Future of Charm Physics In 2005 and Beyond

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http://www-hep.colorado.edu/~ewv/focus-public/cleo_talk.ps

Workshop on B Physics at the Tevatron
Run II and Beyond
Fermilab
February 26, 2000

Charm Physics Issues

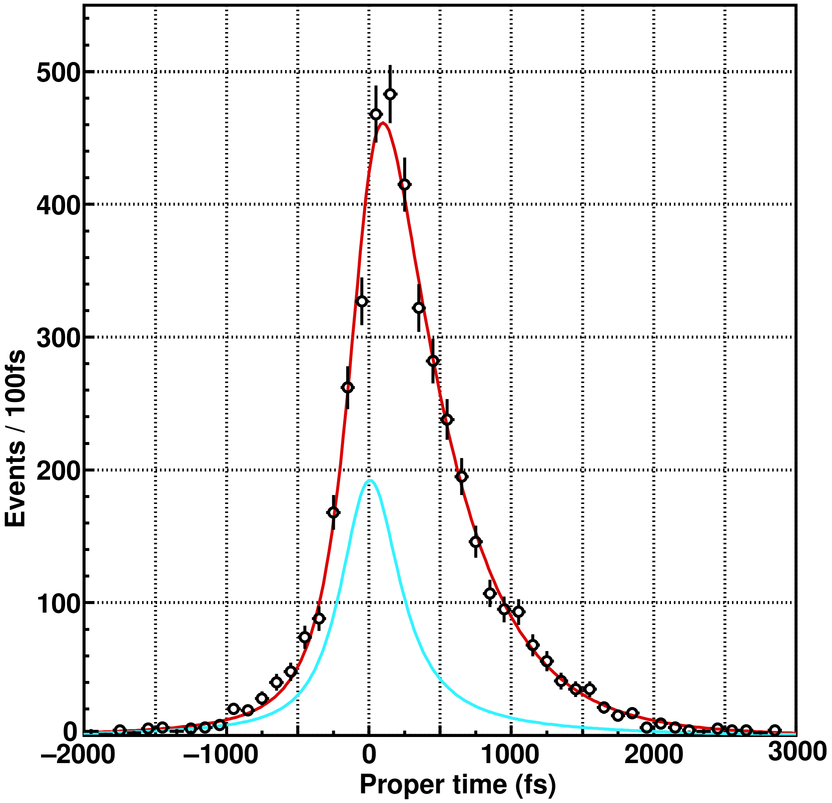
- **Standard Model Tests**
  - $D^0 - \bar{D}^0$ **Mixing**
  - **CP- Violation**
    - **Indirect**
    - **Direct**
  - **Rare Decays**

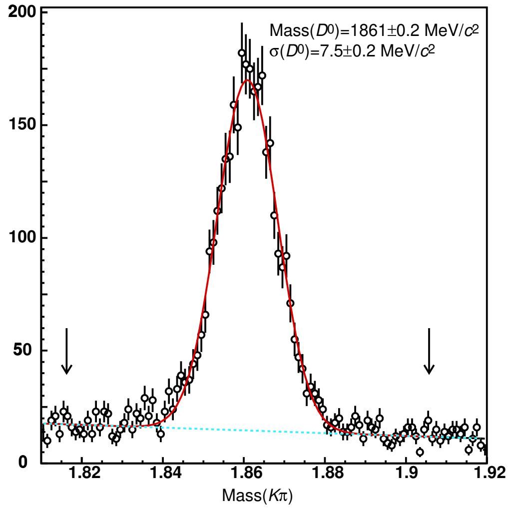
- **Hadronic Physics**
  - **Semileptonic Decays**
  - **Leptonic Decays**
  - **Charm Baryons**
  - **Spectroscopy**
  - **Lifetimes**
  - **Production**

Charm Experiments

- **Fixed Target**
  - E791 , Hadroproduction, 1991, 100K
  - SELEX , Hyperon Production, 1997, Baryons
  - FOCUS , Photoproduction, 1997, > 1M
  - COMPASS, Hadroproduction, 2003, $4 \times 10^6 K^- \pi^+$
  - HERA-B, Hadroproduction, 2001, High rates ??
- **e^+e^- Collider**
  - CLEO, 30×10^6 produced, 10 fb^{-1} now
  - BaBar, 1×10^9 produced, $>$ 100 fb^{-1}
  - Belle, 1×10^9 produced $>$ 100 fb^{-1}
  - BES, 25M $+$ 25M J/Ψ, Scan of R (85 pts 2-5 GeV
- **Hadron Collider**
  - D0
  - CDF
  - BTeV, 2005, 4×10^7, $K^- \pi^+$ reconstructed
  - LHCb, 200?, Planned Program

D^0 Lifetime Measurment



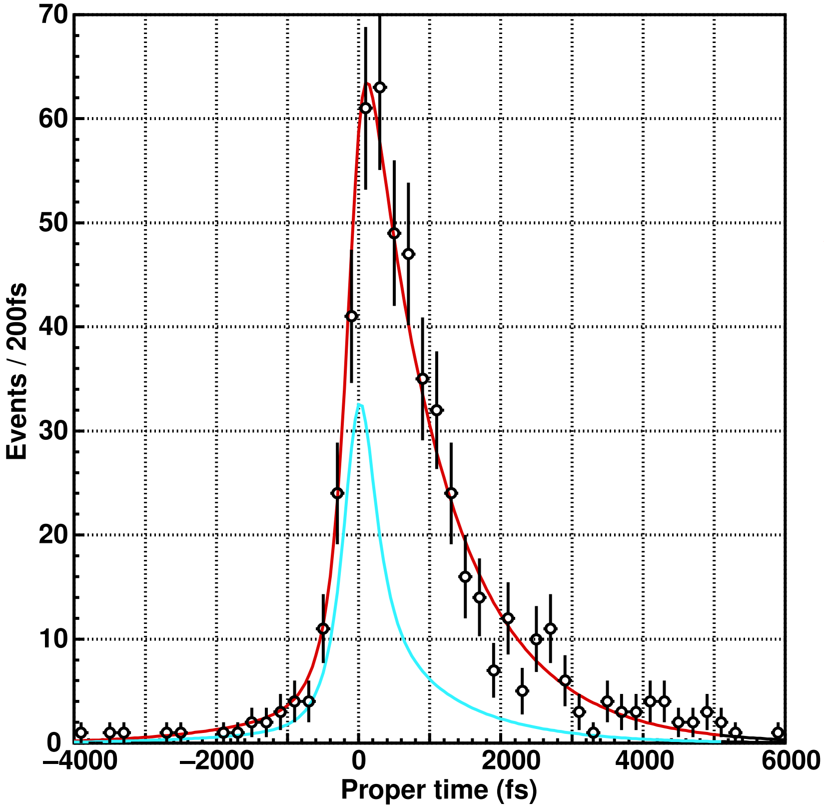


$\tau(D^0)$=405±10 (fs) @0.42fb^{-1}

# of signal=2904±65

Preliminary

D^+ Lifetime Measurment



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

$\tau(D^+)=970\pm80$ (fs) @$0.42\mathrm{fb}^{-1}$

Preliminary

Charm Mixing

- **If you start with a D^0 at time t, the probability it is a $\bar{D}^0$ is given by:**
  - $\Gamma(D^0 \to \bar{D}^0) = \frac{1}{4}|\frac{q}{p}|^2[e^{-\Gamma_H t} + e^{-\Gamma_L t} - 2e^{-\Gamma t} cos\Delta M t]$
  - where $\Delta M = (M_H - M_L)$ and $\Delta\Gamma = \Delta\Gamma_H - \Delta\Gamma_L$
  - and $D_H = pD^0 + q\bar{D}^0 \quad ; \quad D_L = pD^0 - q\bar{D}^0$
  - for charm $\Delta M << \Gamma$; $\Delta\Gamma << \Gamma$
  - $r_{mix}(t) = \frac{1}{4}e^{-\Gamma t}|\frac{q}{p}|^2(\Delta M^2 + \frac{1}{4}\Delta\Gamma^2)t^2$
  - define $x = \Delta M/\Gamma$ and $y = \Delta\Gamma/2\Gamma$
  - $r_{mix}(t) = \frac{1}{2}|\frac{q}{p}|^2 e^{-\Gamma t}(x^2 + y^2)(\Gamma t)^2$
  - Integrating over all time yields:

$$r_{mix} = \frac{1}{4}|\frac{q}{p}|^2(x^2 + y^2)$$

- **Note $r_{mix} = \bar{r}_{mix}$ only if $|\frac{q}{p}| = 1$**

Mixing Searches

- **Lifetime Difference Searches:**
  - ○ In the limit of no CP Violation, D_H and D_L are CP$^+$ and CP$^-$ eigenstates, so:

