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

Ian Shipsey,
Purdue University
• 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

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

Charm as a Probe of New Physics:
  Mixing
  CP Violation & Rare Decays

Summary & Outlook
Charm Physics: the context

This Decade

Flavor Physics: is in “the sin2β era” akin to precision Z. Over constrain CKM matrix with precision measurements. Limiting factor: non-pert. QCD.

The Future

LHC may uncover strongly coupled sectors in the physics that lies beyond the Standard Model. The LC will study them. Strongly-coupled field theories are an outstanding challenge to theoretical physics. Critical need for reliable theoretical techniques & detailed data to calibrate them.

Example: The Lattice

Complete definition of pert & non. Pert. QCD. Matured over last decade, can calculate to 1-5% B,D,Υ,Ψ...

Charm can provide the data to calibrate QCD techniques

(See Peter Lepage’s lectures for details of Lattice QCD)
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

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

- **strong coupling in**: Physics beyond the Standard Model
  - Improved $V_{ub}, V_{cb}, V_{td}$ & $V_{ts}$
  - 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.
Goal for the decade: high precision measurements of $V_{ub}$, $V_{cb}$, $V_{ts}$, $V_{td}$, $V_{cs}$, $V_{cd}$, & associated phases. Over-constrain the “Unitarity Triangles”
- Inconsistencies $\rightarrow$ New physics!

Many experiments will contribute. Measurement of absolute charm branching ratios will enable precise new measurements at Bfactories/Tevatron to be translated into greatly improved CKM precision.
Importance of measuring absolute charm leptonic branching ratios: \( f_D \) & \( f_{Ds} \): \( V_{td} \) & \( V_{ts} \)

\[
\Delta M_d = 0.50 \text{ps}^{-1} \left[ \frac{\sqrt{B_{B_d} f_{B_d}}}{200 \text{MeV}} \right]^2 \left[ \frac{|V_{td}|}{8.8 \times 10^{-3}} \right]^2
\]

\[
\frac{\sigma (\rho)}{\rho} = 0.5 \frac{\sigma (\Delta M_d)}{\Delta M_d} \oplus \frac{\sigma (f_B \sqrt{B_{B_d}})}{f_B \sqrt{B_{B_d}}}
\]

\( \sigma \) & \( \rho \) from (ICHEP02) 1.2\% & ~15\% (LQCD)

\[
\frac{\Delta M_d}{\Delta M_s} \propto \left[ \frac{\sqrt{B_{B_d} f_{B_d}}}{\sqrt{B_{B_s} f_{B_s}}} \right]^2 \left[ \frac{|V_{td}|}{|V_{ts}|} \right]^2
\]

\( \rho + i \eta \) & \( 1 - \rho - i \eta \) & \( 1 \)

Lattice predicts \( f_B / f_D \) & \( f_{Bs} / f_{Ds} \) with small errors if precision measurements of \( f_D \) & \( f_{Ds} \) existed (they do not)

We could obtain precision estimates of \( f_B \) & \( f_{Bs} \) and hence precision determinations of \( V_{td} \) and \( V_{ts} \)

Similarly \( f_D / f_{Ds} \) checks \( f_B / f_{Bs} \)

\( \delta \frac{f_{Dc}}{f_{Dc}} \sim 14\% \)

\( \delta \frac{f_{Dc}}{f_{Dc}} \sim 100\% \)
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 $D \rightarrow \pi$ form factor in $D \rightarrow \pi l \nu$. Calibrate LQCD uncertainties.
2) Extract $V_{ub}$ at BaBar/Belle using calibrated LQCD calc. of $B \rightarrow \pi$ form factor.
3) But: need absolute $\text{Br}(D \rightarrow \pi l \nu)$ and high quality $d\Gamma (D \rightarrow \pi l \nu)/dE_\pi$ neither exist.
The Importance of Precision
Charm Absolute Branching Ratios I

\[ V_{cb} \text{ from zero recoil in } B \rightarrow D^{*}\ell^{+}\nu \]

CLEO hep-ex/0203032
Accepted for publication in PRL

\[ |V_{cb}| = (46.9 \pm 1.4 \pm 2.0 \pm 1.8) \times 10^{-3} \]

CLEO has single most precise \( V_{cb} \) by this technique

Stat: 3.0%  Sys 4.3% theory 3.8%

Dominant Sys: \( \varepsilon_{\pi} \text{ slow, form factors} \)
As B Factory data sets grow, and theory improves

\[ \frac{dB(D \rightarrow K\pi)}{dB(D \rightarrow K\pi)} \Rightarrow \frac{dV_{cb}}{V_{cb}} = 1.3\% \]
The Importance of Precision
Charm Absolute Branching Ratios II

\[ B^0 \rightarrow D_s^{(*)+}\pi^- \]  Extraction of \( V_{ub} \) ?

Dominated by \( b \rightarrow u \) transition
BABAR/Belle have signals
Theory error probably large

Experimental error dominated by \( B(D_s \rightarrow \phi\pi) \) which is known to 25%

\[ V_{ub}/V_{cb} \text{ from } \frac{\Gamma(\Lambda_b \rightarrow p\ell^-\nu)}{\Gamma(\Lambda_b \rightarrow \Lambda_c\ell^-\nu)} \]  at hadron machines requires:

\[ B(\Lambda_c \rightarrow pK\pi) \text{ poorly known: } 9.7% > B > 3.0\% \text{ at 90\% C.L} \]
The importance of precision absolute Charm BRs III

HQET spin symmetry test

\[ \frac{\Gamma(\bar{B}^0 \rightarrow D^{*+} h^-)}{\Gamma(\bar{B}^0 \rightarrow D^{+} h^-)} = 1 \]

since \( D^{*+} \rightarrow \pi^+ D^0 \) is most useful mode,

this compares \( D^0/D^+ \) absolute rates

Compare \( B^0 \rightarrow D^{(*)+} h^- \) and \( B^+ \rightarrow D^{(*)0} h^- \) rates to extract color suppressed amplitudes

Test factorization with \( B \rightarrow DD_s \)

Need Abs Br \( D_s \)
The importance of precision absolute Charm BRs IV

\[ BR_{SL} = B(b \to c \ell \nu), \] is low compared to theory. A possible explanation is that the \( c \) quark effective mass is low \( \to \) large decay rate for \( b \to c \bar{c}s(d) \)

\[ \to n_c = (n_c + n_{\bar{c}}) \] is negatively correlated to \( BR_{SL} \)

The simultaneous measurement of \( BR_{SL} \) and \( n_c \) can clarify the theoretical picture

\[ b \to c \ell \bar{\nu} + c\bar{u}d + c\bar{c}s \]

\( BR_{SL} \) and \( n_c \) are anti-correlated

To measure \( n_c \) need absolute charm BR’s

- QCD prediction:
  
As a function of the effective charm quark mass & scale at which QCD corrections are evaluated

Theory can accommodate present values but experimental errors are large \( \to \) test becomes more incisive if abs charm BR’s were known precisely

(Plot from Parodi at HF9)
The importance of precision absolute Charm BRs V

Test of the Standard Model.
Precision: $Z \rightarrow bb$ and $Z \rightarrow cc$ ($R_b$ & $R_c$) is systematically limited by knowledge of absolute charm branching ratios.

