*+} \rightarrow D^0 \pi^+ \]
\[ D^0 \rightarrow \pi^+ \pi^- \]

mass(\( \pi^+, \pi^- \)) (GeV)

<table>
<thead>
<tr>
<th>mode</th>
<th>ULx10^{-6}</th>
</tr>
</thead>
<tbody>
<tr>
<td>e^+e^-</td>
<td>prev</td>
</tr>
<tr>
<td>\mu^+\mu^-</td>
<td></td>
</tr>
<tr>
<td>e^m\mu^\pm</td>
<td></td>
</tr>
</tbody>
</table>

Big Improvement!

Large backgrounds, only D^0 final states are tractable in e^+e^- at 10 GeV so far.
Use D*→D^0\pi tag.
Measure relative to D→π π.

Forbidden.
In charm very difficult to calculate the SM rate for rare decays reliably. one of the most reliable:

In the SM

\[ B(D^+ \Rightarrow \pi^+ e^+ e^-) \sim 2 \times 10^{-6} \]

R-parity violating SUSY:

\[ B(D^+ \Rightarrow \pi^+ e^+ e^-) \sim 2.4 \times 10^{-6} \]

Increase in rate is small but significant at low dilepton mass

Current experimental limit CLEO II:

\[ B(D^+ \Rightarrow \pi^+ e^+ e^-) \sim 4.5 \times 10^{-5} \text{ ar } 90\% CL \]

Goal observe, and one day study dilepton mass
Rare D\(^+\) Decays CLEO-c

This is an untagged analysis, to increase sensitivity and similar to rare B decay search at the Y(4S)

\[ \Delta E = E_D - E_{\text{beam}} \]

(signal box is ± 20 MeV) (resolution is 6 MeV)

\[ \Delta M_{bc} = \sqrt{(E^2_{\text{beam}} - p^2_D)} - M_D \]

(signal box is ± 5 MeV/c\(^2\)) (resolution is 1.5 MeV/c\(^2\))

Multiple candidates are resolved by taking the best |\(\Delta M_{bc}\)|

\[ D^+ \Rightarrow \phi \pi^+ \]

\[ \Rightarrow \pi^+e^+e^- \]

\[ \pi^+e^+e^- \]
\[ \pi^-e^+e^+ \]
\[ K^+e^+e^- \]
\[ K^-e^+e^+ \]

281 pb\(^{-1}\) at \(\psi(3770)\)

\(\Delta M_{bc}\) vs. \(\Delta E\) plots

Panel 1: \(\pi^+e^+e^-\) (limit) has \(\phi \Rightarrow e^+e^-\) removed
Results:

\[
\begin{align*}
B \ (D^+ \Rightarrow \pi^+e^+e^-) &< 7.4 \times 10^{-6} \ (90\% \ CL) \\
B \ (D^+ \Rightarrow \pi^-e^+e^+) &< 3.6 \times 10^{-6} \ (90\% \ CL) \\
B \ (D^+ \Rightarrow K^+e^+e^-) &< 6.2 \times 10^{-6} \ (90\% \ CL) \\
B \ (D^+ \Rightarrow K^-e^+e^+) &< 4.5 \times 10^{-6} \ (90\% \ CL)
\end{align*}
\]

These improve upon previous limits and are \(\sim 4\) above SM rates.

With 1/fb signal may show up

More likely observation of these modes and studies of the dilepton mass (20 MeV mass resolution adequate) will be the province of BES III and Super B factories (~100 event samples)

G. Burdman and I. Shipsey


arXivhep-ph/0310076
Rare Decay Summary

For D^+ all charged final states are well-suited to fixed target and Tevatron CDF/DZero beginnig to enter the game

Expt. sensitivity 10^{-5}-10^{-6}
Just beginning to confront models of New Physics in an interesting way.

Close to Long Distance Predictions

Sets MSSM constraint

Presented at this lecture August 2005

Still plenty of room for New Physics.

Outlook: bright CDF/D0, B factories, charm factories,

G. Burdman and I. Shipsey
Summary

New Physics searches in D mixing, D CP violation and in rare decays by BABAR, Belle and CDF have become considerably more sensitive in the past year, however all results are null. CLEO-c and BES III will undertake complementary studies.

In charm’s role as a natural testing ground for QCD techniques there has been solid progress. The start of data taking at the ψ(3770) by BESII and CLEO-c (and later BESIII) promises an era of precision absolute charm branching ratios.

The precision with which the charm decay constant fD+ is known has already improved from 100% to ~8%. And the $D \to K$ semileptonoc form factor has been checked to 10%. A reduction in errors for decay constants and form factors to the few % level is promised.

This comes at a fortuitous time, recent breakthroughs in precision lattice QCD need detailed data to test against. Charm is providing that data. If the lattice passes the charm test it can be used with increased confidence by: BABAR/Belle/CDF/D0/LHC-b/ATLAS/CMS/BTeV to achieve precision determinations of the CKM matrix elements $V_{ub}$, $V_{cb}$, $V_{ts}$, and $V_{td}$ thereby maximizing the sensitivity of heavy quark flavor physics to physics beyond the Standard Model.

Charm is enabling quark flavor physics to reach its full potential. Or in pictures….
Precision theory + charm = large impact

Theoretical errors dominate width of bands
Precision theory + charm = large impact

Precision QCD calculations tested with precision charm data

- theory errors of a few % on B system decay constants & semileptonic form factors

+ 500 fb⁻¹ @ BABAR/Belle
The CLEO Collaboration wish.