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

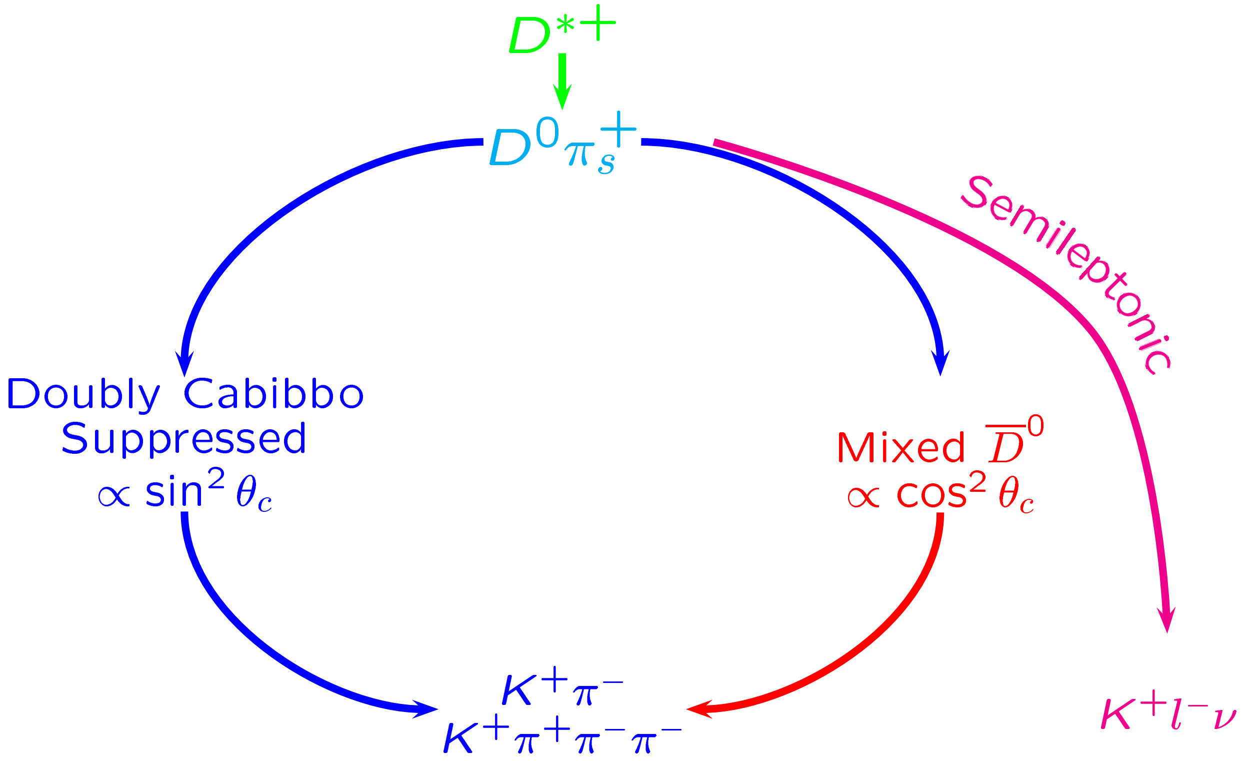
  - ○ τ^+ and τ^- can be measured using final states of definite CP, such as:

$$D^0 \to K^+K^-(CP^+);\ D^0 \to K_s^0\phi(CP^-)$$

  - ○ "No CP Violation" is assumed!

- **Direct ("Wrong Sign") Searches:**
  - ○ Look for $D^0 \to \bar{D}^0 \to K^+\pi^-, K^+\pi^-\pi^+\pi^- K^+l^-\nu_l, ...$
  - ○ Sign of K or lepton distinquishes final $\bar{D}^0$ from a D^0.
  - ○ Critical to correctly tag the produced D^0.
  - ○ Use distinctive decay time signature.