To understand the Higgs at LHC/LC
$B(H \rightarrow bb)$ $B(H \rightarrow cc)$
precision will depend on absolute charm branching ratios.
The Unity of Quark Flavor Physics

B decays

$Br(b \rightarrow ulvX)$
$Br(b \rightarrow clvX)$

Charm Physics (Semileptonic & hadronic)

$m_c, m_b, \mu^2_\pi$, Form Factors, F(1), duality...

Moment analysis
$(b \rightarrow s\gamma ...)$

Kaon Physics

$Br(K - \pi \nu \nu)$
$\varepsilon_K \sim \eta(1 - \rho)$

Radiative decays (future)

Oscillations

$\Delta m_d$
$\Delta m_s$

$B \rightarrow \pi \pi, \rho \pi, ...$

Theory

$V_{ub} / V_{cb}$
$V_{td} / V_{ts}$

Plot inspired By A. Stocchi

Charm Physics (Leptonic)

$B \rightarrow DK$

$a_{CP}(J / \Psi, K^0)$ + other charmonium
Charm discovery SLAC and BNL November 1974

$e^+e^- \rightarrow$ multihadron enhancement
$J/\Psi$ width $\ll 2$ MeV (beam width)

Goldhaber, Perl, Richter 1974
Charm Physics: 1974

\[ p + Be \rightarrow e^+ e^- \]

Broad band probe, clean final state

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FIG. 2. Mass spectrum showing the existence of \( J \). Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.
The $J/\Psi$ as a frontier

$\Psi'$s are narrow, insufficient energy to decay to open charm, (i.e. $D\bar{D}$) or $(c\bar{u})(\bar{c}u)$

$C=-1$ easy to produce with virtual photon, but decay into three gluons suppressed

Despite this, 88% of $J/\Psi$ decays are hadronic

(only the $\sim 12\%$ to $e^+e^-/\mu\mu$) used in $\sin2\beta$ measurements

Radiative $J/\Psi$ $Br\sim 6\%$ are very useful for glueball searches

SSI 2002  Lecture 1  I. Shipsey
Charmonium Spectroscopy
Open Charm Production at Threshold

D meson discovered 1976 Goldhaber/Trilling (LBL)

At $\Psi'' = \Psi(3S) = \Psi(3770)$

$\Psi'' \rightarrow D^0 \overline{D^0}, D^+ D^-$

$\Psi'' \rightarrow L = 1$

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

Beam constrained mass

Mark III

Events where both D’s are reconstructed

The role of the $\Psi(3770)$ in charm physics is analogous to the role of the $Y(4S)$ in B physics
Absolute Branching Ratio Measurements at the Y(4S) and \(\psi(3770)\)

\[ Br(D \rightarrow X) = \frac{\#X \text{ Observed}}{\text{efficiency} \times \#D's \text{ produced}} \]

In B decay absolute branching ratios are measured at the Y(4S)

\[ \int L dt \sigma_{Y(4S)} = N_{Y(4S)} \]

\[ N_{Y(4S)} \cdot Br(Y(4S) \rightarrow B\bar{B}) = 2N_B \]

\[ Br(Y(4S) \rightarrow B\bar{B}) = 1 \]

With sufficient statistics, it is possible to eliminate the Y(4S) Br assumption, and complications from the fraction of B\(^+\) B\(^+\) and B\(^0\) B\(^0\) at the Y(4S) by tagging (fully reconstructing one B in the event)

\[ Br(B \rightarrow X) = \frac{\#X \text{ Observed}}{\text{efficiency} \times \#B\text{tags}} \]

Full B reconstruction has a low efficiency \(\varepsilon\text{(tag)} \sim 0.7\%?\), but will become a staple as B Factory data sets grow. Similarly, charm branching ratios could be measured at the \(\psi(3770)\)
Absolute Charm Branching Ratios at Threshold

\[
\psi(3770) \rightarrow DD
\]

\[
Br(D \rightarrow X) = \frac{\#X \text{ Observed}}{\text{ efficiency} \times \#D\text{'s produced}}
\]

Where the \# of D’s produced
Is the \# of tags

The tag efficiency at the
\psi(3770) is expected
to be about 20\% as the
D has large branching
ratios to 2-body final states

\[
\sigma \psi(3770) = 10 \text{ nb} \ (\sim x 10 \sigma \ Y(4S))
\]
Open Charm Production

As we will see, the $\Psi(3770)$ is by far the best place to determine absolute charm branching ratios. But nobody has operated there since 1984. There are plans to change this situation.

<table>
<thead>
<tr>
<th>Experiment</th>
<th># D’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mark III</td>
<td>9.6 pb$^{-1}$</td>
</tr>
<tr>
<td>CLEO-c (proposed)</td>
<td>3 fb$^{-1}$</td>
</tr>
<tr>
<td>BESIII (proposed)</td>
<td>30 fb$^{-1}$</td>
</tr>
</tbody>
</table>

**Diagram:**
- **MARKIII**
- **BESII**
- **BESIII**
  - Construction
  - Engineer & phys. run

**Timeline:**
- 1984
- 1988
- 2000
- 2005
- 2010

**Graph:**
- Number of Event (Million)
  - J/psi
  - psi(2S)
  - psi(3770)
  - Ds Pairs(4100)
  - Psi Family
  - MARKIII
  - BESII
  - CLEOC
  - BESIII

**Text:**
- As we will see, the $\Psi(3770)$ is by far the best place to determine absolute charm branching ratios. But nobody has operated there since 1984. There are plans to change this situation.
Charm Hadrons

Heavy quark (Q) hadrons: Q spin decouples $\propto 1/m_Q$. Spin of Q and total spin $j$ of light quark are separately conserved quantum numbers.

$$J = j_{\text{light}} \pm 1/2 \ (\text{degenerate doublet})$$

Corrections go like $\Lambda_{\text{QCD}}/m_Q$

$$\Delta m = m(D^* - D) \sim 142 \text{ MeV}$$

$$\Delta m = m(B^* - B) \sim 46 \text{ MeV}$$

The same description works for heavy baryons

(cq)
Many of the charm facilities that have finished running but are still producing results, currently running facilities, and future facilities are listed above. Most charm physics facilities are also B physics facilities, exceptions are the fixed target experiments.
Charm Production near/at the Y(4S)

Non-resonant production to all hadrons u,d,s,c $\sigma_{cc} \approx 1$ nb

$\rightarrow D, D_s, \Lambda_c, \Xi_c \ldots$

$+ \sigma(B \rightarrow c) \approx 1$ nb $\quad 1 + 1 = 2$ nb

D’s move ~150 microns, but, energy of D’s is a priori unknown and the charm, and anti-charm hadron types are not strongly correlated

