Two themes:

1) Why Charm Physics allows B Physics to reach its full potential
2) Charm physics as a probe of physics beyond the Standard Model
• I am completely deaf
• I communicate by lip reading
• BUT lip reading obeys an inverse square law, and the audience is too far away
• Please write down your questions
• Pass them up to me
• I will read out your question before answering it
Outline of the Lectures

Lecture 1
- Overview: How Charm Physics Helps B Physics
  - Precision Quark Flavor Physics
- Experiments That Contribute To Charm Physics
- Precision CKM Physics:
  - Lifetimes
  - Hadronic Decays
  - Leptonic Decays and Decay constants
- Semileptonic Decays and CKM matrix elements
- Tests of Unitarity
- Spectroscopy

Lecture 2
- Charm as a Probe of New Physics:
  - Mixing
  - CP Violation & Rare Decays
- Summary & Outlook
Charm Physics:
What do we need to measure?

- **flavor physics**: overcome the non pert. QCD roadblock
  - precision charm lifetimes exist
  - precision charm abs. branching ratio measurements do not exist

- Leptonic decays: decay constants
  - Tests QCD techniques in c sector, apply to b sector
  - Improved $V_{ub}, V_{cb}, V_{td}$ & $V_{ts}$

- Semileptonic decays: $V_{cs}, V_{cd},$ unitarity form factors
  - $\rightarrow$ Abs D hadronic Br's normalize B physics

- **strong coupling in Physics beyond the Standard Model**
  - precise measurements of quarkonia spectroscopy & decay provide essential data to calibrate theory.
  - Important Input for the lattice

- **Physics beyond the Standard Model:**
  - D-mixing, CPV, rare decays. + measure strong phases

Charm physics builds the tools to enable this decade's flavor physics and the next decade's new physics.
$f_{D_s}$ from Absolute $\text{Br}(D_s \rightarrow \mu^+\nu)$

- Measure absolute $\text{Br} \ (D_s \rightarrow \mu\nu)$
- Fully reconstruct one D (tag)
- Require one additional charged track and no additional photons

$|f_D|^2 \quad |V_{\text{CKM}}|^2$

• Compute $M M^2$
• Peaks at zero for $D_s^+ \rightarrow \mu^+\nu$ decay.
Expect resolution of $\sim M_{\pi 0}$

$V_{\text{cs}}, (V_{\text{cd}})$ known from unitarity to 0.1% (1.1%)

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Energy(MeV)</th>
<th>L fb$^{-1}$</th>
<th>PDG</th>
<th>CLEO-c</th>
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<tbody>
<tr>
<td>$f_{D_s}$</td>
<td>$D_s^+ \rightarrow \mu\nu$</td>
<td>4140</td>
<td>3</td>
<td>17%</td>
</tr>
<tr>
<td>$f_{D_s}$</td>
<td>$D_s^+ \rightarrow \tau\nu$</td>
<td>4140</td>
<td>3</td>
<td>33%</td>
</tr>
<tr>
<td>$f_{D^+}$</td>
<td>$D^+ \rightarrow \mu\nu$</td>
<td>3770</td>
<td>3</td>
<td>UL</td>
</tr>
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</table>
Absolute Branching Ratios

~ Zero background in hadronic tag modes

Measure absolute
Br (D → X) with double tags
Br = # of X/# of D tags

<table>
<thead>
<tr>
<th>Decay</th>
<th>√s (GeV)</th>
<th>L fb⁻¹</th>
<th>Double tags</th>
<th>PDG (δB/B %)</th>
<th>CLEO-c (δB/B %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D⁰ → K⁻π⁺</td>
<td>3770</td>
<td>3</td>
<td>53,000</td>
<td>2.4</td>
<td>0.6</td>
</tr>
<tr>
<td>D⁺ → K⁻π⁺π⁺</td>
<td>3770</td>
<td>3</td>
<td>60,000</td>
<td>7.2</td>
<td>0.7</td>
</tr>
<tr>
<td>Dₛ → φπ</td>
<td>4140</td>
<td>3</td>
<td>6,000</td>
<td>25</td>
<td>1.9</td>
</tr>
</tbody>
</table>

CLEO-c potential: set the absolute scale for all heavy quark measurements
Compare B factories & CLEO-C

CLEO: \( f D_s : D_s^* \rightarrow D_S \gamma D_S \rightarrow \mu \nu \)

\[ \Delta M = M(\mu\nu\gamma) - M(\mu\nu) \quad \text{GeV/c} \]

B Factory CLEO technique with improvements

CLEO-c 3 fb\(^{-1}\)

BFFactory 400 fb\(^{-1}\)

Systematics & Background limited

Statistics limited

\( S/N \sim 14 \)

\( \text{Br}(D_s \rightarrow \phi\pi) \)

\( \text{Br}(D^+ \rightarrow K\pi\pi) \)

\( \text{Br}(D^0 \rightarrow K\pi) \)
Best way to determine magnitudes of CKM elements, in principle, is to use semileptonic decays.

Nuclear $\beta$ decay $\rightarrow V_{ud}, K \rightarrow \pi e \nu \rightarrow V_{us}$

D $\rightarrow$ Kev $\rightarrow V_{cs} b \rightarrow c l v \rightarrow V_{cb} b \rightarrow u l v \rightarrow V_{ub}$

- Kinematics:
  \[ q^2 = (p_D\mu - p_{\text{hadron}}\mu)^2 = m_D^2 + m_P^2 - 2E_p m_D \]

- Weak current is understood. The work is in the hadronic matrix element expressed in terms of form-factors. For D $\rightarrow$ Pseudoscalar $\ell^+ \nu$

  \[ \left \langle P(P_P) \left| J_\mu \right| D(P_D) \right \rangle = f_+(q^2)(P_D + P_P)\mu + f_-(q^2)(P_D - P_P)\mu \]

- For $\ell = e$, contribution of $f_-(q^2) \rightarrow 0$, only way to get information on $f_-$ is to use $\ell = \mu$, (for D decays)
Uses of Semileptonic Decay

Contraction with the leptonic current gives

\[
\frac{d\Gamma(D \to P\ell\nu)}{dq^2} = \frac{|V_{cq}|^2 P_p^3}{24\pi^3} |f_+(q^2)|^2
\]

Note: For PS \( \to V \) there are three form factors.

Quark models, HQET, and LGT have all been invoked to calculate form factor absolute normalizations. Until recently these calculations have been done mostly at \( q^2 = q^2_{\text{max}} \) (i.e., \( w=1 \), just like \( F \) in \( V_{cb} \) in \( B \to D^* \ell\nu \)).

To find \( V_{cs} \) & \( V_{cd} \) Need models for \( f \) at one fixed \( q^2 \) point.

For PS \( \to PS \) decays the data is mostly at \( q^2 = 0 \). There is a need to interpolate. To do this models predict (or make educated guesses) about the shapes of the form factors as a function of \( q^2 \).