Mixing Searches



D^{*+}

$D^0\pi_s^+$

Semileptonic

Doubly Cabibbo
Suppressed
$\propto \sin^2\theta_c$

Mixed $\overline{D}^0$
$\propto \cos^2\theta_c$

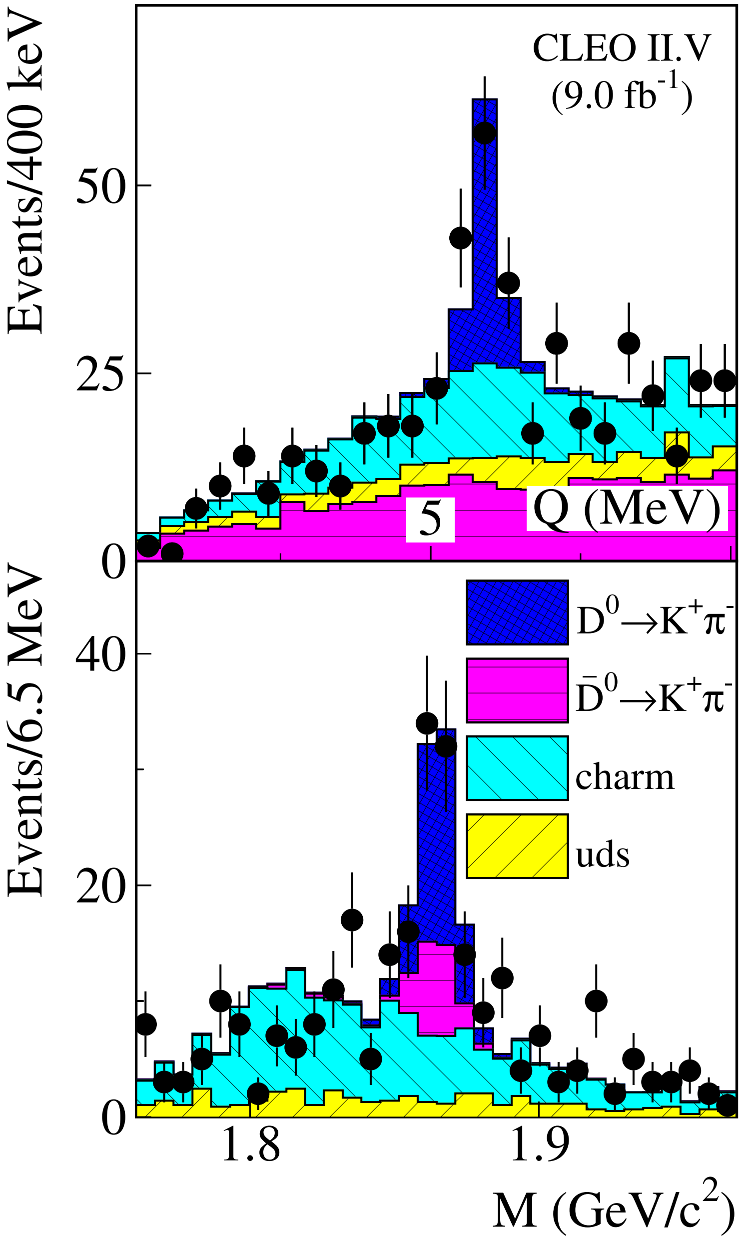
$K^+\pi^-$
$K^+\pi^+\pi^-\pi^-$

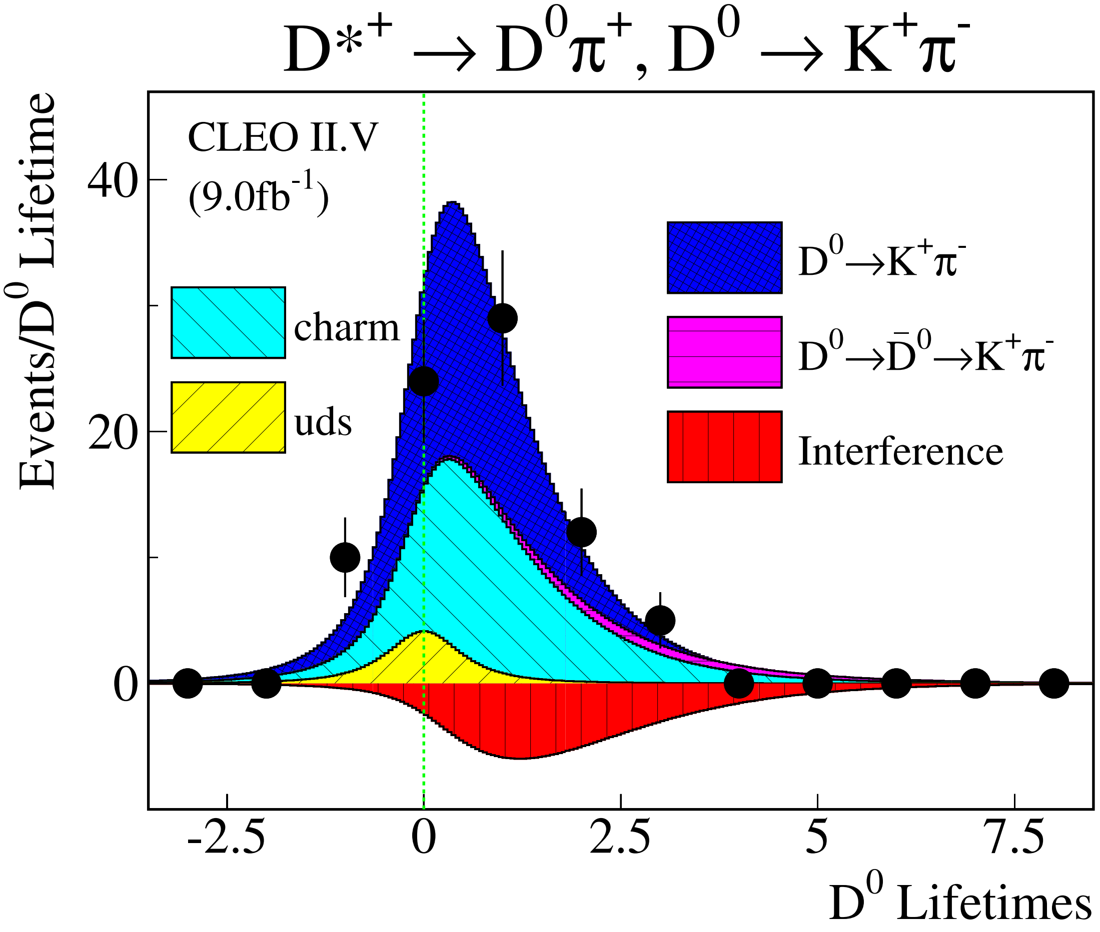
$K^+l^-\nu$

$$R_{ws} = [R_D + \sqrt{R_D}\,y'\Gamma t + \frac{1}{4}(x'^2 + y'^2)\Gamma^2 t^2]e^{-\Gamma t}$$

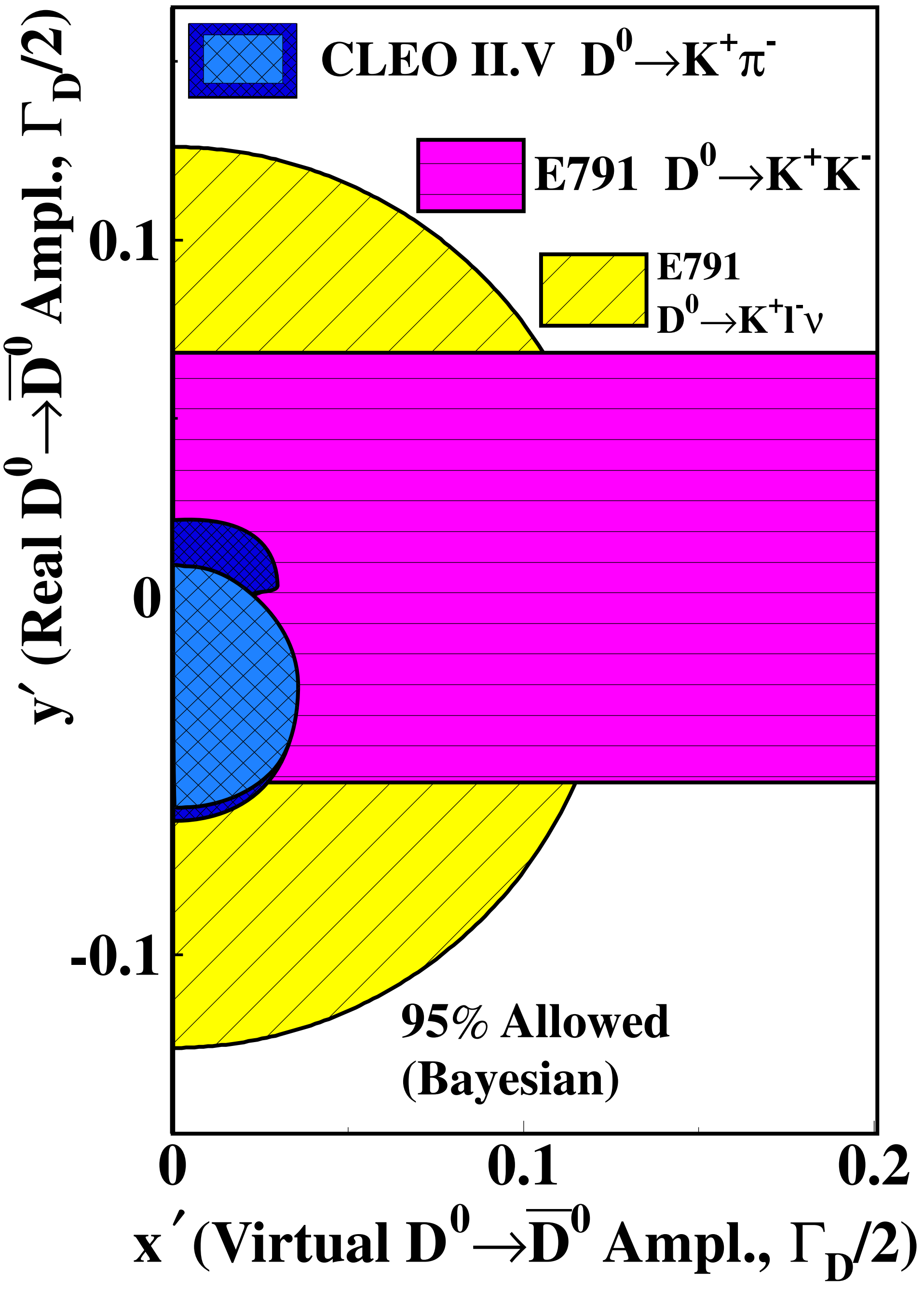
$x = \frac{\Delta M}{\Gamma}$ Mass Diff. for Weak Eigenstates