Reconstructing a $D^0$ does not mean the charm hadron in the event is a $D^0$, a $D^+$, $D_s$, $\Lambda_c$, $\Xi_c$, $\Omega_c$ or any other ground state or excited charm hadron is also a possibility

$\rightarrow$ absolute charm Br’s difficult

3 experiments, CLEO #c’s = 34x10^6 produced
BABAR, BELLE #c’ = x(5-6) CLEO now, by 2005 x40 CLEO
Charm Production at the $Z^0$

$\text{Br}(Z^0 \rightarrow cc) \sim 11\%$
$\rightarrow 3 \times 10^6$ c’s /LEP expt
$\rightarrow D, D_s, \Lambda_c, \Xi_c...$
$\rightarrow <p> \sim 40 \text{ GeV}$
$\rightarrow \text{Excellent reconstruction of Charm vertices}$

As at 10GeV, the flavors of charm anti-charm pairs produced in $Z^0$ decays are not correlated $\rightarrow$ absolute charm Br’s are difficult

Main LEP contributions to charm physics: (my opinion)
- electro-weak measurements: $R_c=(Z^0 \rightarrow cc)/(Z^0 \rightarrow \text{had})$
  $A_{FB}^c$ (charge asymmetry in $e^+e^- \rightarrow cc$)
See: http://lepewwg.web.cern.ch/LEPEWWG/
- c-quark fragmentation function
- $D_s$ decay constant

Will not discuss
In lecture
Fixed target experiments have long been at the frontier of charm physics
Detector scale typical, tiny front end
FOCUS: photoproduction

Garbincius 1995

$\sqrt{s} \rightarrow \text{GeV} \ 20 \ 200$

$\sim 10^8 \ c \text{ produced}$

$> 10^6 \ c \text{ reconstructed}$

Excellent:

- Vertex Resolution
- Particle ID & $\delta p_T/p_T$
- $D, D_s, \Lambda_c, \Xi_c$...
- Lifetimes. Mixing
- No absolute Br’s

(Also HERA)
FOCUS: close-up

Microvertex frame i projection

$\bar{\pi}^0 \rightarrow K^+\pi^-$ candidate
$M_{\pi\pi} = 1.86510.012$ GeV
$\sigma = 7.76$
$N/\sigma = 3.03$
Track points: 1 7

$\eta^0 \rightarrow K^+\pi^-\pi^+$ candidate
$M_{\pi\pi\pi} = 1.87010.012$ GeV
$\sigma = 24.71$
$N/\sigma = 1.97$
Track points: 3 4 8 2
Hadroproduction

- SELEX (E791) at FNAL
  $10^4 (10^5)$ c’s reconstructed
  * Millibarns at the Tevatron
    $\sim 10^{13}$ c’s/year Run II
    (also BTeV)
  * X 10 at LHC
  * HERA-B

Ryskin, Shabelski, Shuvaev, 2000

\[ \sigma (\mu b) \]

$\sqrt{s} \rightarrow$ GeV $100$ $10^3$ $10^4$

CC

BB

TeV
Charm at CDF

The hadronic B trigger a major milestone
~150 VME boards find and fit tracks in Silicon, offline accuracy in a 15µs pipeline

Secondary vertex level 2 trigger

$|D| > 100 \, \mu m$ (2 body)
Charm at CDF

\[ \Gamma(D \to KK)/\Gamma(D \to K\pi) = (11.17 \pm 0.48 \pm 0.98)\% \] (PDG: 10.83 ± 0.27)

Main systematic (8%): background subtraction (E687, E791, CLEO2)

\[ \Gamma(D \to \pi\pi)/\Gamma(D \to K\pi) = (3.37 \pm 0.20 \pm 0.16)\% \] (PDG: 3.76 ± 0.17)

Already comparable!

Cabbibo suppressed

Great potential if charm stays within the trigger

Bandwidth: expect \[10^7 D^0 \to K\pi\] reconstructed in RunII 2 fb\(^{-1}\)

CDF can address D mixing, DCPV and rare decays

Not absolute branching ratios
Summary of current & future charm particle data sources

<table>
<thead>
<tr>
<th></th>
<th>Fixed Target</th>
<th>e+ e- Collider</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E791</td>
<td>CLEO</td>
</tr>
<tr>
<td></td>
<td>SELEX</td>
<td>BABAR</td>
</tr>
<tr>
<td></td>
<td>FOCUS (E687)</td>
<td>BELLE</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beam Type</th>
<th>Charm</th>
<th>Hadronic</th>
<th>Photon</th>
<th>Off-resonance e+ e-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charm</td>
<td>(\sim 10^5)</td>
<td>(\sim 10^4)</td>
<td>(\sim 10^6)</td>
<td>(&gt; 10^6)</td>
</tr>
<tr>
<td>(\sigma t)</td>
<td>(\sim 40) fs</td>
<td>(\sim 20) fs</td>
<td>(\sim 40) fs</td>
<td>(\sim 140) fs</td>
</tr>
</tbody>
</table>

CDF 10^7 D \rightarrow K^-\pi^+ reconstructed in RunII

BTeV could have 10^9 D’s

F.T. expts. Measure the c-hadron decay time very precisely this is also crucial to isolate clean event samples

e+e- : higher relative production rate of charm compared to background, better mass resolution and great PID mean samples of comparable purity even though time resolution is X10 worse

CLEO-c 3 x10^6 tagged DD

\(\rightarrow X40\) CLEO By 2005
Lifetimes

Muon decay: \[ \Gamma_o = \frac{G_F^2 m_\mu^5}{192\pi^3} \]

Naïve spectator model for charm

\[ e, \mu, u\bar{d} \times 3 \text{ colors} \]

\[ \Gamma_c = (2 + 3)\Gamma_0 \quad \Gamma_o = \frac{G_F^2 m_c^5}{192\pi^3} |V_{cs}|^2 \]

Scaling from the muon:

\[ \tau_c = \frac{1}{5} \left( \frac{0.105}{1.5} \right)^5 \times 2.2 \times 10^{-6} = 7 \times 10^{-13} \text{s} \]

(700 fs)

\[ \tau(D^+) \sim 1,000 \text{ fs} \quad \tau(D^0) \sim 400 \text{ fs}. \] Not too bad. Including baryons lifetimes vary between \( \sim 100 \) and 1000 fs, \( \rightarrow \) non-spectator processes and higher order corrections
Charm Hadron Lifetimes

\[
\frac{Br}{\tau} = \Gamma \quad \text{Lifetime needed to compare Br(expt) to } \Gamma \text{ (theory)}
\]

Interpreted with O.P.E.

\[
\Gamma(H_c) = \Gamma_{\text{spect}} + O(1/m_c^2) + \Gamma_{PI,WA,WS}(H_c) + O(1/m_c^4)
\]