More recently the lattice has calculated rates as a function of \( q^2 \), and charm semileptonic decays provide a powerful test of the lattice predictions. Once validated, the lattice predictions can be used with confidence in the extraction of CKM matrix elements in other \( D \) and \( B \) semileptonic decays.
Current Status of D semileptonic decays

- Absolute Br’s poorly known dB/B- 5% - 73% because no running at the ψ(3770).
- $V_{cs} f_+(0)$ measured for $D \rightarrow Kl\nu$: $0.79 \pm 0.01 \pm 0.04$ (CLEO)
- Shape of $f_+(q^2)$, given by $f_+(0)/(1-q^2/m_p)$
  measured for $D \rightarrow Kl\nu$: $m_n=2.00 \pm 0.12 \pm 0.18$ GeV

\[ D^*+ \rightarrow D^0 \pi_s, \]
\[ D^0 \rightarrow K^- \ell^+ \nu \]

\[ \Delta m = m(\pi_s K \ell) - m(K \ell) \]
PS → V Relative BR \[ \Gamma(D^+ \rightarrow K^{*0} \mu^+ \nu) \]

\[ \frac{\Gamma(D^+ \rightarrow K^{*0} \mu^+ \nu)}{\Gamma(D^+ \rightarrow K^- \pi^+ \pi^+)} = 0.602 \pm 0.01(\text{stat}) \pm 0.021(\text{sys}) \]

3.9% relative error

All values consistent with their average value with a CL of 19%

Significant improvement in 2002

Precision measurements but they are relative not absolute
\( \Gamma(D^+ \rightarrow K^{*0} \mu^+\nu) \)  \textbf{Form Factor Ratios}

The vector and axial form factors are generally parametrized by a pole dominance form

\[
A_i(q^2) = \frac{A_i(0)}{1 - q^2/M^2_i} \quad V(q^2) = \frac{V(0)}{1 - q^2/M^2_v}
\]

Parametrized by

\[
r_v \equiv \frac{V(0)}{A_1(0)} \quad r_2 \equiv \frac{A_2(0)}{A_1(0)}
\]

Decay intensity

\[
r_V = \frac{r_1}{r_2} = 4.6\% \quad \delta r_1/r_1 = 9.2\%
\]

\[
M_A = 2.5 \text{ GeV}/c^2 \quad M_V = 2.1 \text{ GeV}/c^2
\]

Nominal spectroscopic pole masses

\[
\text{New FOCUS Results much more precise Than previous work:}
\]

\[
\begin{align*}
\text{FOCUS} & : 1.504 \pm 0.057 \pm 0.039 \quad 0.875 \pm 0.049 \pm 0.064 \\
\text{BEATRICE} & : 1.45 \pm 0.23 \pm 0.07 \quad 1.00 \pm 0.15 \pm 0.03 \\
E791(e) & : 1.90 \pm 0.11 \pm 0.09 \quad 0.71 \pm 0.08 \pm 0.09 \\
E791(\mu) & : 1.84 \pm 0.11 \pm 0.09 \quad 0.75 \pm 0.08 \pm 0.09 \\
E687 & : 1.74 \pm 0.27 \pm 0.28 \quad 0.78 \pm 0.18 \pm 0.11 \\
E653 & : 2.00 \pm 0.33 \pm 0.16 \quad 0.82 \pm 0.22 \pm 0.11 \\
E691 & : 2.0 \pm 0.6 \pm 0.3 \quad 0.0 \pm 0.5 \pm 0.2
\end{align*}
\]

Beautiful measurements. Ratios of form factors are known precisely known absolute magnitudes of the form factors cannot be measured with these experiments.

hep-ex/0207049
Cabbibo suppressed semileptonic decays

The form factors governing $D \to \pi \ell \nu$, $D \to \rho \ell \nu$ and $B \to \pi \ell \nu$, $B \to \rho \ell \nu$ are related by HQS.

$D \to \pi \ell \nu$

$E687$

$D \to \rho \ell \nu$

$E791$

$\Delta m = m(\pi_s \pi \ell) - m(\pi \ell)$

Expect the BABAR, Belle and CLEO to improve on this

These modes are difficult to observe as their rates are low, and due to Cabbibo allowed semileptonic decay backgrounds. No absolute rates, only relative rates to $\sim 20\%$ accuracy.
Importance of absolute charm semileptonic decay rates.

\[ \frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cs}|^2 p_K^3 |f_+(q^2)|^2 \]

I. Absolute magnitude & shape of form factors are a stringent test of theory.  
II. Absolute charm semileptonic rate gives direct measurements of $V_{cd}$ and $V_{cs}$.
III Key input to precise $V_{ub}$ vital CKM cross check of $\sin^2\beta$

1) Measure $D \to \pi$ form factor in $D \to \pi l \nu$. Calibrate LQCD uncertainties.
2) Extract $V_{ub}$ at BaBar/Belle using calibrated LQCD calc. of $B \to \pi$ form factor.
3) But: need absolute $Br(D \to \pi l \nu)$ and high quality $d\Gamma (D \to \pi l \nu)/dE_\pi$ neither exist.

The program in charm semileptonic decay studies does not provide this…
Semileptonic Decays $|V_{CKM}|^2 |f(q^2)|^2$

$D^0 \rightarrow \pi^+ \nu$

Tagged Events Low Bkg!

$U = E_{\text{miss}} - P_{\text{miss}}$

Assume 3 generation unitarity: for the first time measure complete set of charm PS $\rightarrow$ PS & PS $\rightarrow$ V absolute form factor magnitudes and slopes to a few% with ~zero bkgd in one experiment. Stringent test of theory!
Pseudoscalar to Vector transitions

The four-fold joint angular decay distribution for $D \to K^*/\rho \ell \nu$:

$$
\frac{d\Gamma}{dq^2 d\cos \theta_K d\cos \theta_\ell d\chi} = \frac{3G_F^2}{8(4\pi)^3 |V_{ue}|^2} \times \frac{p_{K^* q^2}}{M_D^2} \\
\times \left[(1 + \cos \theta_\ell)^2 \sin^2 \theta_K |H_+(q^2)|^2 \right. \\
+ (1 - \cos \theta_\ell)^2 \sin^2 \theta_K |H_-(q^2)|^2 \right. \\
- 4 \sin^2 \theta_\ell \cos^2 \theta_K |H_q - (q^2)|^2 \right. \\
+ 4 \sin \theta_\ell (1 + \cos \theta_\ell) \sin \theta_K \cos \theta_K \cos \chi H_+(q^2) E \right. \\
- 4 \sin \theta_\ell (1 - \cos \theta_\ell) \sin \theta_K \cos \theta_K \cos \chi H_-(q^2) E \right. \\
- 2 \sin^2 \theta_\ell \sin^2 \theta_K \cos 2 \chi H_+(q^2) H_- (q^2) \right. \\
\times B(K^* \to K \pi).
$$

Yet to be observed:

$D^+ \to \rho^- e^+\nu$

$1.0 \text{ fb}^{-1}$

$B \to \rho \ell \nu$

$D \to K^* \ell \nu$

$HQS & SU(3)$

$D \to \rho \ell \nu$

Note: figure also applies to $D \to \rho \ell \nu$. 

SSI 2002 Lecture 2 I. Shipsey
D^+ \to \bar{K}^*0\text{ev} form factor determination at threshold

\[ r_v = \frac{V}{A_1} \quad r_2 = \frac{A_2}{A_1} \]

CLEO-C 12 K events/3 fb^{-1} S/B~20/1

\[ \frac{\delta r_v}{r_v} \approx 2\% \text{(stat)} \quad \frac{\delta r_2}{r_2} \approx 3\% \text{(stat)} \]

E791 3K S/B 5/1 (FOCUS 40K S/B 8/1)

\[ \frac{\delta r_v}{r_v} \approx 7\% \quad (4.6\%) \quad \frac{\delta r_2}{r_2} \approx 17\% \quad (9.2\%) \]

From CLEO-c determined abs Br
Lifetime and unitarity:

\[ \frac{\delta A_1(0)}{A_1(0)} \approx 1\% \quad \frac{\delta A_2(0)}{A_2(0)} \approx 3\% \quad \frac{\delta V(0)}{V(0)} = 3\% \]

E791 PDG Br, Lifetime & unitarity

\[ \frac{\delta A_1(0)}{A_1(0)} \approx 5\% \quad \frac{\delta A_2(0)}{A_2(0)} \approx 15\% \quad \frac{\delta V(0)}{V(0)} = 8\% \]

+ excellent for form factor determination in the Cabibbo suppressed modes D \to \text{pev}
CLEO-c Impact semileptonic dB/B