$y = \frac{\Delta \Gamma}{\Gamma}$ Lifetime Diff. for Weak Eigenstates


CLEO II.V
(9.0 fb^{-1})
Events/400 keV
50
25
0
5
Q (MeV)
Events/6.5 MeV
40
20
0
$D^0 \to K^+\pi^-$
$\bar{D}^0 \to K^+\pi^-$
charm
uds
1.8
1.9
M (GeV/c^2)


D*+ → D0π+, D0 → K+π-
CLEO II.V
(9.0fb-1)
Events/D0 Lifetime
40
20
0
charm
uds
D0→K+π-
D0→D̄0→K+π-
Interference
-2.5
0
2.5
5
7.5
D0 Lifetimes

D^0-$\overline{D}^0$ Mixing Limits



Mixing Summary

- **CLEO now has the best mixing limits, surpassing E791 and will do better in the future:**
  - Their most general fit yields:
  - $y' = (-2.5^{+1.4}_{-1.6} \pm 0.3)\%$ or $-5.8\% < y' < 1.0\%$ @95%CL
  - $x' = (0 \pm 1.5 \pm 0.2)\%$ or $|x'| < 2.9\%$ @95%CL
  - $(\frac{1}{2})x'^{\,2} < 0.041\%$ @95%CL

- **FOCUS lifetime results available soon on y with sensitivity <0.02 @95%CL**

- **FOCUS semileptonic decay results available this summer at comparable errors to CLEO.**

- **BaBar/Belle should lower limits another order of magnitude.**

CPV Formalism

Require two amplitudes with different phases.

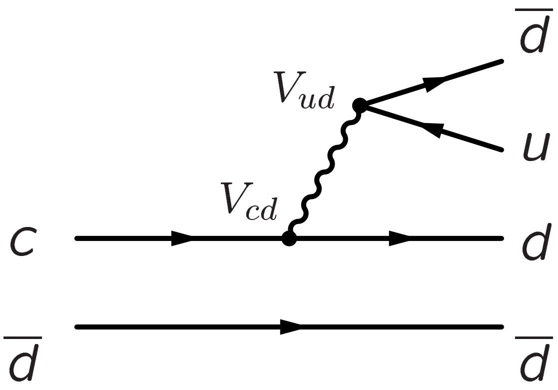
$$Ae^{i\delta_A} + Be^{i\delta_B}$$

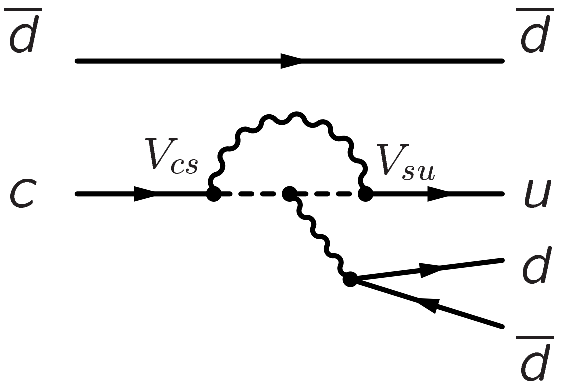
In singly Cabibbo suppressed decays(**SCSD**) one has a "tree" amplitude and a "penguin" amplitude with different weak phases.

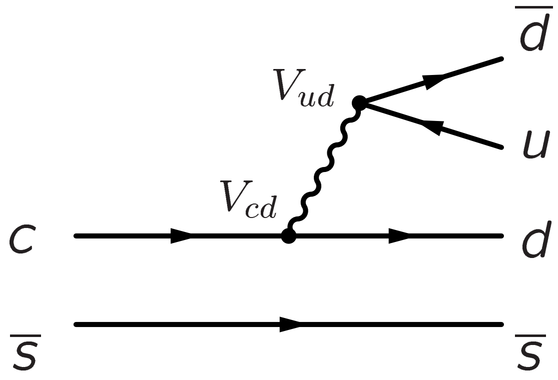
FSI provide a strong phase shift.

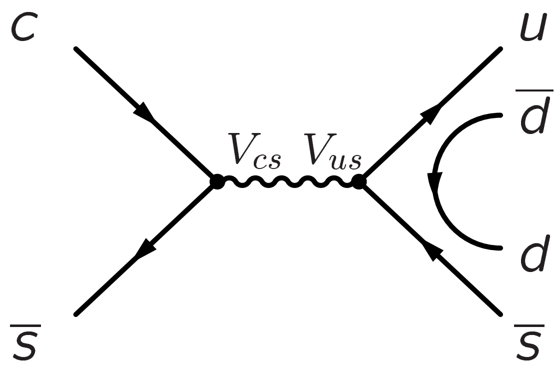
Under CP the weak phases change sign whereas the strong ones do not ⇒CPV

$$A_{CP} = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})} \propto \Im(AB^*) \sin[\delta_B - \delta_A]$$


$\overline{d}$
V_{ud}
u
V_{cd}
c
d
$\overline{d}$
$\overline{d}$


$\overline{d}$
$\overline{d}$
V_{cs}
V_{su}
c
u
d
$\overline{d}$


$\overline{d}$
V_{ud}
u
V_{cd}
c
d
$\overline{s}$
$\overline{s}$


c
u
$\overline{d}$
V_{cs}
V_{us}
d
$\overline{s}$
$\overline{s}$

CPV Formalism

For the case of D^0 decays one can have indirect CPV due to interference with the $D^0 - \bar{D}^0$ mixing amplitude. Such mixing is expected to be small but extensions to the SM can again lead to larger effects.

For decays which have a K^0 in the final state the situation is complicated by the presence of CPV in the decays of the K.

Buccella et. al. [Phys. Lett. **B302**,319 (1993)] observe that a measurement of A_{CP} will be "essentially hopeless" if the the value is a lot less than the asymmetry in K_L semileptonic decays
ie. $\simeq 10^{-3}$.

Experimental Technique

We need to account for the different production rates of D and $\bar{D}$ mesons.
Write the CP asymmetry as a double ratio:

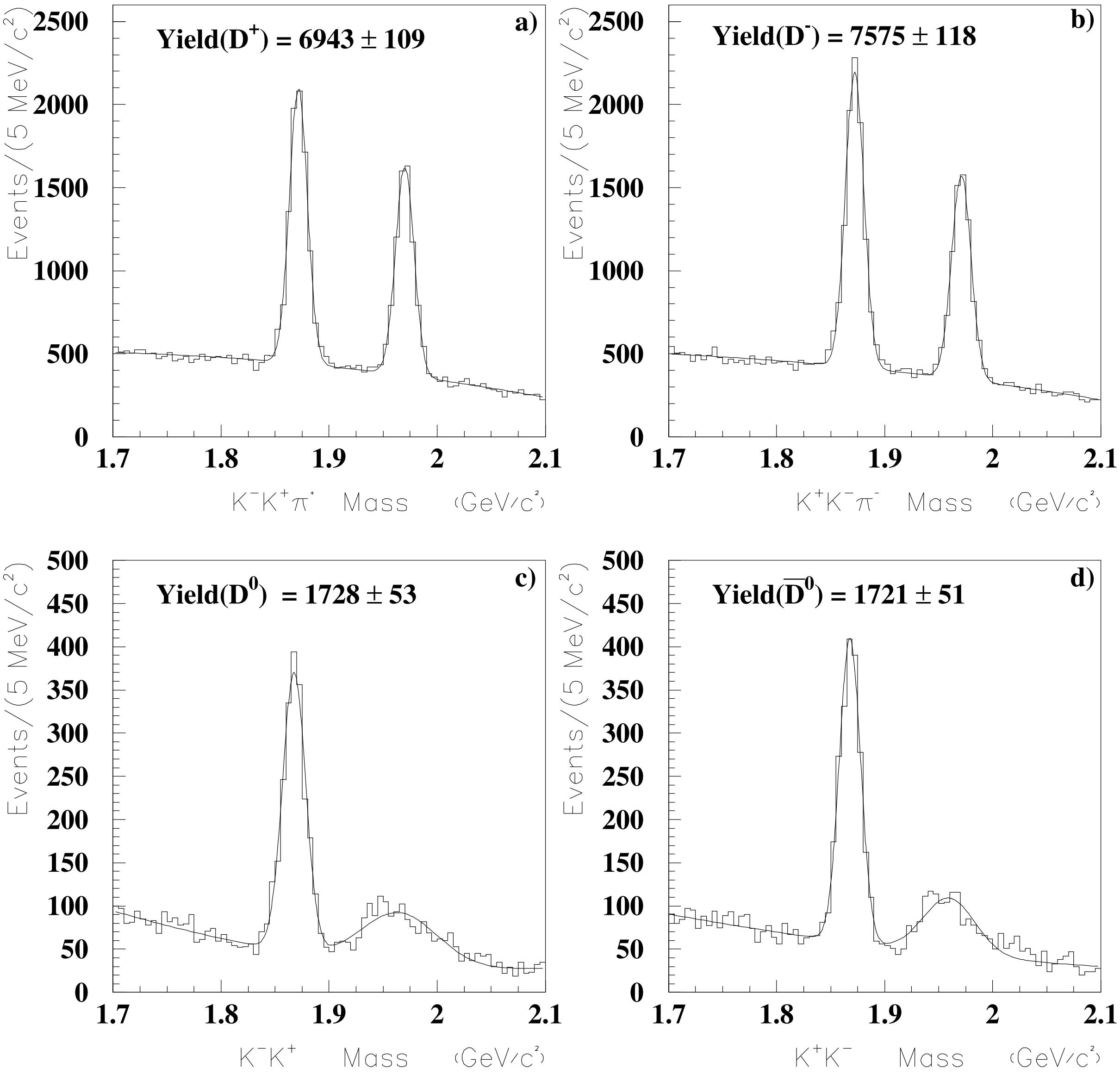
$$A_{CP} = \frac{\eta^+ - \eta^-}{\eta^+ + \eta^-}$$

where $\eta^\pm$ is the ratio of the efficiency corrected **SCSD** yield to that of a Cabibbo favoured mode *eg.*

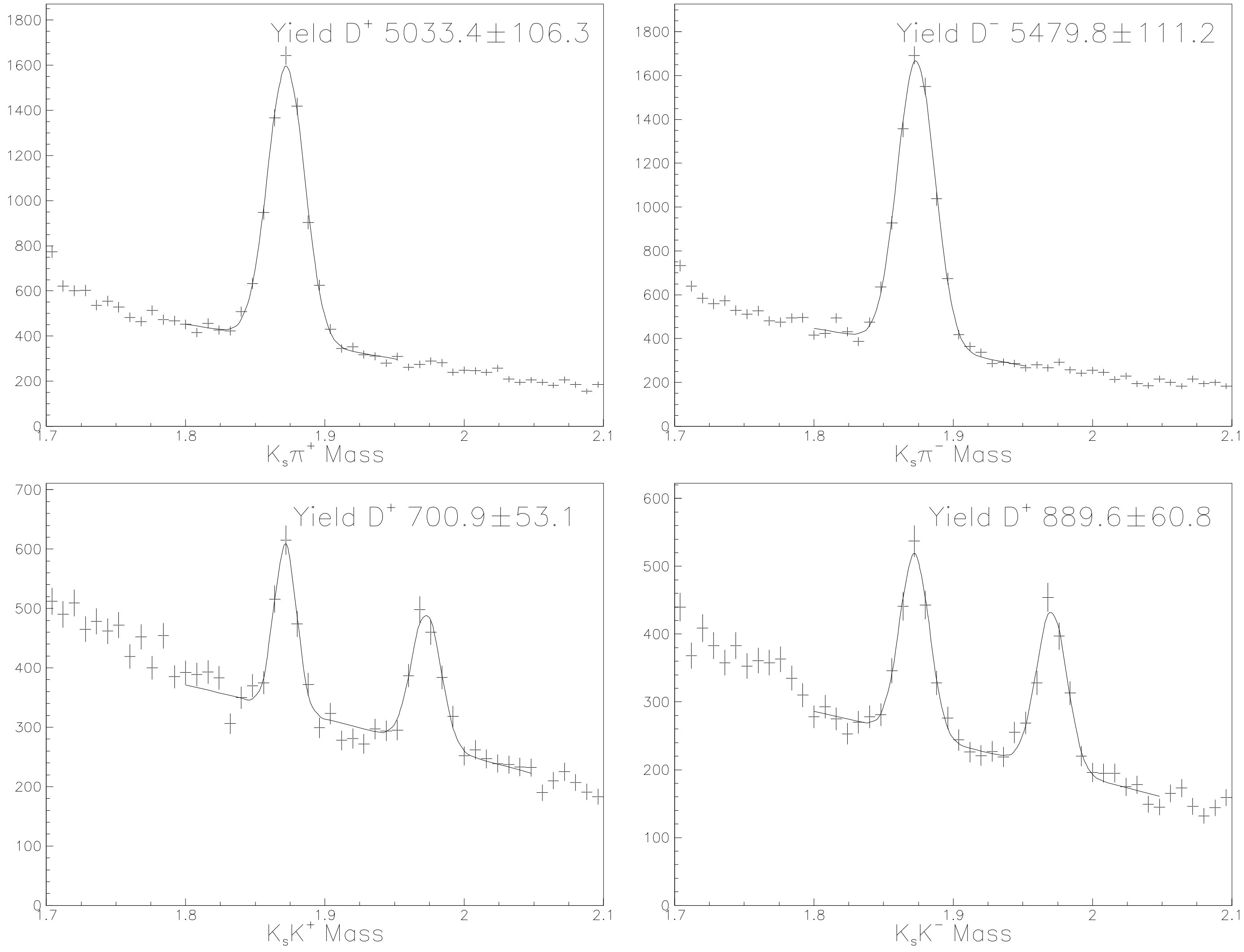
$$\eta^\pm = \frac{N(D^\pm \to K_s K^\pm)}{N(D^\pm \to K_s \pi^\pm)}$$

For D^0 decays we have the added complication of requiring a "soft pion tag" from the decay $D^{*+} \to D^0\pi^+$ in order to distinguish between D^0 and $\bar{D}^0$ decays.

FOCUS preliminary: invariant masses for $D^\pm \to K^- K^+ \pi^\pm$, $D^0(\overline{D}^0) \to K^- K^+$



FOCUS preliminary: invariant masses for $D^{\pm} \to K_s\pi^{\pm}$, $D^{\pm} \to K_s K^{\pm}$.



The preliminary results for the decay modes $D^0(\bar{D}^0) \to K^+K^-$ and $D^\pm \to K^+K^-\pi^\pm$ are presented in the table below.