Spectator effects (PI,WA,WS) are \(O(1/m_c^3)\) but phase space enhanced

Note: hadrons behave more like free quarks the heavier the quark

See G. Bellini, I.I Bigi & P. Dornan

Gross features of the lifetime hierarchy can be explained
Lifetimes at Fixed Target Experiments

\[ t = 10^{-12} - 10^{-13} \text{ sec} \]

\[ 1000 - 100 \text{ femtoseconds} \]

\[ \sigma_t \sim 40 \text{ femtoseconds} \]

- Short flight path, need silicon
- \( L > N \sigma_L \) (and outside target)
- Reduced proper time:
  \[ t' = \frac{L}{\beta \gamma c} - N \sigma_L / \beta \gamma c \]
  to reduce acceptance corrections
- Acceptance checked with data (K_S)
- Systematics from acceptance &/or background

Acceptance vs. \( t \)

Acceptance vs. \( t' \)
Charm Meson Lifetimes

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

139433 ±520 evts

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

68274 ±360 evts

\( D^+ \rightarrow K^- \pi^+ \pi^+ \)

109877 ±385 evts

\( D^0, D^+ \) Signal

\( D^0, D^+ \) Lifetime fits
Lifetimes at $e^+e^-$ colliders

* Silicon vertex detectors $\Rightarrow$ charm lifetimes
But poorer time resolution $\sim$ 140 fsec (CLEO)
• Needs average IP position
• Uses 2-D (or 1-D) decay length
• Needs good knowledge of mass and t resolutions
• Complicated fits using parameterized resolution and background functions
• Systematics from vertexing, resolutions and fit biases

Y(4S) stationary
L $\langle D, \Xi_c^+ \rangle$ 150 $\mu$m

$\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$

PRD 650311
2002

$\tau(\Xi_c^+) = 503 \pm 47 \pm 18$ fs
New precise measurements of $\tau(D^0)$, $\tau(D^+)$, $\tau(D_s)$ from FOCUS

$\tau(D^0) = 409.6 \pm 1.1(stat) \pm 1.5(sys)$

$\tau(D^+) = 1039.4 \pm 4.3(stat) \pm 7.0(sys)$

$\frac{\tau_{D^+}}{\tau_{D^0}} \approx 2.583 \pm 0.023$

$\tau_{D^0} = 410.5 \pm 1.5$

Abs. Exclusive semileptonic decays key to interpreting lifetime ratio

$\frac{\Gamma(D^0 \to eX)}{\Gamma(D^+ \to eX)} = \frac{B(D^0 \to eX)}{B(D^+ \to eX)} \times \frac{\tau(D^+)}{\tau(D^0)} = 1.01 \pm 0.13$

Large observed lifetime ratio must arise due to destructive interference in hadronic diagrams contributing only to $D^+$ decays (see later)

Note: lifetimes much better known than absolute BR’s

PDG2002
**Lifetime Summary I**

<table>
<thead>
<tr>
<th>Lifetime</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau(D^0)$</td>
<td>$411.7 \pm 1.3 \text{ fs}$</td>
</tr>
<tr>
<td>$\tau(D^+)$</td>
<td>$1041.5 \pm 6.2 \text{ fs}$</td>
</tr>
<tr>
<td>$\tau(D_s)$</td>
<td>$501.7 \pm 6.1 \text{ fs}$</td>
</tr>
<tr>
<td>$\tau(\Lambda_c)$</td>
<td>$199.7 \pm 3.3 \text{ fs}$</td>
</tr>
<tr>
<td>$\tau(\Xi^+_c)$</td>
<td>$422.3^{+20.1}_{-18.7} \text{ fs}$</td>
</tr>
<tr>
<td>$\tau(\Xi^0_c)$</td>
<td>$106.3^{+9.2}_{-7.8} \text{ fs}$</td>
</tr>
<tr>
<td>$\tau(\Omega_c)$</td>
<td>$73.6^{+11.8}_{-12.1} \text{ fs}$</td>
</tr>
</tbody>
</table>

Updated after ICHEP02

\[
\frac{\tau(D^+)}{\tau(D^0)} = 2.53 \pm 0.02 \quad \text{P.I.(-)}
\]

\[
\frac{\tau(D_s)}{\tau(D^0)} = 1.22 \pm 0.02 \quad \text{W.A. or ??}
\]

\[
\frac{\tau(\Lambda_c)}{\tau(D^0)} = 0.49 \pm 0.01 \quad \text{W.S./P.I.(-)}
\]

\[
\frac{\tau(\Xi^+_c)}{\tau(\Lambda_c)} = 2.11 \pm 0.14 \quad \text{W.S.P.I.(±)}
\]

To interpret this important to check $\Gamma(D_s \rightarrow eX)$ / $\Gamma(D^0 \rightarrow eX)$
But absolute $B(D_s \rightarrow eX)$ is only known to 63%!

**Shipsey Averages**

- $D^+ 6\%$, $D^0 3\%$, $D_s 2\%$, $\Lambda_c 2\%$, $\Xi^0 10\%$, $\Xi^+_c 6\%$, $\Omega_c 15\%$

**some lifetimes known as precisely as kaon lifetimes**

**Lifetimes span 1 order of magnitude**
Charm quarks are much more influenced by the hadronic environment than are beauty quarks.

Very precisely determined lifetimes. The agreement with theory is still qualitative.

Important message: errors on lifetimes are not a limiting factor in our ability to calculate absolute rates. The limiting factor is errors on absolute branching ratios.
D Nonleptonic Decays

Nonleptonic decays dominate the total rate

\[
D^+ (c\bar{d}) : \tau_+ = 1042.7 \pm 6.9 \text{ fs} \\
D^0 (c\bar{u}) : \tau_0 = 410.5 \pm 1.5 \text{ fs}
\]

\[\tau_+ / \tau_0 \approx 2.5\]

Quarks or hadrons? ……in between

Compare to kaons and B-mesons:

\[
K^+ (\bar{s}u) : \tau_+ = 12390 \pm 20 \text{ ps} \\
K^0 (\bar{s}d) : \tau_0 = 178.7 \pm 0.16 \text{ ps}
\]

\[\tau_+ / \tau_0 \approx 70\] Hadrons

\[
B^+ (\bar{b}u) : \tau_+ = 1655 \pm 24 \text{ fs} \\
B^0 (\bar{b}d) : \tau_0 = 1540 \pm 24 \text{ fs}
\]

\[\tau_+ / \tau_0 \approx 1.07\] quarks
The lifetime hierarchy 
(quark diagram level)

B decays: small BRs to 2-body final states (phase space)
2-body decays dominate D decays (multi-body decays found to be quasi 2 body) →

Is the $D^0 D^+$ lifetime hierarchy understandable in terms of 2 body hadronic decays?