1: $D^0 \rightarrow K^- e^+ \nu$
2: $D^0 \rightarrow K^{*-} e^+ \nu$
3: $D^0 \rightarrow \pi^- e^+ \nu$
4: $D^0 \rightarrow \rho^- e^+ \nu$
5: $D^+ \rightarrow K^- e^+ \nu$
6: $D^+ \rightarrow K^{*-0} e^+ \nu$
7: $D^+ \rightarrow \pi^0 e^+ \nu$
8: $D^+ \rightarrow \rho^0 e^+ \nu$
9: $D_s \rightarrow K^0 e^+ \nu$
10: $D_s \rightarrow K^{*-0} e^+ \nu$
11: $D_s \rightarrow \phi e^+ \nu$

CLEO-c will make significant improvements in the precision with which each absolute charm semileptonic branching ratio is known.
Determining $V_{cs}$ and $V_{cd}$

Combine semileptonic and leptonic decays eliminating $V_{CKM}$

$\frac{\Gamma(D^+ \rightarrow \pi^+ \nu)}{\Gamma(D^+ \rightarrow \nu)}$ independent of $V_{cd}$

Test rate predictions at $\sim 4\%$

$\frac{\Gamma(D_s^0 \rightarrow \phi \nu)}{\Gamma(D_s^0 \rightarrow \nu)}$ independent of $V_{cs}$

Test rate predictions at $\sim 4.5\%$

Test amplitudes at $2\%$

Stringent test of theory! If theory passes the test.....

I

$D^0 \rightarrow K^- e^+ \nu \quad \delta V_{cs}/V_{cs} = 1.6\%$ (now: 11\%)

$D^0 \rightarrow \pi^- e^+ \nu \quad \delta V_{cd}/V_{cd} = 1.7\%$ (now: 7\%)

II

Use CLEO-c validated lattice to calc. $B$ semileptonic form factor, then $B$ factories can use $B \rightarrow \rho/\pi/\eta/\nu$ for precise $V_{ub}$
Unitarity Constraints from threshold running

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix} =
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

\[
V_{\text{CKM}} =
\begin{pmatrix}
  1 - \frac{1}{2} \lambda^2 & \lambda & A\lambda^3 (\rho - i\eta) \\
  -\lambda & 1 - \frac{1}{2} \lambda^2 & A\lambda^2 \\
  A\lambda^3 (1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + O(\lambda^4)
\]

\[|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \text{ ??}
\]
With current values this test fails at \sim 2.7\sigma \text{ (PDG2002)}

\[|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1 \text{ ??}
\]
CLEO -c: test to \sim 3\% (if theory D \rightarrow K/\pi l\nu good to few %)
Also 1st column

\[|V_{ud}V_{cd}*| \quad |V_{ub}V_{cb}*| \quad |V_{us}V_{cs}*|
\]
Compare ratio of long sides to 1.3%
Also major contributions to Vub, Vcb, Vtd, Vts.
Why study D mixing?

Mixing has been fertile ground for discoveries:

\[ |K^0\rangle \quad |\bar{K}^0\rangle \]

\[
\Delta \Gamma = \Gamma_- - \Gamma_+ = \Gamma_{K_L^0} - \Gamma_{K_S^0} \approx -\Gamma_{K_S^0} \approx 10^{10} \text{ s}^{-1}
\]

\[
\Delta M = M_- - M_+ = M_{K_L^0} - M_{K_S^0} = (0.5304 \pm 0.0014) \times 10^{10} \text{ s}^{-1}
\]

\[
\Delta m / \Delta \Gamma \approx 1 / 2
\]

CKM factors \( \propto \Theta_\text{c}^2 \) same order as \( \tau_{\text{kaon}} \)

Mixing rate \( \approx 1 \)

Mixing \( \propto (m_\text{c}^2 - m_\text{u}^2)/m_\text{W}^2 \) measured rate in 1958 used to bound c quark mass \( \Rightarrow \) discovery (1974)

CPV part of transition, \( \varepsilon_\text{K} \) measured in 1964 was a crucial clue that the top quark exists (1994)
Why study D mixing?

Mixing dominated by top quark
Mixing \( \propto (m_t^2 - m_{c,u}^2) / m_W^2 \rightarrow \text{Large} \)
B lifetime Cabibbo suppressed \( \propto V_{cb}^2 \)
Mixing rate also Cabibbo suppressed \( (V_{td}^2) \)
But large Mixing rate \( \rightarrow \) early indication
m\(_{\text{top}}\) large
Now: sin\(2\beta\) (in the Standard Model)
Future: once f\(_B\) is known \(\Rightarrow V_{td}\) (in SM)

\[ y = \Delta \Gamma / 2 \Gamma < x = \Delta m / \Gamma \]

Mixing \( \propto (m_t^2 - m_{c,u}^2) / m_W^2 \rightarrow \text{Large} \)
As V\(_{ts}\) >> V\(_{td}\) B\(_s\) mixing >> B\(_d\) mixing
B lifetime Cabibbo suppressed \( \propto V_{cb}^2 \)
Future: Y(5S) & hadron collider studies
Route to \(\gamma\) & sin\(2\chi\).
Once f\(_{Bs}\) is known \(\Rightarrow V_{ts}\) (in SM)
D mixing

CKM factors $\propto \Theta_c^2 \sim 0.05$  
(b-quark contribution $\propto V_{ub}V_{cb}$ can be neglected)  
But $\tau_D$ not Cabbibo suppressed ($V_{cs} \sim 1$)

Mixing $\cdot \tau \sim 0.05$

Additional suppression:  
Mixing $\propto (m_s^2 - m_d^2)/m_W^2 = 0$ SU(3) limit

SM mixing very small $\propto \Theta_c^2$ x additional suppression  
⇒ A window for new physics
Some Formalism

Time evolution of $D^0$ or $D^0$ is determined by Schrodinger’s Equation

$$\frac{\partial}{\partial t} \left( \begin{array}{c} D^0 \\ \bar{D}^0 \end{array} \right) = \left( M - \frac{i}{2} \Gamma \right) \left( \begin{array}{c} D^0 \\ \bar{D}^0 \end{array} \right)$$

\begin{align*}
D^0 & \quad M_{12} \\
\bar{D}^0 & \quad -i \frac{\Gamma_{12}}{2}
\end{align*}

\begin{align*}
H & = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}
\end{align*}

• 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 $D^0 \rightarrow f \rightarrow D^0$ via off-shell intermediate states.
• CP violation in mixing can arise from interference between on-shell and off-shell amplitudes. This leads to $\Gamma(\bar{P}^0 \rightarrow P^0) \neq \Gamma(P^0 \rightarrow \bar{P}^0)$
• Note in the $B$ system $\Gamma_{12}$ is very small; mixing is dominated by $\Delta M = 2M_{12}$. 