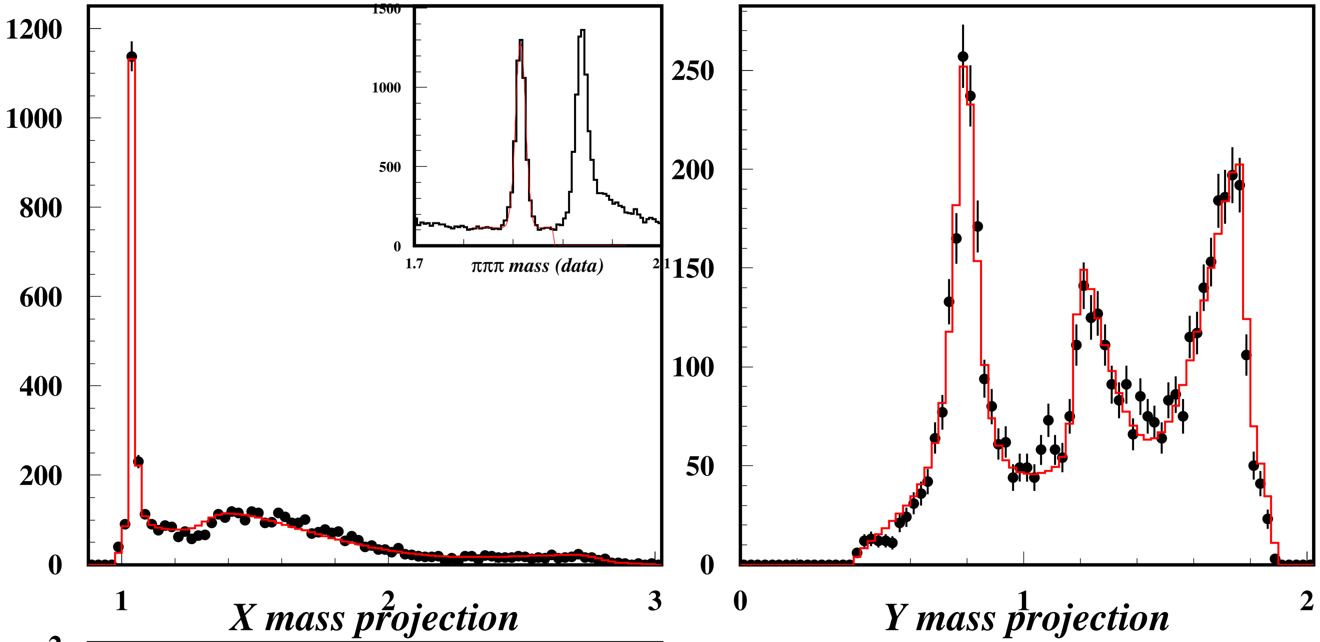
Decay	FOCUS	E791
$D^0 \to K^+K^-$	0.0002 ± 0.0219	$-0.10 \pm 0.049 \pm 0.012$
$D^+ \to K^+K^-\pi^+$	-0.012 ± 0.011	-0.014 ± 0.029

The statistical sensitivity for the mode $D^\pm \to K_sK^\pm$ is expected to be $\pm 5.3\%$.

In addition to measuring the branching ratio asymmetry, an analysis of the $D^\pm \to K^+K^-\pi^\pm$ Dalitz plot will be completed to measure a phase shift between the D^+ and D^- amplitudes.

99/06/28 15.22

$D^+ \rightarrow KK\pi$ dalitz plot and projections (data)



Model

Fit results

NR =0.000E+00±0.

$\bar{K}^*(892)^\circ$ =1.000E+00±0.

Φ =9.548E-01±2.

f_0 =0.000E+00±0.

$\bar{K}^*_o(1430)$ =1.108E+00±2.

$f_j(1710)$ =0.000E+00±0.

FNR =0.000E+00±0.

$F\bar{K}^*(892)^\circ$ =0.000E+00±0.

FΦ =-2.967E+00±5

Ff_0 =0.000E+00±0.

$F\bar{K}^*_o(1430)$=-1.997E+00±4

$Ff_j(1710)$=0.000E+00±0.

α =8.592E-01±3.

SB Model

SB Fit

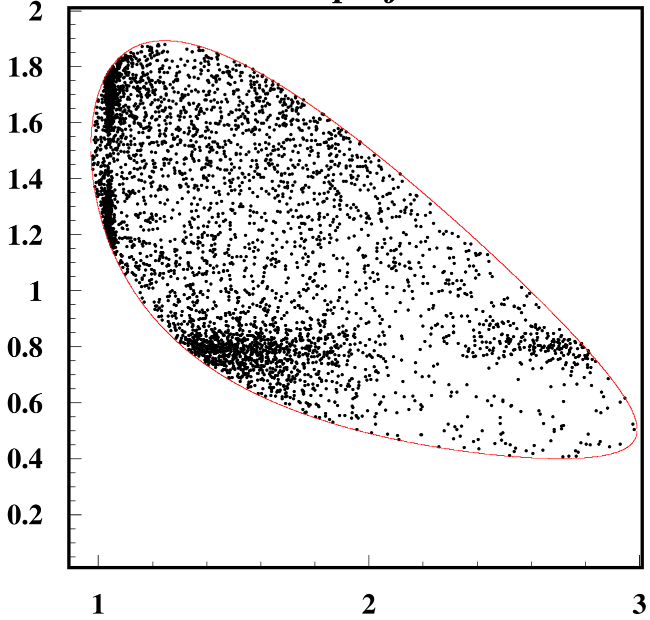
P1 = -2.426E-01±1.026

P2 = -1.038E-01±2.903

Fit Information

FLike =-4.5665500E+03

Status=Accurate



Analysis Cuts

Mode = 7

MulPri > 1

Runnum > 9750

IlTrig = Not Used

Sigma = 2.000E+00

Elsig > 10.000

Aiso1 < 1.000E-02

Aiso2 < 1.000E-03

Aiso3 < Not Used

ZOut > 2.000

PZMin > Not Used

PtENE > Not Used

dWcut1 = 3.000

dWcut2 = 3.000

dWcut3 = 3.000

dWKPi1 = 0.000

dWKPi2 = 0.000

dWKPi3 = 0.000

Dmom > 25.000

YieldDp = 4545.90±78.13

SToNDp = 6.11±0.18

SFracDp = 0.86±0

N.Pairs = 5118

D$^+$ Asymmetry Estimates

- Branching Ratios and CP Asymmetry for Cabibbo-suppressed decays of D$^+$ mesons.

$D^+ \to$	B_{exp}(%)	B_{th}(%)	CP Asymmetry
$\pi^+\pi^0$	0.25±0.07	0.185	$--$
$\pi^+\eta$	0.75±0.25	0.38	-0.77× 10^{-3}
$\pi^+\eta\prime$	$<$ 0.9	0.768	+0.90× 10^{-3}
$K^+\bar{K}^0$	0.72±0.12	0.763	-0.52× 10^{-3}
$\pi^+\rho^0$	$<$ 0.14	0.104	-1.99× 10^{-3}
$\pi^0\rho^+$	$--$	0.451	+0.89× 10^{-3}
$\pi^+\eta$	$<$ 1.2	0.064	-1.60× 10^{-3}
$\pi^+\eta\prime$	$<$ 1.5	0.122	≈ 0
$\pi^+\omega$	$<$ 0.7	0.038	-0.60× 10^{-3}
$\pi^+\phi$	0.61±0.06	0.619	-0.09× 10^{-3}
$K^+\bar{K}^{*0}$	0.42±0.05	0.436	+0.68× 10^{-3}
$K^{*+}\bar{K}^0$	3.0±1.4	1.52	-0.19× 10^{-3}

D_s^+ Asymmetry Estimates

- Branching Ratios and CP Asymmetry for Cabibbo-suppressed decays of D_s^+ mesons.

$D_s^+ \to$	$B_{exp}(\%)$	$B_{th}(\%)$	CP Asymmetry
$K^+\pi^0$	$--$	0.146	$+1.07\times 10^{-3}$
$K^+\eta$	$--$	0.299	-0.05×10^{-3}
$K^+\eta\prime$	$--$	0.495	-0.64×10^{-3}
$\pi^+\bar{K}^0$	< 0.8	0.373	$+0.48\times 10^{-3}$
$K^+\rho^0$	< 0.29	0.198	$+0.25\times 10^{-3}$
$K^{*+}\pi^0$	$--$	0.076	-0.92×10^{-3}
$K^{*+}\eta$	$--$	0.146	-0.41×10^{-3}
$K^{*+}\eta\prime$	$--$	0.029	-0.09×10^{-3}
$K^+\omega$	$--$	0.178	-0.34×10^{-3}
$K^+\phi$	< 0.05	0.008	$+1.79\times 10^{-3}$
$K^{*0}\pi^+$	0.65 ± 0.28	0.444	-0.75×10^{-3}
$K^0\rho^+$	$--$	1.29	$+0.36\times 10^{-3}$

D^0 Asymmetry Estimates

- Branching Ratios and CP Asymmetry for Cabibbo-suppressed decays of D^0 mesons.