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

$BR \sim 3.83\%$

$A \propto \sqrt{\frac{BR}{\tau}} = 1$

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

$D^0 \rightarrow \bar{K}^0 \pi^0$

$BR \sim 2.11\%$

$A = 0.74$

$D^+ \rightarrow \bar{K}^0 \pi^+$

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

For the $D^0$ ($D^+$) the two states are distinct (identical)
100% Destructive interference predicts: $A = 1 - 0.74 = 0.26$
Measure: $A = 0.54$
Difference due to hadronic final state interactions

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.....and at the hadronic level

Simple factorization picture describes 2 body hadronic decays established for B’s. For charm sizeable final state interactions are the norm.

\[ A(D^0 \rightarrow K^- \pi^+) = \sqrt{\frac{2}{3}} A_{1/2} + \sqrt{\frac{1}{3}} A_{3/2} \]

\[ A(D^0 \rightarrow \bar{K}^0 \pi^0) = -\frac{1}{\sqrt{3}} A_{1/2} + \sqrt{\frac{2}{3}} A_{3/2} \]

\[ A(D^+ \rightarrow \bar{K}^0 \pi^+) = \sqrt{3} A_{3/2} \]

\[ |A_{1/2} + A_{3/2}|^2 = |A_{1/2}|^2 + |A_{3/2}|^2 + 2|A_{1/2}|A_{3/2}| \cos(\delta_{3/2} - \delta_{1/2}) \]

\[ |A_{1/2} + A_{3/2}|^2 = |A_{1/2}|^2 + |A_{3/2}|^2 \]

\[ |A(D^0 \rightarrow K^- \pi^+)|^2 + |A(D^0 \rightarrow \bar{K}^0 \pi^0)|^2 = |A_{1/2}|^2 + |A_{3/2}|^2 \]

\[ |A(D^+ \rightarrow \bar{K}^0 \pi^+)|^2 = 3|A_{3/2}|^2 \]

\[ |A_{3/2}|/|A_{1/2}| = 0.37 \pm 0.03 \quad \delta = (\delta_2 - \delta_0) = 90^\circ \pm 7^\circ \]

Many similar cases. Substantial modification of hadronic 2-body BR’s due to FSI.

The presence of strong phases between amplitudes is an important ingredient in mixing studies and in CP violation.
Charm branching ratios

$Br = \frac{\Gamma}{\tau}$

Most branching ratios in contrast to lifetimes are not well known

We have just seen that $\tau$ is measured very precisely

Key charm decay modes used to normalize B physics

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mode</th>
<th>PDG (%)</th>
<th>Error(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0$</td>
<td>$K^-\pi^+$</td>
<td>3.83±0.09</td>
<td>2.3</td>
</tr>
<tr>
<td>$D^+$</td>
<td>$K^-\pi^+\pi^+$</td>
<td>9.0±0.6</td>
<td>6.7</td>
</tr>
<tr>
<td>$D_s$</td>
<td>$\phi\pi^+$</td>
<td>3.6±0.9</td>
<td>25</td>
</tr>
<tr>
<td>$\Lambda_c$</td>
<td>$pK^-\pi^+$</td>
<td>9.7$&gt;\beta&gt;3.0$</td>
<td>@90% c.l</td>
</tr>
<tr>
<td>J/$\psi$</td>
<td>$\mu^+\mu^-$</td>
<td>5.88±0.10</td>
<td>1.7</td>
</tr>
</tbody>
</table>

$Br(D \rightarrow X) = \frac{\#X \text{ Observed}}{\text{efficiency} \times \#D\text{'s produced}}$

Because #D’s produced is not well known
Measurement of $B(D^0 \rightarrow K^-\pi^+)$

- **Method:**
- Detect $D^{*+} \rightarrow \pi^+ D^0$, $D^0 \rightarrow K^-\pi^+$
  (CLEO & ALEPH Use same technique)
- compare to:
  $D^{*+} \rightarrow \pi^+ D^0$, $D^0 \rightarrow \text{unobserved}$
- **Problem:** Systematic error due to background extrapolation

<table>
<thead>
<tr>
<th>Source</th>
<th>$B$ (%)</th>
<th>Error(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO</td>
<td>3.82±0.07±0.12</td>
<td>3.6</td>
</tr>
<tr>
<td>ALEPH</td>
<td>3.82±0.09±0.12</td>
<td>3.8</td>
</tr>
<tr>
<td>PDG</td>
<td>3.83±0.09</td>
<td>2.3</td>
</tr>
</tbody>
</table>

$D^{*+} \rightarrow D^0\pi^+ \quad Q \sim 6\text{MeV}$

$225 < p_\pi < 250$
$275 < p_\pi < 300$
$325 < p_\pi < 350$
$375 < p_\pi < 400$

$\alpha$ is $\angle$ between thrust axis & slow $\pi^+$
(4 of 8 intervals shown)

(Thrust is a measure of the direction of the primary quark pair in the event)
**B(D^+ → K^-π^+π^+)**

<table>
<thead>
<tr>
<th>B (%)</th>
<th>Error (%)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.3±0.6±0.8</td>
<td>10.8</td>
<td>CLEO</td>
</tr>
<tr>
<td>9.1±1.3±0.4</td>
<td>14.9</td>
<td>MKIII</td>
</tr>
<tr>
<td>9.1±0.7</td>
<td>7.7</td>
<td>PDG</td>
</tr>
</tbody>
</table>

- **Method (CLEO):** Measure:
  Assume this ratio is of Strong decays is given by isospin symmetry
  (this bootstrap method can never yield a measurement of B(D^+ → K^-π^+π^+) more accurate than B(D^0 → K^-π^+)

- **Method (MKIII):** ψ′′ → D^+D^- full reconstruction, limited by size of data sample
  The determination of B(D^+ → φπ^+), which has a 25% error also bootstraps on B(D^0 → K^-π^+)}
How can we do better? Recall:
Absolute Charm Branching Ratios at Threshold

\[ \psi(3770) \rightarrow DD \]

\[ Br(D \rightarrow X) = \frac{\#X \text{ Observed}}{\text{efficiency} \times \#D's \text{ produced}} \]

Where the \# of D’s produced
Is the \# of tags

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Unique Opportunities at Charm Thresholds

- Unique event properties
  - Only DD not DDx produced
  - Can get D^o D^o, D^+ D^-, D_s D_s, Λ_c Λ_c
  - Probably other charmed baryons as well (not yet measured)

- Large cross sections
  \( \sigma(D^o D^o) = 5.8 \text{ nb} \)
  \( \sigma(D^+ D^-) = 4.2 \text{ nb} \)
  \( \sigma(D_s D_s) = 0.5 \text{ nb} \)

\[ \psi(3770) \rightarrow DD \]
\[ \sqrt{s} \sim 4140 \rightarrow D_s D_s \]

\( R \) (units of \( \sigma(\mu^+ \mu^-) \))

\( \sigma(\mu^+ \mu^-) = 5.4 \text{ nb at 4 GeV} \)
\( \psi(3770) \) events are simple