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Switching to $x$ and $y$

\[
\begin{align*}
\alpha(t) |D^0 & > + \beta(t) |\bar{D}^0 > \\

i \frac{\partial}{\partial t} \begin{pmatrix} a \\ b \end{pmatrix} &= \begin{pmatrix} M - \frac{i}{2} \Gamma \\ 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 \\ M^* \frac{i}{2} - \frac{i}{2} \Gamma^* \frac{i}{2} \end{pmatrix} \\
&= \begin{pmatrix} 0 \\ M^* \frac{i}{2} - \frac{i}{2} \Gamma^* \frac{i}{2} \end{pmatrix} \end{align*}
\]

\[\begin{pmatrix} a \\ b \end{pmatrix} \]

But initially assume conservation here

\[\frac{1}{2} \begin{pmatrix} 0 & -i & 0 \\ -i & -x-y & 0 \\ 0 & 0 & 0 \end{pmatrix} \]

\[12 12 12 12: 22\]

\[K^0 - \bar{K}^0 : |M_{12}| \sim |\Gamma_{12}| \]

\[B^0 - \bar{B}^0 : |M_{12}| \gg |\Gamma_{12}| \]

\[D^0 - \bar{D}^0 : \text{to be determined} \]

C.P.T assumed

\[\tau_D^0 \]

\[\text{Measures time in units of } \tau_D^0 \]

\[|D^0\rangle \rightarrow |K^+\bar{K}^-\rangle \text{ or } |\pi^+\pi^-\rangle \rightarrow |\bar{D}^0\rangle \]

\[CP\text{ even} \]

\[\text{shifts energy of CP eigenstates} \]

\[\text{shifts lifetimes of CP eigenstates} \]

\[x = \frac{2M_{12}}{\Gamma} \]

\[y = \frac{\Gamma_{12}}{\Gamma} \]
New Physics Alters x not y

Assume:
CP Conserved

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

\[ \Delta M = \frac{x}{\tau_{D^0}} \]

\[ \Delta \Gamma = \frac{2y}{\tau_{D^0}} \]

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

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

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.
x in the Standard Model

\[ D^0 \xrightarrow{-\frac{i}{2}xt} \bar{D}^0 \]

\[ D^0 \quad \bar{u} \quad c \]

\[ \bar{D}^0 \quad x \sim \sum_{n} \left\langle \bar{D}^0 \left| H \right| n \right\rangle \left\langle n \left| H \right| D^0 \right\rangle \frac{m_{D^0} - E_n}{n} \]

\[ \begin{align*}
\text{d} & \quad + \sin^2 \theta_c \cos^2 \theta_c \\
\text{d} & \quad - \sin^2 \theta_c \cos^2 \theta_c \\
\text{s} & \quad - \sin^2 \theta_c \cos^2 \theta_c \\
\text{s} & \quad \sin^2 \theta_c \cos^2 \theta_c 
\end{align*} \]

\[ V_{cd}^2 \]
\[ V_{cd} V_{us} \]
\[ V_{ed} V_{us} \]
\[ V_{su}^2 \]

Sum \(\approx 0\) when \(m_s = m_d\)

(b case suppressed by \(V_{cb} V_{ub}\))

In SU(3) limit \(x = 0\)

But large range

\[ \text{Estimate: } x \leq 10^{-3} \]

Because \(x\) is very small, \(x\) is a window for new physics
y in the Standard Model

\[ y \sim \sum \text{Common States} \]

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

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

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

\[ D^0 \rightarrow \text{Common State} \]

\[ A \propto \sqrt{BR} \]

Recent work by Falk, Grossman, Ligeti, Nir, Petrov indicate \( y \approx 1\% \) possible (see later)

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

Hadronic Problem:
\[ \frac{\Gamma(D^0 \rightarrow K^+K^-)}{\Gamma(D^0 \rightarrow \pi^+\pi)} \approx 3.0 \pm 0.2 \]

\( \Rightarrow \) 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_{top} \sim m_{charm} then B and D mixing would be analogs.

For y B \rightarrow 4\pi is cancelled B \rightarrow 4K in the SU(3) limit but 4K is kinematically forbidden so it cannot contribute to y

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

For x both B \rightarrow 4\pi & B \rightarrow 4K can contribute. For x there is more effective SU(3) cancellation than in y. Nobody know s how big the size of this effect by. It is feasible that y>x (SM)

New physics 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
Non-standard model mixing

Several classes of model exist
- Higgs Doublet
- Flavor Changing Neutral Currents
- SUSY
- Fourth Generation Quarks
- Iso(singlet quarks)

Non-standard model DD mixing rate depends on the chosen model of new physics

Predictions span orders of magnitude!
$D^0 \bar{D}^0$ Mixing Measurements I Theoretically Cleanest

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

Theoretically clean usually means experimentally challenging.

$$m(\pi_s K^+ \ell^-) - m(K^+ \ell^-) \rightarrow \text{Missing } \nu$$
D^0 D^0 Mixing Measurements E791
Semileptonics

Width: \rightarrow \text{Missing } \nu

E791 (fixed target \pi Pt)
(after t requirement)

The \(t^2 e^{-t}\) particularly suits fixed target experiments, but x and y not separated

\[
R_{\text{mix}} = \frac{1}{2} \left( x^2 + y^2 \right) < 0.5\% \text{ at 90\%C.L.}
\]
Measurements of the Mixing Rate Using Wrong Sign Semileptonic $D^0$ Decays

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

- Measurements from
  - **E791 ($D^0 \rightarrow K^0 \nu$):** $< 0.5\%$ at 90\% C.L.
  - **CLEO ($D^0 \rightarrow K^+ \nu$):** $R = (0.00 \pm 0.31 \pm 0.32)\%$, or 0.87\% @90\%CL
- **FOCUS (ICHEP02):** $R < 0.12\%$ @90\%CL (best)
- **B factories** will have results soon
- Accessible to future experiments
  - Hadron machines
    - Lepton helps triggering
  - CLEO-c
    - Opposite side tag
  - Will need separate measurement of $y$ if that turns out to be larger or comparable to $x$
D⁰D⁰ Mixing II from hadronic decays

- Production: e⁺e⁻→cc; c→D*⁺→D⁰⁺π⁺
- Charge of the “soft pion” tags whether the initial state was D⁰ or D⁰ (as before)
- Cabibbo favored decay: D⁰→K⁻π⁺ (4%) gives “right-sign” charge correlation
- Mixing is a potential source of wrong-sign decays: D⁰→D⁰→K⁺π⁻
- Doubly Cabibbo suppressed decay D⁰→K⁺π⁻ also gives wrong-sign (π⁺π⁻K⁺) charge correlation with strong phase δ
- Use time dependence to distinguish:

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

\[ R_D = |B/A|^2 \]

\[ r_{ws}(t) = (R_D + \sqrt{R_D} y't + \frac{1}{4} [x't^2 + y'y'^2] t^2) e^{-t} \]
Currently, best constraints come from this mode if assumptions about strong phase are made.

Unknown strong phase difference weakens these constraints.

\( N_{WS} = 44.8^{+9.7}_{-8.7} \)

\( N_{RS} = 13527 \pm 116 \)

\[ |x'| < 2.8\% \]
\[ -5.2\% < y' < 0.2\% \]
\[ 0.24\% < R_D < 0.69\% \] \text{@95\% C.L.}
$x$, $y$, and $R_D$ from $D^0 \rightarrow K^+\pi^-$

$N_{WS} = 148.5 \pm 31.3$
$N_{RS} = 36760 \pm 195$

CLEO limit (still best constraint on $x$)

$|x'| < 3.9\%$
$-12.4\% < y' < -0.6\% \quad @95\%$ C.L.
$0.43\% < R_D < 1.73\%$

$x' = x \cos \delta - y \sin \delta$
$y' = y \cos \delta - x \sin \delta$

set $\delta = 0$ for comparison
$R_{WS}$ from $D^0 \rightarrow K^+ \pi^-$

$N_{WS} = 317 \pm 26$

$N_{RS} = 82960 \pm 310$

$R_{WS} = \left(0.38 \pm 0.04 \pm 0.02\right)\%$

$R_{WS} \equiv \frac{\Gamma(WS)}{\Gamma(RS)}$

$R_{WS} = \left(0.38 \pm 0.03 \pm \sim 0.03\right)\%$
Belle and BaBar
- Significant improvements in $R_{WS}$
- $x'$ and $y'$ proper time fits soon!