$D^0 \to$	B_{exp}(%)	B_{th}(%)	CP Asymmetry
$\pi^+\pi^-$	0.152±0.011	0.152	-0.10×10^{-3}
$\pi^0\pi^0$	0.084±0.022	0.115	$+0.51\times 10^{-3}$
K^+K^-	0.442±0.027	0.427	-0.10×10^{-3}
$K^0\bar{K}^0$	0.13±0.04	0.108	$+0.26\times 10^{-3}$
$\pi^0\omega$	$--$	0.013	-0.01×10^{-3}
$\pi^0\phi$	< 0.14	0.105	-0.04×10^{-3}
$\eta^0\phi$	< 0.28	0.080	-0.15×10^{-3}
$K^0\bar{K}^{*0}$	< 0.16	0.052	-0.56×10^{-3}
$\bar{K}^0K^{*0}$	< 0.08	0.062	-0.65×10^{-3}
K^-K^{*+}	0.35±0.08	0.431	-0.04×10^{-3}
K^+K^{*-}	0.18±0.10	0.290	$+0.27\times 10^{-3}$
$\pi^0\eta$	$--$	0.054	-1.44×10^{-3}
$\pi^+\eta'$	$--$	0.175	$+0.89\times 10^{-3}$
$\eta\eta$	$--$	0.093	-0.51×10^{-3}
$\eta\eta'$	$--$	0.186	-0.31×10^{-3}
$\eta\rho^0$	$--$	0.020	-0.53×10^{-3}
$\eta'\rho^0$	$--$	0.008	$+0.01\times 10^{-3}$
$\eta\omega$	$--$	0.209	-0.02×10^{-3}
$\eta'\omega$	$--$	0.0002	-3.66×10^{-3}
$\pi^0\rho^0$	$--$	0.216	-0.01×10^{-3}
$\pi^+\rho^-$	$--$	0.485	-0.43×10^{-3}
$\pi^-\rho^+$	$--$	0.706	$+0.34\times 10^{-3}$

FCNC Studies

- $c \to u$ transitions
  - Standard Model short distance contributions give very small decay rates.
  - Often argued that there is a opportunity to search for new phenomena, but —
  - SM long-distance effects not well known and could overwhelm new contributions to short distance 1-loop effects from new physics.
- $c \to u\gamma$
  - Rate suppressed to lack of heavy down-type quark
  - b-quark couplings $|V_{cb}|$ and $|V_{ub}|$ are small
  - $B(D \to \rho\gamma)/B(D \to K\gamma)$ different from $tan^2\theta_C$.
- $D^0 \to l^+l^-$
  - Helicity Suppressed (10^7 muons, 10^3 electrons)
  - Short Distance 10^{-19}, Long Dist. 10^{-15}
  - New Physics for BR above 10^{-15}

FCNC Studies, cont.

- $D^0 \to \gamma\gamma$
  - Short Dist. 10^{-16}, Long Dist. 10^{-9}
  - Very challenging experimentally
- $c \to u l^+ l^-$
  - Long Distance rate 10^{-6} for $D^+ \to \pi^+\mu^+\mu^-$
  - Should see signal within next few years, but unlikely to be new physics
- $c \to u\nu\nu$
  - $B(D^0 \to \pi^0\nu\nu)$ of order 6×10^{-16}
  - $B(D^+ \to \pi^+\nu\nu)$ of order 8×10^{-16}

Limits on FCNC Decays

- Branching Ratios and CP Asymmetry for Cabibbo-suppressed decays of D^0 mesons.

Decay Channel	Exp. Limit	SM Expectation
$D^0 \to \mu^+\mu^-$	4.1×10^{-6}	$< 3 \times 10^{-15}$
$D^0 \to \pi^0\mu^+\mu^-$	1.8×10^{-4}	$--$
$D^0 \to \pi^0 e^+e^-$	4.5×10^{-5}	$--$
$D^0 \to K^0\mu^+\mu^-$	2.6×10^{-4}	$< 2 \times 10^{-15}$
$D^0 \to K^0 e^+e^-$	1.1×10^{-4}	$< 2 \times 10^{-15}$
$D^0 \to \rho^0\mu^+\mu^-$	2.3×10^{-4}	$(3.5\text{-}4.7) \times 10^{-7}$
$D^0 \to \bar{K}^{*0}\mu^+\mu^-$	1.2×10^{-3}	$(1.6\text{-}1.9) \times 10^{-6}$
$D^0 \to \rho^0\gamma$	2.4×10^{-4}	$(0.1\text{-}6.0) \times 10^{-5}$
$D^0 \to \phi\gamma$	1.9×10^{-4}	$(0.1\text{-}3.4) \times 10^{-5}$
$D^0 \to \bar{K}^{*0}\gamma$	7.6×10^{-4}	$(0.7\text{-}8.0) \times 10^{-4}$
$D^+ \to \pi^+\mu^+\mu^-$	1.5×10^{-5}	1×10^{-6}
$D^+ \to \pi^+e^+e^-$	5.2×10^{-5}	1×10^{-6}
$D^+ \to K^+\mu^+\mu^-$	4.5×10^{-5}	$< \times 10^{-15}$
$D^+ \to K^+e^+e^-$	2.0×10^{-4}	$< \times 10^{-15}$
$D^+ \to \rho^+\mu^+\mu^-$	5.6×10^{-4}	$(1.5\text{-}1.9) \times 10^{-6}$
$D^+ \to \rho^+\gamma$	$--$	$(0.4\text{-}6.3) \times 10^{-5}$
$D_s^+ \to \rho^+\mu^+\mu^-$	$--$	3×10^{-5}
$D_s^+ \to \rho^+\gamma$	$--$	$(0.6\text{-}3.8) \times 10^{-4}$

Lepton Family or Number Violation

- Branching Ratios and CP Asymmetry for Cabibbo-suppressed decays of D^0 mesons.

Decay Channel	Exp. Limit	SM Expectation
$D^0 \to \mu^\pm e^\mp$	8.1×10^{-6}	0
$D^+ \to \pi^+\mu^\pm e^\mp$	5.0×10^{-5}	0
$D^+ \to K^+\mu^\pm e^\mp$	6.8×10^{-5}	0
$D^+ \to \pi^-\mu^+\mu^+$	1.7×10^{-5}	0
$D^+ \to K^-\mu^+\mu^+$	1.2×10^{-4}	0
$D^+ \to \rho^-\mu^+\mu^+$	5.6×10^{-4}	0
$D_s^+ \to K^+\mu^\pm e^\mp$	6.3×10^{-4}	0
$D_s^+ \to K^-\mu^+\mu^+$	1.8×10^{-4}	0
$D_s^+ \to K^-e^+e^+$	6.3×10^{-4}	0
$D_s^+ \to K^-\mu^+e^+$	6.8×10^{-4}	0

Semileptonic Decays

- Main issues are form factors and CKM elements, with $|V_{cs}|$ and $|V_{cd}|$ better determined by three generation unitarity.

- Might argue that semileptonic decays of charm will be complete in five years, but ....