**\( \psi(3770) \) event:**

\[ D^0 \rightarrow K^- \pi^+ \quad D^0 \rightarrow K^+ e^- \nu \]

- Charm events produced at threshold are extremely clean
- Large \( \sigma \), low multiplicity
- Pure initial state: no fragmentation
- Signal/Background is optimum at threshold

- Double tag events are pristine
  - These events are key to making absolute \( Br \) measurements
  - Neutrino reconstruction is clean
  - Quantum coherence aids D mixing & CP violation studies

**But:** D’s don’t move

---

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CESR-c & CLEO-c

One day scan of the $\Psi'$:
(1/29/02)

$\Psi' \rightarrow J/\Psi \pi \pi$

$J/\Psi \rightarrow \mu \mu$

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>$L \left(10^{32} \text{ cm}^{-2} \text{ s}^{-1}\right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 GeV</td>
<td>2.0</td>
</tr>
<tr>
<td>3.77 GeV</td>
<td>3.0</td>
</tr>
<tr>
<td>4.1 GeV</td>
<td>3.6</td>
</tr>
</tbody>
</table>

$\Delta E_{\text{beam}} \sim 1.2 \text{ MeV at } J/\psi$
CLEO-c Proposed Run Plan

2002: Prologue: Upsilon ~1-2 fb^{-1} each at Y(1S), Y(2S), Y(3S),…
Spectroscopy, matrix element, $\Gamma_{ee}, \eta_B h_b$
10-20 times the existing world’s data (Fall 2001- Fall 2002)

2003: $\psi(3770)$ – 3 fb^{-1}
30 million DD events, 6 million tagged D decays
(310 times MARK III)

2004: $\sqrt{S} \sim 4140$ MeV – 3 fb^{-1}
1.5 million $D_s D_s$ events, 0.3 million tagged $D_s$ decays
(480 times MARK III, 130 times BES)

2005: $\psi(3100)$, 1 fb^{-1} –1 Billion J/$\psi$ decays
(170 times MARK III, 20 times BES II)

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83% of 4π
Kaon ID with 0.2% π fake @0.9 GeV

CLEO III Detector → CLEO-c Detector

93% of 4π
σ_p/p = 0.35% @1 GeV
dE/dx: 5.7% π @ minI

93% of 4π
σ_E/E = 2% @1 GeV
= 4% @100 MeV

Trigger: Tracks & Showers
Pipelined
Latency = 2.5 μs

Data Acquisition:
Event size = 25 kB
Throughput < 6 MB/s

85% of 4π
For p > 1 GeV
$\psi(3770)$ events: simpler than $Y(4S)$ events

$\psi(3770)$ event:

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

* CLEO III state of the art detector, well understood
* CLEO-c Replace Si $\rightarrow$ low mass drift chamber (under construction)
* The demands of doing physics at 3-5 GeV are easily met by the existing detector.
Tagging Technique, Tag Purity @ Threshold CLEO-c simulation

- $\psi(3770) \rightarrow DD$  \hspace{1cm} $\sqrt{s} \sim 4140 \rightarrow D_sD_s$

Charm mesons have many large branching ratios (~1-15%)  
low multiplicity: high reconstruction efficiency  

$\rightarrow$ high net tagging efficiency $\sim 20\%$ !

In 1 year At Each $\sqrt{s}$

Anticipate 6M D tags 300K $D_s$ tags:

$D \rightarrow K\pi$ tag. $S/B \sim 5000/1$ !  

$D_s \rightarrow \phi\pi$ ($\phi \rightarrow KK$) tag. $S/B \sim 100/1$

Beam constrained mass

Log scale!  
Log scale!
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 (fb)</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
Leptonic Decays $\rightarrow$ Decay Constants

\[
M = \frac{G_F}{\sqrt{2}} V_{Qq} \langle 0 \left| \bar{J}_\mu \right| M \rangle \bar{u}(k, \sigma) \gamma^\mu (1 - \gamma_5) \nu(p, s)
\]

the meson decay constant $f_M$ measures the probability for the $Q$ and $q$ to have zero separation the annihilation probability is $\propto$ to wave function overlap

\[
\Gamma(M_{Qq} \rightarrow \ell^- \nu) = \frac{G_F^2}{8\pi} \left| V_{qQ} \right|^2 f_M^2 M m_\ell^2 \left( 1 - \frac{m_\ell^2}{M^2} \right)^2
\]

$\mathbf{q}^2 = m_W^2 = M^2$

Fixed

(Pseudoscalar Meson)

\[
0 \left| \bar{q} \gamma_\mu \gamma_5 Q \right| P(p) \rangle = if_M p_\mu
\]

(For a meson with two heavy quarks) (Rosner)
Decay constants are important in many processes.
\[ \Gamma(M_{Qq} \rightarrow \ell^- \bar{\nu}) = \frac{G_F^2}{8\pi} |V_{qQ}|^2 f_M^2 Mm_{\ell}^2 \left(1 - \frac{m_{\ell}^2}{M^2}\right)^2 \]

Decay is forbidden as \( m_{\ell} \rightarrow 0 \)

\[ \frac{\Gamma(\pi^+ \rightarrow e^+ \nu_e)}{\Gamma(\pi^+ \rightarrow \mu^+ \nu_\mu)} \approx 10^{-4} \]

\[ \Gamma(D_s^+ \rightarrow e^+ \nu_e): \Gamma(D_s^+ \rightarrow \mu^+ \nu_\mu): \Gamma(D_s^+ \rightarrow \tau^+ \nu_\tau) \approx 10^{-5}:1:10 \]

\[ \Gamma(D^+ \rightarrow \ell^+ \nu_{\ell}) \propto |V_{cd}|^2 \approx (0.22)^2 \]

\[ \Gamma(D_s^+ \rightarrow \ell^+ \nu_{\ell}) \propto |V_{cs}|^2 \approx (0.97)^2 \]

\[ \Gamma(B^+ \rightarrow \ell^+ \nu_{\ell}) \propto |V_{ub}|^2 \approx (0.003)^2 \]
Estimate of the leptonic Br’s using $f_{Bs} = f_{Bs}=200 \text{ MeV}$
$f_{Ds} = 260 \text{ MeV}$, $f_{D} = 220 \text{ MeV}$

<table>
<thead>
<tr>
<th></th>
<th>$B(e\nu)$</th>
<th>$B(\mu\nu)$</th>
<th>$B(\tau\nu)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+$</td>
<td>$8.2 \times 10^{-9}$</td>
<td>$4.2 \times 10^{-4}$</td>
<td>$1.1 \times 10^{-3}$</td>
</tr>
<tr>
<td>$D_s^+$</td>
<td>$7.5 \times 10^{-8}$</td>
<td>$5.7 \times 10^{-3}$</td>
<td>$5.5 \times 10^{-2}$</td>
</tr>
<tr>
<td>$B^+$</td>
<td>$7.5 \times 10^{-12}$</td>
<td>$3.2 \times 10^{-7}$</td>
<td>$7.1 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>$1.2 \times 10^{-4}$</td>
<td>$99.99%$</td>
<td></td>
</tr>
<tr>
<td>$K^+$</td>
<td>$1.6 \times 10^{-5}$</td>
<td>$63.5%$</td>
<td></td>
</tr>
</tbody>
</table>