Information in multi-body modes not yet fully exploited
- $x$, $y$, $CP$ violation

$R_{WS}$ in $D^0 \rightarrow K^+ \pi^-$

$R_{WS} \left( D^0 \rightarrow K^+ \pi^- \right) = (0.38 \pm 0.03)\%$

$R_{WS} \left( D^0 \rightarrow K^+ \pi^- \pi^0 \right) = (0.43^{+0.11}_{-0.10} \pm 0.07)\%$

$R_{WS} \left( D^0 \rightarrow K^+ \pi^- \pi^+ \pi^- \right) = (0.41^{+0.12}_{-0.11} \pm 0.04)\%$

- Situation more complicated
- Time dependent Dalitz plot fits of RS and WS required to get limits on $x$, $y$, $CPV$
- Need lots of statistics, Advantages
- Fit is to amplitudes i.e linear in $x$ and $y$
Measurement of \( y_{CP} \) from \( D^0 \rightarrow K^+ K^- \) & \( D^0 \rightarrow \pi^+ \pi^- \)

\[
\frac{\Delta \Gamma}{2 \Gamma} = \frac{\Gamma_{CP}^+ - \Gamma_{CP}^-}{\Gamma_{CP}^+ + \Gamma_{CP}^-} = \frac{\Gamma + \delta - (\Gamma + \delta)}{2 \Gamma} = \frac{\Gamma}{2 \Gamma} = \frac{1}{2}
\]

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

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

Experimentially, it is easier to measure the lifetime difference of a CP-even decay relative to the non-CP final state \( D^0 \rightarrow K^- \pi^+ \) (assumes no CP violation):
Measurement of $y_{CP}$ from $D^0 \rightarrow K^+K^-$ & $D^0 \rightarrow \pi^+\pi^-$

Many systematic errors cancel in the ratio
Technique, resolution, and systematics are quite
different at fixed target experiments (FOCUS, E791) and
$e^+e^-$ (Belle BaBar, CLEO)
These were some of the first $D$ mixing results to come out
of the $B$ factories.....
Measurement of $y_{CP}$ from $D^0 \rightarrow K^+ K^-$ & $D^0 \rightarrow \pi^+ \pi^-$

$y_{CP} = (1.0 \pm 0.7)\%$
$\gamma_{CP}$ is appears high relative to the limits on $x$ and $y$ form hadronic. The unknown strong phase difference could be the cause.

- Current measurements cutting into range of some non-SM predictions
- Much room for improvement before we hit SM background

"Typical" upper SM predictions
"Typical" non-SM predictions (many higher and lower, however)
Current Status of $D^0$-$\bar{D}^0$ Mixing

$y_{CP}$ is appears high relative to the limits on $x$ and $y$ form hadronic The unknown strong phase difference could be the cause.

What if $\delta=40^\circ$, the estimated maximum of Falk, Nir & Petrov (99)? $Y_{CP}$ and $K\pi$ would be more consistent if $\delta=90^0$. Bergman, Grossman et al (00).

My opinion: the errors are too large to draw any strong conclusion at this time.

- Current measurements cutting into range of some non-SM predictions
- Much room for improvement before we hit SM background

Imagine A 40$^0$ Rotation Of the $K\pi$ ellipses

"Typical" upper SM predictions
"Typical" non-SM predictions (many higher and lower, however)
The Future of these techniques

Babar, Belle the heavyweights by 2005 ~500 1/fb

B Factory $K\pi \propto L^{-1/4}$

can do better with Dalitz analysis

Each experiment, $|x'| \lesssim 0.9\%$

Scaling from CLEO $|y'| \lesssim 0.6\%$

$|y| \lesssim 1.0\%$

$\Delta M \cdot \tau \propto f_{M}^{2}M \cdot \tau$

$K^{0} \rightarrow \bar{K}^{0}$ $\equiv 1$

$D^{0} \rightarrow \bar{D}^{0}$ $\approx 0.03$

Because standard model present and big background in kaon decay
Unique opportunities at Threshold

Angular momentum
\( L = 1 \) for \( \psi(3770) \)

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

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

\[ |D^0 \bar{D}^0 \rangle_L = \frac{1}{\sqrt{2}} \left[ D^0(k_1) \bar{D}^0(k_2) \right] + (-1)^L \left[ D^0(k_2) \bar{D}^0(k_1) \right] \]
Special Opportunities to measure mixing by exploiting Quantum Coherence at the $\Psi''$

$\Psi'' \rightarrow D^0 \overline{D}^0 \rightarrow (K^- \pi^+)(K^- \pi^+)$

\[ \therefore \quad L = 1 \]

p-wave

is sensitive to mixing, and insensitive to Doubly Cabibbo suppressed decays

Add amplitudes, $(-1)^L = -1$ relative sign

\[ |a_1 - a_2|^2 = |A\overline{B} - \overline{B}A + \frac{1}{2}(ix + y)A^2(t_1 - t_2)|^2 = \frac{1}{4} A^4(x^2 + y^2)(t_1 - t_2)^2 \]

(no time information)

Interferes away!
Time integrated mixing at the $\psi(3770)$

normalizing by $\Gamma(D^0 \bar{D}^0) \rightarrow (K^- \pi^+)(K^+ \pi^-)$ implies for the time integrated rate

$$R \left[ \frac{(K^- \pi^+)(K^- \pi^+)}{(K^- \pi^+)(K^+ \pi^-)} \right] = \frac{1}{2}(x^2 + y^2)$$

(in the limit of CP conservation)

same for the semileptonic rate

$$\sqrt{\frac{1}{2} (x^2 + y^2)} < \sqrt{\frac{2.3}{50,000}} < 1.0\%$$

Since, $\Psi^\prime\prime$ likely background free… The above is limited by statistics, measurements at 10 GeV or hadron machines have entirely different systematics errors

note: at $3770 \propto L^{-1/2}$, B Factory $K\pi \propto L^{-1/4}$

Aside: if it were possible To obtain 500 fb$^{-1}$ at $\Psi^\prime\prime$:

$$\sqrt{\frac{1}{2} (x^2 + y^2)} < \sqrt{\frac{2.3}{50,000 \times \frac{500}{3}}} < 0.08\%$$

B-factor my estimate $X < 0.8\%$

With 500 fb so 3770 with 3 fb close

BESIII X3 smaller error

(Unique sensitivity)
CP Eigenstates at $\psi(3770)$

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:

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

$\cdot$Example Two

CP eigenstates of Opposite sign

$$(\pi^+\pi^-)(K_s^0\pi^0)(-1)^l$$

$+$ $-$ $-$ (since $l = 1$)

$+$ $-$ $-$ = CP+

$\cdot$CP eigenstate tag X flavor mode

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

$+$ $-$ $-$ $-$ = CP+
Measuring the DCSD/CF phase $\delta$

at $\Psi(3770) \rightarrow D^0 \bar{D}^0 (f_\pm)(K^- \pi^+)$

\[ f_\pm \]

\( D^0 \)

\( \bar{D}^0 \)

\( x \)

\( \Delta \cos \delta \)

\( \sim 0.05 \).