BES III the best of luck for a smooth completion of the BBES III detector & BEPC II
Additional Slides
Search for D Mixing in Semileptonic Decays

\[ \Delta m = m(D^*) - (D^0) \]

\[ R_{mix} < 1.0 \times 10^{-3} \text{ at 90\% CL (stat + sys)} \]

New best measurement
Search for D Mixing in Semileptonic Decays

- Unbinned extended maximum likelihood fit to transverse lifetime and $\Delta M = M(D^*) - M(D^0)$ with 15 floated parameters $D \rightarrow K$ and $K^* e \nu$ continuum events 80fb$^{-1}$ ON 7.1fb$^{-1}$ OFF

$\Delta m = m(D^*) - (D^0)$

Unmixed D0 yield: $49620 \pm 324$ evts (stat)

$R_{mix} = N_{mix} / N_{unmix}$

$R_{mix} = 0.0023 \pm 0.0012$ (stat) $\pm 0.0004$ (syst)

$R_{mix} < 0.0042$ (90% C.L.)

$\Delta m = m(D^*) - (D^0)$

$N_{mix} = 114 \pm 61$

(\sim 5\% probability of getting a larger result for $R_{mix}$=0)

Note very different horizontal & vertical scales

Beijing Charm L2 8/16/05 Ian Shipsey
Search for D Mixing in $D \to K\pi$

ICHEP ABS11-0704  PRL 94 071801 (2005)

Sensitive to both $x$ and $y$, and linear in $y$.
Best constraints come from this mode.

“right-sign” (RS) => Cabibbo-favored decays
“wrong-sign” (WS) => Mixing or doubly Cabibbo-suppressed decays.

```
| $V_{cs}^2|V_{cd}|^2 \sim \cos^4 \theta_c$ |
| $V_{cd}^2|V_{us}|^2 \sim \sin^4 \theta_c$ |
```

```
\begin{align*}
&D^0 \to \pi^+ \\
&K^- \\
\end{align*}
```

```
\begin{align*}
&D^0 \to \pi^- \\
\end{align*}
```

```
\begin{align*}
&D^0 \to K^+ \\
\end{align*}
```

```
\begin{align*}
&D^0 \to W^+ \\
\end{align*}
```

Need to fit proper decay time in order to distinguish mixing (both $x$ and $y$) from doubly Cabibbo-suppressed (DCS) decays:

```
r(t) = \left( R_{D_c} \sqrt{R_{D}^{DCS}} y' t + \frac{1}{4} \left( x'^2 + y'^2 \right) t^2 \right) e^{-t}
```

Complication: phase difference, $\delta_{K\pi}$, between CF and DCS amplitudes can lead to observable quantities $x'$ and $y'$, related to $x$ and $y$ by a rotation.
CLEO-c INPUTS TO CKM ANGLE $\phi_3 / \gamma$

1. Gronau-London-Wyler Method
   - $B^- \rightarrow D_{CP} K^-$
   - Statistics Limited so far
   - D mixing parameters can alter $\gamma$

2. Atwood-Dunietz-Soni Method
   - $B^- \rightarrow D K^-$
   - Requires very large $L_{dt}$
   - CLEO-c measure $r_D$ & $\cos \delta_D$

3. Dalitz plot Method
   - $B^- \rightarrow D K^-$, $D \rightarrow K_s \pi^+ \pi^-$, $\pi^+ \pi^- \pi^0$, $K_s K^+ K^-$
   - Limited by uncertainty due to Dalitz plot model
   - CLEO-c quantum correlated D’s reduce model dependence

See talks by Asner, Fleischer, Grossman, Petrov WG-5
2. Dalitz plot Method
   - $B^- \rightarrow DK^-, D \rightarrow K_s \pi^+ \pi^-$
   - limited by uncertainty due to Dalitz plot model currently $10^{-11}$
   - CLEO-c CP tagged D’s reduce Dalitz plot model dependence, compare CP+↔DD $\rightarrow K_s \pi^+ \pi^-$, CP-↔DD $\rightarrow K_s \pi^+ \pi^-$, & untagged D $\rightarrow K_s \pi^+ \pi^-$.
   - Extrapolation of Belle study CLEO-c 285 pb$^{-1}$/6fb$^{-1}$ (3770 + DsDs) reduce model error to $\sim 7^0$, $\sim 1^0$

- CP violating asymmetries
  - Unique: $L=1, C=-1$ CP tag one side, opposite side same CP
  - $CP=\pm 1 \leftarrow \psi(3770) \rightarrow CP=\pm 1 = CPV$ Sensitivity (two body final states) $A_{cp} < 0.01$
  - CP tagging allows many searches for CPV in Dalitz plots sensitive to amplitudes

Rare charm decays. Sensitivity: $10^{-6}$
Today: the potential of quark flavor physics to discover new physics is limited by theory errors

Theoretical errors dominate width of bands

Precision QCD calculations tested with precision charm data from CLEO-c

theory errors of a few % on B system decay constants & semileptonic form factors

+ 500 fb-1 @ BABAR/Belle
Precision theory + charm = dramatic increase in the potential of quark flavor physics to discover new physics

Theoretical errors dominate width of bands

**Plot uses** $V_{ub}, V_{cb}$ from exclusive decays only

**500 fb^{-1} @ BABAR/Belle**

**precision** QCD calculations tested with **precision** charm data from CLEO-c

=> theory errors of a few % on B system decay constants & semileptonic form factors

Beijing
BEPCII/BESIII Project

Design

• Two ring machine
• 93 bunches each
• Luminosity
  \(10^{33} \text{ cm}^{-2} \text{ s}^{-1} \) @1.89GeV
  \(6 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \) @1.55GeV
  \(6 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \) @ 2.1GeV
• New BESIII

Status and Schedule

• Most contracts signed
• Linac installed  2004
• Ring installed  2005
• BESIII in place  2006
• Commissioning

BEPCII/BESIII
beginning of 2007