At first sight it is remarkable that: $B(D_s^+ \to \mu^+\nu_\mu) \ll B(K^+ \to \mu^+\nu_\mu)$

While $(f_M^2 M) \to \text{constant}$

$\Gamma(\text{total}) \propto M^5$ so leptonic branching ratio becomes smaller as $M^\uparrow$

If we compare rates instead of branching ratios:

The leptonic rate is higher for the $D_S$ than for the $K^+$

$$\Gamma(K^+ \to \mu^+\nu_\mu) = 5.13 \times 10^7 \text{ s}^{-1}$$

$$\Gamma(D_s^+ \to \mu^+\nu_\mu) = 6.9 \times 10^9 \text{ s}^{-1}$$

$$\Gamma(D_s^+ \to \tau^+\nu_\mu) = 6.6 \times 10^{10} \text{ s}^{-1}$$
\[ \Gamma(D_q^+ \rightarrow \ell \nu) = \frac{1}{8\pi} G_F^2 M_{D^+_q} m_{\ell}^2 \left(1 - \frac{m_{\ell}^2}{M_{D^+}^2}\right) f_{D^+}^2 |V_{cq}|^2 \]

\[ \mathcal{B}(D^+ \rightarrow \ell \nu)/\tau_{D^+} = f_{D^+} |V_{cd}| \]

\[ \mathcal{B}(D_s^+ \rightarrow \ell \nu)/\tau_{D_s} = f_{D_s} |V_{cs}| \]

* Charm meson lifetimes known 0.3-2%
* 3 generation unitarity

\[ V_{cs}, (V_{cd}) \text{ known to } 0.1\% (1.1\%) \Rightarrow f_{D^+} f_{D_s} \]
Example: $f_{Ds}$ near/at the Y(4S)

Signal is a single muon, or single muon + photon tag, very difficult at a hadron machine.

- Search for $D_s^{*} \rightarrow D_s \gamma$, $D_s \rightarrow \mu \nu$
  - Directly detect $\gamma$, $\mu$, Use hermeticity of detector to reconstruct $\nu$
  - Plot mass difference but Backgrounds are LARGE!
- Use $D_s \rightarrow e \nu$ (rate~0) for bkgd determination but precision limited by systematics
- Compare rate to $D_s \rightarrow \phi \pi$, but $Br(D_s \rightarrow \phi \pi)$ not well known-25% error!
  - $FDs$ Error $\sim 17\%$ now (CLEO)

CLEO signal 4.8fb$^{-1}$

$\Delta M = M(\mu \nu \gamma) - M(\mu \nu)$ GeV/c

$f_{Ds} = 280 \pm 19 \pm 28 \pm 34$ (MeV)
$f_{D^+} < 290 \text{ MeV} @ 90\% \text{ CL}$ (Mark III)

$f_{D_s}$ has been measured by several groups, using $D_s \rightarrow \mu \nu$
There are also measurements from LEP using $D_s \rightarrow \tau^+ \nu$
which I have not included in the Table or average. (Inclusion
Of these extra modes requires
The assumption of
Lepton universality, which
 Might be interesting to test.
Note large correlated common
systematic error
from $B(D_s \rightarrow \phi \pi)$

14% relative error
Decay Constant at Threshold (CLEO-c simulation)

- Fully reconstruct 1 D “the tag”
- Require one additional charged track and no additional photons
- Compute MM^2 Peaks at zero for \( D \to \mu^+ \nu \) decay.
  - No need to identify muon-helps systematic error
  - Can identify electrons to check background level
  - Expect resolution of \( \sim M_{\pi^0} \)

\[ \sqrt{s} \sim 4140 \rightarrow D_s D_s \]

\[ D_s \rightarrow \mu \nu \]

\[ \frac{\delta f_{D_s}}{f_{D_s}} \approx 1.7\% \]

(Now: \( \pm 14\% \))
Decay Constant at Threshold (CLEO-c simulation)

$$\psi(3770) \rightarrow DD$$

CLEO-c simulation

$$D^+ \rightarrow K_L \mu \nu$$

$$D^+ \rightarrow \tau \nu$$

$$\frac{\delta f_D}{f_D} \approx 2.3\%$$

(1 year)

Now: upper limit exists
Improved knowledge of the decay constant yields precision determination of $V_{td}$

\[
\Delta M_d = 0.50 \text{ps}^{-1} \left[ \frac{\sqrt{B_{B_d} f_{B_d}}}{200 \text{MeV}} \right]^2 \left[ \frac{|V_{td}|}{8.8 \times 10^{-3}} \right]^2
\]

\[
\frac{\sigma(\rho)}{\rho} = 0.5 \frac{\sigma(\Delta M_d)}{\Delta M_d} \oplus \frac{\sigma(f_B \sqrt{B_{B_d}})}{f_B \sqrt{B_{B_d}}}
\]

(LQCD) $\sim 15\%$

\[
\delta f_D \approx 2.3\%
\]

→ Lattice predicts $f_B/f_D$ with small errors
→ precision measurement of $f_D$
→ precision estimates of $f_B$
→ precision determination of $V_{td}$
Additional Slides
Summary of Decay Constant Reach at CLEO-c

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Signal</th>
<th>$\tau\nu/\mu\nu$</th>
<th>Bkgd</th>
<th>$\delta B/B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_s^+ \to \mu\nu$</td>
<td>1221</td>
<td>165</td>
<td>87</td>
<td>3.2%</td>
</tr>
<tr>
<td>$D_s^+ \to \tau\nu$</td>
<td>1740</td>
<td>0</td>
<td>114</td>
<td>2.4%</td>
</tr>
<tr>
<td>$D^+ \to \mu\nu$</td>
<td>672</td>
<td>30</td>
<td>60</td>
<td>3.8%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\frac{1}{2} \Delta B/B$</th>
<th>$\frac{1}{2} \Delta \tau/\tau$</th>
<th>$\Delta V_{cq}/V_{cq}$</th>
<th>CLEO-c $\delta f/f$</th>
<th>PDG $\delta f/f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{Ds}$</td>
<td>$D_s^+ \to \mu\nu$</td>
<td>1.6%</td>
<td>1%</td>
<td>0.1%</td>
<td>1.9%</td>
</tr>
<tr>
<td>$f_{Ds}$</td>
<td>$D_s^+ \to \tau\nu$</td>
<td>1.2%</td>
<td>1%</td>
<td>0.1%</td>
<td>1.6%</td>
</tr>
<tr>
<td>$f_{D^+}$</td>
<td>$D^+ \to \mu\nu$</td>
<td>1.9%</td>
<td>0.6%</td>
<td>1.1%</td>
<td>2.3%</td>
</tr>
</tbody>
</table>