- $\frac{BR(K^-\mu^+\nu)}{BR(K^-\pi^+)} = 0.852 \pm 0.034 \pm 0.028$; E687

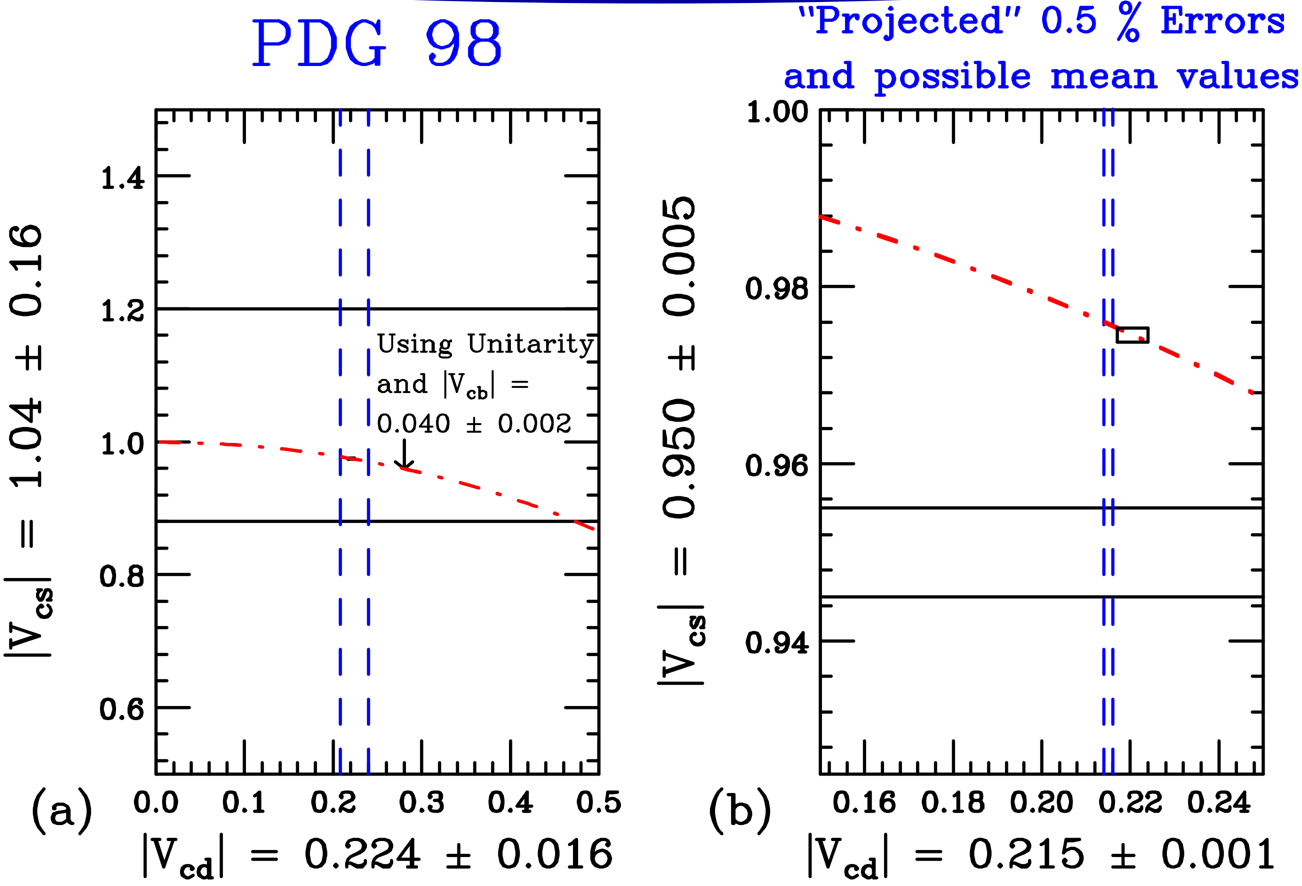
- $\frac{BR(K^-l^+\nu)}{BR(K^-\pi^+)} = 0.978 \pm 0.027 \pm 0.044$; CLEO

- $BR(D^0 \rightarrow K^-\mu^+\nu) \;\; \alpha \;\; |V_{cs}|^2 |f_+^K(0)|^2$
  - $|f_+^K(0)| = 0.716 \pm 0.029 \pm 0.019$; E687
  - $|f_+^K(0)| = 0.77 \pm 0.01 \pm 0.04$; CLEO
  - Theory only good to 10% which implies 10% error in $|V_{cs}|$

- $BR(D^0 \rightarrow \pi^-\mu^+\nu) \;\; \alpha \;\; |V_{cd}|^2 |f_+^\pi(0)|^2$

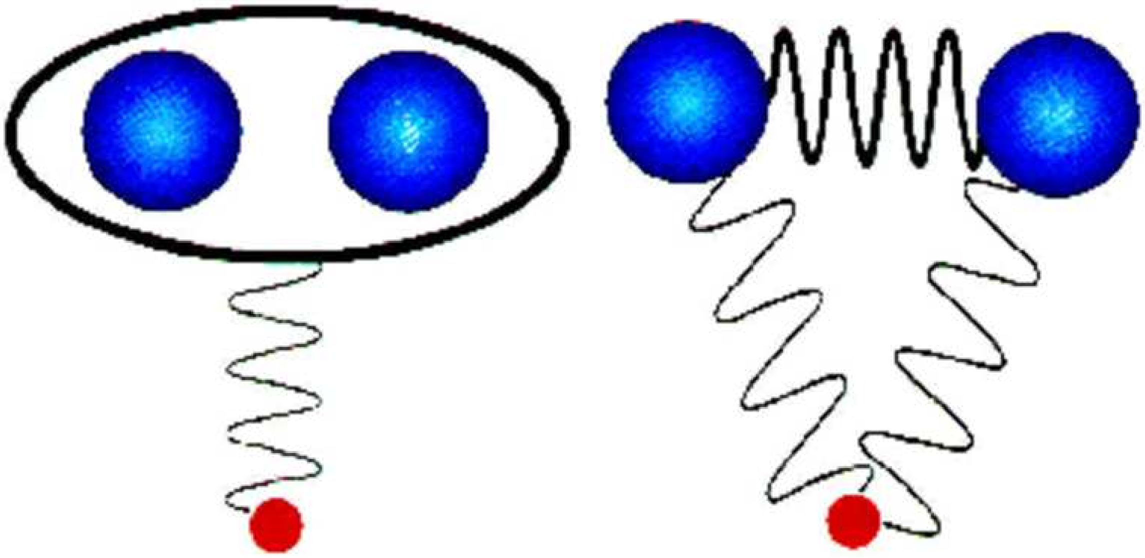
- Expect new measurements from FOCUS, CLEO, BaBar, and Belle

Semileptonic Projections



- PDG 98 Values are dominated by theory.
- $|V_{cs}|^2 + |V_{cd}|^2 =$ 1. - $|V_{cb}|^2$
- Collaboration between experimenters and theorists will be required.

Double Charmed Baryons



- Unknown Baryon with molecular type excitations
- Lifetime determination gives insight to decay diagrams:
  - Ξ_{cc}^{++} spectator + u - interference
  - Ξ_{cc}^{+} spectator + W - exchange
  - Ω_{ccs}^{+} spectator + s - interference
  - Ω_{ccc}^{+} spectator , free quark decay
- See 'Estimates of Decay Branching Ratios for Hadrons Containing Charm and Bottom Quarks', JD Bjorken (86)

Conclusions

- Much still to do!
- Hadronic Decays not covered, but doubt that all will be done - widths of states - DCSD decays in D_s^+.
- FOCUS will soon be publishing and has a big data set.
- e^+e^- Collider Experiments will have a big impact and should measure fully leptonic channels.
- Without a surprise or new physics direct CP violation will still be waiting to be measured.
- High rate experiment with dedicated charm triggers will be needed. Major question is the level of background.