\( \text{Measures strong phase diff.} \)

\( \text{CF/DCSD} \)

\( \text{input for B factories} \)

\( \text{Needed for} \)

\( \gamma \) in $B \rightarrow DK$

\[ J. \ Silva \ and \ A. \ Soffer \ Phys. \ Rev. \ D61: \ 112001, \ 2000, \ (hep-ph/9912242) \]

\( \text{Gronau Grossmann J.Rosner (hep-ph/0103110).} \)

\[ \int dt \cong 1 \pm 2 \sqrt{R_D \cos \delta} \]

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

\[ x' = x \cos \delta + y \sin \delta \]
\[ \Psi \rightarrow D^0 \bar{D}^0 (f_\pm)(K^- \pi^+) \]

\[ \int dt \approx \pm 2\sqrt{R_D} \cos \delta \quad A = \frac{(K^- \pi^+)f_+ - (K^- \pi^+)f_-}{(K^- \pi^+)f_+ + (K^- \pi^+)f_-} = 2\sqrt{R_D} \cos \delta \]

**CP(+) eigenstates**

<table>
<thead>
<tr>
<th>Channel</th>
<th>B.F.(x10^3)</th>
<th>#( 3fb^{-1} \psi(3770))</th>
<th>#(3fb^{-1} \gamma D^0 D^0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K^-K^+</td>
<td>4.1</td>
<td>110,000</td>
<td>9,400</td>
</tr>
<tr>
<td>\pi^-\pi^+</td>
<td>1.6</td>
<td>36,000</td>
<td>3,000</td>
</tr>
<tr>
<td>\rho^0\pi^0</td>
<td>15.0</td>
<td>54,200</td>
<td>4,600</td>
</tr>
</tbody>
</table>

**CP(-1) eigenstates**

<table>
<thead>
<tr>
<th>Channel</th>
<th>B.F.(x10^3)</th>
<th>#( 3fb^{-1} \psi(3770))</th>
<th>#(3fb^{-1} \gamma D^0 D^0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K_s\eta</td>
<td>3.5</td>
<td>61,600</td>
<td>5,300</td>
</tr>
<tr>
<td>K_s\rho^0</td>
<td>6.0</td>
<td>98,400</td>
<td>8,400</td>
</tr>
<tr>
<td>K_s\pi^0</td>
<td>10.6</td>
<td>176,000</td>
<td>15,000</td>
</tr>
<tr>
<td>K_s\eta'</td>
<td>10.0</td>
<td>141,000</td>
<td>12,000</td>
</tr>
<tr>
<td>K_s\phi</td>
<td>4.3</td>
<td>39,100</td>
<td>3,300</td>
</tr>
</tbody>
</table>

Expect 32,000

\( K^- \pi^+ f_- \)

\( A \) is expected to be small

\[ \Delta \cos \delta \approx \frac{1}{2\sqrt{R_D} \sqrt{N}} \]

\[ \Delta \cos \delta \approx \pm 0.05 \]

BESIII X3 smaller

Error (0.006 500 fb^{-1})
1. Time-dependent analyses are not possible, Are time dependent Analyses possible?

Semileptonic: quadratic in x,y: not so sensitive wanted: \textit{linear in x or y}

2. Recalll: (quantum-mechanically) entangled initial state

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

… so one can measure decay rates for CP-tagged decays

The semi-leptonic width of a meson should be independent of the CP quantum number since it is flavor specific. So the semi-leptonic branching ratio in CP tagged events is inversely proportional to the total width of that meson. Since we know whether the D is CP even or CP odd we can extract y

\textbf{CP eigenstate tag X flavor mode}

\[
\begin{align*}
K^+ K^- &\quad \leftrightarrow \quad D_+ &\quad \leftrightarrow \quad \psi(3770) &\quad \rightarrow \quad D_- &\quad \rightarrow \quad X \text{ lv} \\
K_s^0 \pi^0 &\quad \leftrightarrow \quad D_- &\quad \leftrightarrow \quad \psi(3770) &\quad \rightarrow \quad D_+ &\quad \rightarrow \quad X \text{ lv}
\end{align*}
\]

D. Atwood, A.A. Petrov, hep-ph/0207165
Experimental constraints on $y$ at Threshold

\[
\left[ \frac{\text{Br}(D_+ \to X \ell \nu)}{\text{Br}(D_- \to X \ell \nu)} - \frac{\text{Br}(D_- \to X \ell \nu)}{\text{Br}(D_+ \to X \ell \nu)} \right] = 4y
\]

in 3 $fb^{-1}$
- $CP = +$   \( \sim 800K \)
- $CP = -$   \( \sim 200K \)

$\# \text{tag} + \ell$   \( 9.8K \)

$\# \text{tag}$   \( 39.2K \)

for \( y = 0.75\% \), \( \delta y = 0.4\% \)

at BEPCII \( \delta y = 0.13\% \)

Expect background free systematics entirely different to lifetime measurements

once $y$ is obtained $x$ can be obtained from \( \sqrt{1/2(x^2 + y^2)} \)
CPV in D Decays

**Indirect CPV:**
\[
\Gamma(D^0 \rightarrow f) \neq \Gamma(\bar{D}^0 \rightarrow f)
\]
Very small in charm since mixing is suppressed
(i.e. good hunting ground for new physics)

**Direct CPV:**
\[
\Gamma(D \rightarrow f) \neq \Gamma(\bar{D} \rightarrow f)
\]
\[
A_{CP} = \frac{\Gamma(f) - \Gamma(f)}{\Gamma(f) + \Gamma(f)} = \frac{2 \text{Im}A_1A_2^* \sin(\delta_1 - \delta_2)}{|A_1|^2 + |A_2|^2 + 2 \text{Re}A_1A_2^* \cos(\delta_1 - \delta_2)} < 10^{-3}
\]

2 different amplitudes

strong phase-shift
1) Consider $D^0 \rightarrow \pi^+\pi^-$  
(same for $K^+K^-, K^+K^-\pi^+, K^+K^-\pi^0, \phi\pi^+$, $\pi^+\pi^-\pi^+$, $\pi^+\pi^-\pi^0$, etc...)

Since this decay is Singly Cabibbo Suppressed...

$V_{cd}V_{ud}$

$V_{cb}V_{ub}$

Expected $A_{CP} < 10^{-3}$ in most cases
Anti-matter production asymmetry can be studied using the Cabbibo allowed (Acp=0) mode. The mass distributions for the reactions $D^+ \rightarrow K^- K^+ \pi^+$ and $D^- \rightarrow K^+ K^- \pi^-$ are shown. The numbers of events for these reactions are $6860 \pm 110$ and $7355 \pm 112$, respectively. The mass distributions for $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D^- \rightarrow K^+ \pi^- \pi^-$ are also shown, with event counts of $68607 \pm 282$ and $73710 \pm 292$, respectively. These modes are used to take into account matter-anti-matter production asymmetry.
**D± ACP Summary**  
Self tagging no D* tag needed

**D0 ACP Summary**  
Use D* decays to tag D0 flavor

* All analyses statistics limited.  
* None are background free.
$D^0 \rightarrow K^- \pi^+ \pi^0$

- Look for CPV in Dalitz Plots:
**CPV at the $\psi(3770)\rightarrow D^0 D^0 \rightarrow f_+ f_+ \text{ or } f_- f_-$**

\[(f_+ = K^+ K^-, \pi^+ \pi^-, K_s \eta, . . .)\]

- Recall if two decays are observed with the same CP in a single background free event → CP violation in the D system is established

---

<table>
<thead>
<tr>
<th>CP eigenstate 1</th>
<th>CP eigenstate 2</th>
<th># for 100% CPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ K^-$</td>
<td>$K^+ K^-$</td>
<td>174</td>
</tr>
<tr>
<td>$K^+ K^-$</td>
<td>$K_s \pi^0$</td>
<td>171</td>
</tr>
<tr>
<td>$K^+ K^-$</td>
<td>$\rho^0 \pi^0$</td>
<td>183</td>
</tr>
<tr>
<td>$K_s \pi^0$</td>
<td>$K_s \pi^0$</td>
<td>136</td>
</tr>
</tbody>
</table>

CLEO-c estimates

---

Statistics can be increased x3-4 using a MM technique. This technique is very different to the method at 10 GeV and at hadron machines. Sensitivity is at the ~1% level (X3 better at BEPCII)
CPV Outlook

• E791 and FOCUS
  – Working on $A_{CP}$ analyses (for example Dalitz plots).

• CLEO-c..
  • ~30 million DD events (and new $A_{CP}$ search modes).

• B Factories
  ~by 2005 100 times the integrated luminosity that CLEO has
  at the $Y(4S)$ Improve on present CLEO limits by at least
  a factor of 10.