(not updated for improved lifetimes)
**$D_s$ Meson Lifetime**

$D_s \rightarrow \phi \pi$ signal

Lifetime $506 \pm 8$ fs

5668 ± 95 events (50% FOCUS data)

PDG 2002 $490 \pm 9$ fs

**New at ICHEP**

Preliminary

\[
\frac{\tau(D_s)}{\tau(D^0)} = 1.23 \pm 0.02
\]

To interpret this important to check $\Gamma(D_s \rightarrow eX)$

But absolute $dBR/BR = 63%$

Theoretical prediction (Bigi Uraltsev)

1.00-1.07 (no WA)

0.8-1.27 (different process interference)

4 x statistics including
Lifetime Summary

We know the charm meson lifetimes with extraordinary precision, in the best cases <1/2% (major improvement in the past year: FOCUS). Non spectator effects are similar in size to the spectator contributions, the lifetime hierarchy is consistent with the OPE formalism, but debatable if OPE should apply to c-quark (mass). More stringent tests of this idea would be provided if precise absolute semileptonic branching ratios of \(D_s, \Lambda_c, \Xi^0, \Xi^+_c, \Omega_c\) were known.
Charmed Baryon Lifetimes

- Unlike charmed mesons, decays of charmed baryons are not color or helicity suppressed, this results in a reduced lifetime relative to

\[
\tau_{\text{average}}(\Xi_c^+) = 422^{+20}_{-19} \text{ fs}
\]

\[
\tau_{\text{average}}(\Lambda_c^+) = 200 \pm 3 \text{ fs}
\]

\[
\Gamma(\Xi_c^+) < \Gamma(\Lambda_c^0) < \Gamma(\Xi_c^0) \sim \Gamma(\Omega_c^0)
\]

\( D_s^\pm - D^\pm \) mass difference

- Both \( D \rightarrow \phi \pi \) (\( \phi \rightarrow KK \))
- \( \Delta m = 99.28 \pm 0.43 \pm 0.27 \) MeV
  - PDG: 99.2 \pm 0.5 MeV
  - (CLEO2, E691)
- Systematics dominated by background modeling

![Graph showing KK mass distribution with peaks at 1.90 GeV/c^2 and 1.95 GeV/c^2 with ~1400 events and ~2400 events, CDF Run II Preliminary, 11.6 pb^{-1}, Unbinned likelihood fit projected]
D Hadronic decays

Simple factorization picture describes 2 body hadronic decays established for B’s. For charm sizeable final state interactions are the norm.

\[ A(D^0 \rightarrow \pi^- \pi^+) = \frac{1}{\sqrt{3}} (\sqrt{2}A_0 + A_2) \]

\[ A(D^0 \rightarrow \pi^0 \pi^0) = \frac{1}{\sqrt{3}} (-A_0 + \sqrt{2}A_2) \]

\[ A(D^+ \rightarrow \pi^0 \pi^+) = \frac{\sqrt{3}}{2} A_2 \]

Isospin decomposition (same as B→ππ, K→ππ)

\[ \delta \]

\[ A_I = A_I e^{i \delta} \]

\[ |A_0 + A_2|^2 = |A_0|^2 + |A_2|^2 + 2|A_0||A_2|\cos(\delta_2 - \delta_0) \]

\[ |A(D^0 \rightarrow \pi^- \pi^+)|^2 + |A(D^0 \rightarrow \pi^0 \pi^0)|^2 = |A_0|^2 + |A_2|^2 \]

\[ |A(D^+ \rightarrow \pi^0 \pi^+)|^2 = \frac{3}{2} |A_2|^2 \]

Find:

\[ |A_2| / |A_0| = 0.63 \pm 0.13 \quad \delta = (\delta_2 - \delta_0) = 81^\circ \pm 10^\circ \]
\[ \mathcal{B}(D_s^+ \rightarrow \phi \pi^+) \]

<table>
<thead>
<tr>
<th>( \mathcal{B} ) (%)</th>
<th>Error(%)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.59( \pm )0.77( \pm )0.48</td>
<td>25.3</td>
<td>CLEO</td>
</tr>
<tr>
<td>3.6( \pm )0.9</td>
<td>25.0</td>
<td>PDG</td>
</tr>
</tbody>
</table>

- **Method:** Reconstruct
  \[ \mathcal{B} \rightarrow D^{*+}D_s^{-}, \quad D_s^{-} \rightarrow \gamma D_s^{-} \text{ or } \]
  \[ D^{*+} \rightarrow \pi^+D^0 \]

- **Observe signal both with \& without explicit** \( D_s \) or \( D^0 \) reconstruction

- **Measure** \( \mathcal{B}(D_s \rightarrow \phi \pi^+)/\mathcal{B}(D^0 \rightarrow K^-\pi^+) \)
\[ \Lambda_c^+ \rightarrow pK^-\pi^+ \]

- Lower limit: Measure p and \( \Lambda \) yield in B decays and assume all such production is due to \( \bar{B} \rightarrow \Lambda_c^+\bar{N}X \). Find \( B = (4.14 \pm 0.91)\% \)

- Upper limit: Measure \( \Lambda_c \rightarrow \Lambda \ell \nu \), and assume that \( \Lambda \) saturates the rate (no \( \Sigma \), for example). Find \( B = (7.7 \pm 1.5)\% \)

- Conclude: \( 9.7\% > B > 3.0\% \) @ 90% c. l.
\[ J/\psi \rightarrow \mu^+\mu^- \]

<table>
<thead>
<tr>
<th>B (%)</th>
<th>Error(%)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.84\pm0.06\pm0.10</td>
<td>2.0</td>
<td>BES</td>
</tr>
<tr>
<td>6.08\pm0.33</td>
<td>5.4</td>
<td>BES</td>
</tr>
<tr>
<td>5.88\pm0.10</td>
<td>1.7</td>
<td>PDG</td>
</tr>
</tbody>
</table>

- Systematic error is the limitation. Completely correlated between the two BES measurements.
- Currently, best way to determine b yields at hadron colliders
Charm Production near/at the Y(4S)

\[ L_{\text{peak}} \times 10^{33} \text{ cm}^{-2} \text{s}^{-1} \int L dt \#B' s \times 10^6 \]

<table>
<thead>
<tr>
<th>Accelerators at the Y(4S)</th>
<th>BB/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>CESR/CLEO(*)</td>
<td>1.3</td>
</tr>
<tr>
<td>KEKB/Belle</td>
<td>7.2</td>
</tr>
<tr>
<td>PEPII/BABAR</td>
<td>4.6</td>
</tr>
</tbody>
</table>

(*) CLEO
No longer Operating at Y(4S)
Belle/ BaBar
ON/OFF
June 13 ‘02