• Hadron Machines
  – CDF & D0 are getting into the game.
  – BTeV could have $10^9$ reconstructed charm events.

• BESIII
Rare Decays

• Rare and decays, Standard Model estimates:

\[
\begin{align*}
Br(D^0 \rightarrow Xl^+l^-) & \sim 1 \times 10^{-9} \quad (S.D.: 10^{-8}) \\
Br(D^0 \rightarrow X\nu\bar{\nu}) & \sim 2 \times 10^{-15} \quad (S.D.: 10^{-15}) \\
Br(D^+ \rightarrow \pi\nu\bar{\nu}) & \sim 8 \times 10^{-16} \quad (S.D.: 10^{-16})
\end{align*}
\]

…background-free tests of New Physics!

Some very difficult to do anywhere except at the (3770) in tagged events. Sensitivity at the 10^{-6} level

A wide range of modes were looked at by CLEO-c

Conclusion was that B Factories with 500 fb and CLEO-c will be complementary. Hadron machines have statistical advantages in certain final states.
Probing QCD

→ Verify tools for strongly coupled theories
→ Quantify accuracy for application to flavor physics

• ψ and Y Spectroscopy
  – Masses, spin fine structure

• Leptonic widths for S-states.
  – EM transition matrix elements

• Y resonances winter ’01-summer’02 ~ 4 fb⁻¹ total

J/Ψ running 2005 10⁹ J/Ψ x 20 BES II

• Uncover new forms of matter – gauge particles as constituents
  – Glueballs G=|gg⟩ Hybrids H=|gqq⟩

The current lack of strong evidence for these states is a fundamental issue in QCD. Requires detailed understanding of ordinary hadron spectrum in 1.5-2.5 GeV mass range.
Gluonic Matter

- Gluons carry color charge: *should bind!*
- But, like Jim Morrison, glueballs have been sighted too many times without confirmation....
- CLEO-c 1st high statistics experiment with modern 4\(\pi\) detector covering 1.5-2.5 GeV mass range.
- Radiative \(\psi\) decays: ideal glue factory: \(\frac{C}{C}\bullet\gamma\)
  - \((60 \text{ M } J/\psi \rightarrow \gamma X)\)

Example: \(f_\mu(2220)\) Inclusive \(\gamma\)

Exclusive:

BES '96 44
CLEO-c 18K

**corroborating checks:**
Anti-search in \(\gamma\gamma\): /Search in \(\gamma(1S)\)
Note: with more data BESII no longer see evidence of \(f_\mu(2220)\)
CLEO-c: Helping the B Factories & Tevatron Experiments

- **Crucial Validation of Lattice QCD**: Lattice QCD will be able to calculate with accuracies of 1-2%. The CLEO-c decay constant and semileptonic data will provide a “golden,” & timely test. QCD & charmonium data provide additional benchmarks. (E2 Snowmass WG)

Imagine a world where we have theoretical mastery of non-perturbative QCD at the 2% level

B Factories only ~2005
**Crucial Validation of Lattice QCD:** Lattice QCD will be able to calculate with accuracies of 1-2%. The CLEO-c decay constant and semileptonic data will provide a “golden,” & timely test. QCD & charmonium data provide additional benchmarks. (E2 Snowmass WG)

Imagine a world
Where we have theoretical mastery of non-perturbative QCD at the 2% level

Theory errors = 2%

B Factories only ~2005
**CLEO-c: Helping the B Factories & Tevatron Experiments CLEO-c**

- **Knowledge of absolute charm branching fractions** is now contributing significant errors to measurements involving b’s. CLEO-c can also resolve this problem in a timely fashion.
- **Improved Knowledge of CKM elements**, which is now not very good.

<table>
<thead>
<tr>
<th></th>
<th>Vcd</th>
<th>Vcs</th>
<th>Vcb</th>
<th>Vub</th>
<th>Vtd</th>
<th>Vts</th>
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<tr>
<td>PDG</td>
<td>7%</td>
<td>11%</td>
<td>5%</td>
<td>25%</td>
<td>36%</td>
<td>39%</td>
</tr>
<tr>
<td>CLEO-c data and LQCD</td>
<td>1.7%</td>
<td>1.6%</td>
<td>3%</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
</tr>
</tbody>
</table>

(Snowmass E2 WG)
Additional topics At Threshold

- $\Psi'$ spectroscopy (10^8 decays) $\eta'_c h_c$...

- $\tau^+\tau^-$ at threshold (0.25 fb^{-1})
  - measure $m_\tau$ to $\pm$ 0.1 MeV
  - heavy lepton, exotics searches

- $\Lambda_c\Lambda_c$ at threshold (1 fb^{-1})
  - calibrate absolute BR($\Lambda_c \rightarrow pK\pi$)

- $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$
  - spot checks
The Charm Program: Summary

- Powerful physics case
  - Precision flavor physics - finally
  - Nonperturbative QCD - finally
  - Probe for New Physics

Direct: $V_{cs}$, $V_{cd}$ & tests QCD techniques aids BABAR/Belle/CDF/D0/BTeV/LHC-b with $V_{ub}$, $V_{cb}$, $V_{td}$, $V_{ts}$

- 1 and 2 can only be done at threshold CLEO-c is a logical choice now
- Unique: not duplicated elsewhere
- Highest performance detector to run @ charm threshold
- Flexible, high-luminosity accelerator
- Experienced collaboration

Optimal timing
- LQCD maturing
- allows Flavor physics to reach
- its full potential this decade
- Beyond the SM in next decade

The most comprehensive & in depth study of non-perturbative QCD yet proposed in particle physics
Probes of charm for new physics

Threshold machines and those operating at Y(4S) are complimentary

CLEO-c is statistics limited

Y(4S) and hadron machines have very important role to play and will extend the new physics reach considerably

If BESIII is a detector with the same capabilities as BaBar/Belle/CLEO and a luminosity of a few $10^{33}$ is reached it is a natural next step at the charm threshold
**ISR Charm Events at B Factories**

Initial State Radiation photon reduces the  $\gamma$s

**Measurement** | **#events**
--- | ---
BaBar/Belle | CLEOc
$D_s^+ \rightarrow \mu\nu$ | 330 | 1,221
$D^+ \rightarrow \mu\nu$ | 50 | 672
$D^+ \rightarrow K^-\pi^+\pi^+$ | 6,750 | 60,000
$D_s^+ \rightarrow \phi\pi$ | 221 | 6,000

**Details:**

- ISR projections made by BaBar show the ISR technique is not statistically competitive with CLEO-c.
- Systematic errors are also much larger.
\( Y(1S) \rightarrow \gamma X \) as a preview of \( J/\Psi \rightarrow \gamma X \)

- The \( Y(1S) \) is also glue rich but...

\[
\frac{\Gamma(\Psi \rightarrow \gamma X)_{1-2\text{GeV}}}{\Gamma(Y \rightarrow \gamma X)_{1-2\text{GeV}}} \sim \frac{\sigma_\Psi}{\sigma_Y} \left( \frac{q_c}{q_b} \right)^2
\]

\[
\begin{align*}
\Psi \rightarrow \gamma X_{1-2\text{GeV}} \\
Y \rightarrow \gamma X_{1-2\text{GeV}} \\
\Psi \rightarrow \gamma X \\
Y \rightarrow \gamma X
\end{align*}
\]

\(~10^2 \cdot 4 \cdot 10 \sim 4000\)

- No PWA at \( Y(1S) \) but we can show existence of states
A useful check: look at current 2γ data

- Anti-search in glue-poor environment

  - Eg. $e^+e^- \rightarrow e^+e^-\gamma\gamma \rightarrow e^+e^-X$

![Diagram showing anti-search in glue-poor environment with examples of diagrams for $e^+e^-\rightarrow e^+e^-\gamma\gamma$ and $e^+e^-\rightarrow e^+e^-X$.]
The $f_J(2220)$: A case study

Glueballs are hard to pin down, often small data sets & large bkgds

New BES data does not find the $f_J(2220)$!
(but not published)

MARKIII (1986)

LEAR 1998

Crystal barrel: $pp \rightarrow K^{0}_s K^{0}_s$
f_J(2220) in CLEO-c?

Anti-search in Two Photon Data: γγ→f_J(2220):
- CLEO II: Γ_{γγ}B( f_J (2220)→ππ/K_S K_S) < 2.5(1.3) eV
- CLEO III: sub-eV sensitivity (new UL to appear ~1 week)
- Upsilonium Data: Υ(1S): Tens of events

<table>
<thead>
<tr>
<th></th>
<th>BES</th>
<th>CLEO-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>π⁺π⁻</td>
<td>74</td>
<td>32000</td>
</tr>
<tr>
<td>π⁰π⁰</td>
<td>18</td>
<td>13000</td>
</tr>
<tr>
<td>K⁺K⁻</td>
<td>46</td>
<td>18600</td>
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<td>K_S K_S</td>
<td>23</td>
<td>5300</td>
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<tr>
<td>pp</td>
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<td>8500</td>
</tr>
<tr>
<td>ηη</td>
<td>–</td>
<td>5000</td>
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</table>

CLEO-c has corroborating checks:
Inclusive Spectrum $J/\psi \to \gamma X$

Inclusive photon spectrum a good place to search: monochromatic photons for each state produced

Unique advantages of CLEO-c
+ Huge data set
+ Modern $4\pi$ detector (Suppress hadronic bkg: $J/\psi \to \pi^0 X$)
+ Extra data sets for corroboration $\gamma\gamma$, $\gamma(1S)$:
  Lead to Unambiguous determination of $J^{PC}$ & gluonic content
**Comparison with Other Expts**

**China:**

- BES II is running now.
- BES II --> BES III upgrade
- BEPC I --> BEPC II upgrade, $10^{32}$
- 2 ring design at $10^{33}$ under consideration (workshop 10/01)
- Physics after 2006? if approval & construction goes ahead.

**BES III** complimentary to CLEO-c if new detector is Comparable

<table>
<thead>
<tr>
<th>Quantity</th>
<th>BES II</th>
<th>CLEO-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>J/psi yield</td>
<td>50M</td>
<td>&gt; 1000M</td>
</tr>
<tr>
<td>dE/dx res.</td>
<td>9%</td>
<td>4.9%</td>
</tr>
<tr>
<td>K/πi separation up to</td>
<td>600 MeV</td>
<td>1500 MeV</td>
</tr>
<tr>
<td>momentum res. (500 MeV)</td>
<td>1.3%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Photon resolution (100 MeV)</td>
<td>70 MeV</td>
<td>4 MeV</td>
</tr>
<tr>
<td>Photon resolution (1000 MeV)</td>
<td>220 MeV</td>
<td>21 MeV</td>
</tr>
<tr>
<td>Minimum Photon Energy</td>
<td>80 MeV</td>
<td>30 MeV</td>
</tr>
<tr>
<td>Solid angle for Tracking</td>
<td>80%</td>
<td>94%</td>
</tr>
</tbody>
</table>

**HALL-D at TJNAL (USA)**

- γp to produce states with exotic Quantum Numbers
- Focus on light states with $J^{PC} = 0^+, 1^+$, ...
- Complementary to CLEO-C focus on heavy states with $J^{PC}=0^{++}, 2^{++}$, ...
- Physics in 2009?

+ HESR at GSI Darmstadt $p p$ complementary, being proposed: physics in 2007?
Current Status of exotic QCD bound states

• Experimental
  – Far from clear! Looks messy now due to insufficient statistics
  – List of “glue ball” suspects
    • $\eta(1400)$ region
    • $f_0(1500)$
    • $f_J(1710)$
    • $\xi(2220)$ or $f_J(2220)$
  – Experimental results are contradictory
  – Sorting it out will be challenging!
The core run plan is intended to provide as much physics as possible with ~70% of the expected luminosity.

```
<table>
<thead>
<tr>
<th>Resonance</th>
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<th>Off</th>
<th>Scan</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
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<td>1.0</td>
<td>0.1</td>
<td>0.1</td>
<td>1.2</td>
</tr>
<tr>
<td>Y(2S)</td>
<td>1.0</td>
<td>0.1</td>
<td>0.1</td>
<td>1.2</td>
</tr>
<tr>
<td>Y(1S)</td>
<td>0.5</td>
<td>0.1</td>
<td>0.1</td>
<td>0.7</td>
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<tr>
<td>Total</td>
<td>2.5</td>
<td>0.3</td>
<td>0.3</td>
<td>3.1</td>
</tr>
</tbody>
</table>
```
Comments on Acp at FOCUS

• Since $D^+$ and $D^−$ (and similarly $D^0$ and $\bar{D}^0$) are not produced in equal numbers in FOCUS and E791, these experiments normalize all asymmetries to some known Cabibbo favored mode.

For example:

$$A_{CP}(KK\pi) = \frac{\eta(D^+) - \eta(D^-)}{\eta(D^+) + \eta(D^-)}$$

where

$$\eta(D^\pm) = \frac{N(D^\pm \rightarrow K^{\mp}K^{\pm}\pi^{\pm})}{N(D^\pm \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm})}$$

• $e^+e^−$ experiments need to worry about, $A_{+-}, A_{FB}$
Experimental constraints on y at Threshold

1. Time-dependent analyses are not possible, Are time dependent Analyses possible?

   Semileptonic: quadratic in x,y: not so sensitive wanted: \textit{linear in x or y}

2. Recall\(l\): (quantum-mechanically) entangled initial state

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

… so one can measure decay rates for CP-tagged decays

\[
R^L_\sigma = \frac{1}{\text{Br} (D^0 \rightarrow X \ell \nu)} \frac{\Gamma[\psi_L \rightarrow (D \rightarrow [CP]_\sigma)(D \rightarrow X \ell \nu)]}{\Gamma[\psi_L \rightarrow (D \rightarrow [CP]_\sigma)(D \rightarrow X)]}
\]

… which implies for y

\[
y \cos \phi = (-1)^L \sigma \frac{R^L_\sigma - 1}{R^L_\sigma}
\]

Separately sensitive to y; \(\phi=0\) in the Standard Model

D. Atwood, A.A. Petrov, hep-ph/0207165
\[ \delta_{K\pi} \text{ From } D^0 \rightarrow K^0 \pi^0 \]

- Measurement of ratio of \( D^0 \) rates into \( K^0_L \pi^0 \) and \( K^0_S \pi^0 \) can be used to disentangle the CF and DCS amplitudes:
  - \( K^0_L \) content of \( K^0 \) and \( K^0 \) is equal
  - \( K^0_L \) content of \( K^0 \) and \( K^0 \) is opposite in sign to \( K^0_S \)
  - Get DCS rate from interference between the two

\[
A = \frac{\Gamma(D^0 \rightarrow K^0_S \pi^0) - \Gamma(D^0 \rightarrow K^0_L \pi^0)}{\Gamma(D^0 \rightarrow K^0_S \pi^0) + \Gamma(D^0 \rightarrow K^0_L \pi^0)} = 0.06 \pm 0.05 \pm 0.05
\]

Very important measurement!

Uncertainty still too large to limit \( d_K \), but very interesting with 500 fb^{-1}
What if $\delta = 40^\circ$, the estimated maximum of the model of Falk, Nir & Petrov (99)? We see some overlap...

CLEO and FOCUS would be more consistent if $\delta > 90^\circ$...

Bergmann, Grossman et al (00).

My opinion: the errors are too large to draw any strong Conclusion at this time.