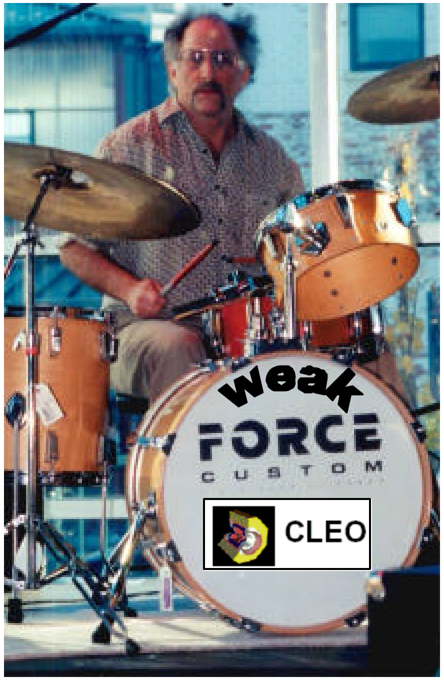
Recent Results on Charm Decays

- Lifetimes
  - mesons
  - baryons
- "Wrong" sign D^0 decays
  - Mixing
  - Doubly suppressed cabibbo decays
- CP violation searches
- Semileptonic charm decay
- Summary/Outlook



Results from:
BABAR
BELLE
CLEO
FOCUS
SELEX

Richard Kass

Charm Particle Lifetimes

Lifetime is a defining property of a “particle”.

necessary to convert BR’s to decay rates ⇒ theoretical comparisons

Weak interaction lifetime modified by strong interaction effects

⇒ non-perturbative QCD

spectator　　color suppressed internal spectator　　exchange　　annihilation

Charmed mesons and baryons provide a rich testing ground:

3 mesons (D^+, D^0, D_s)

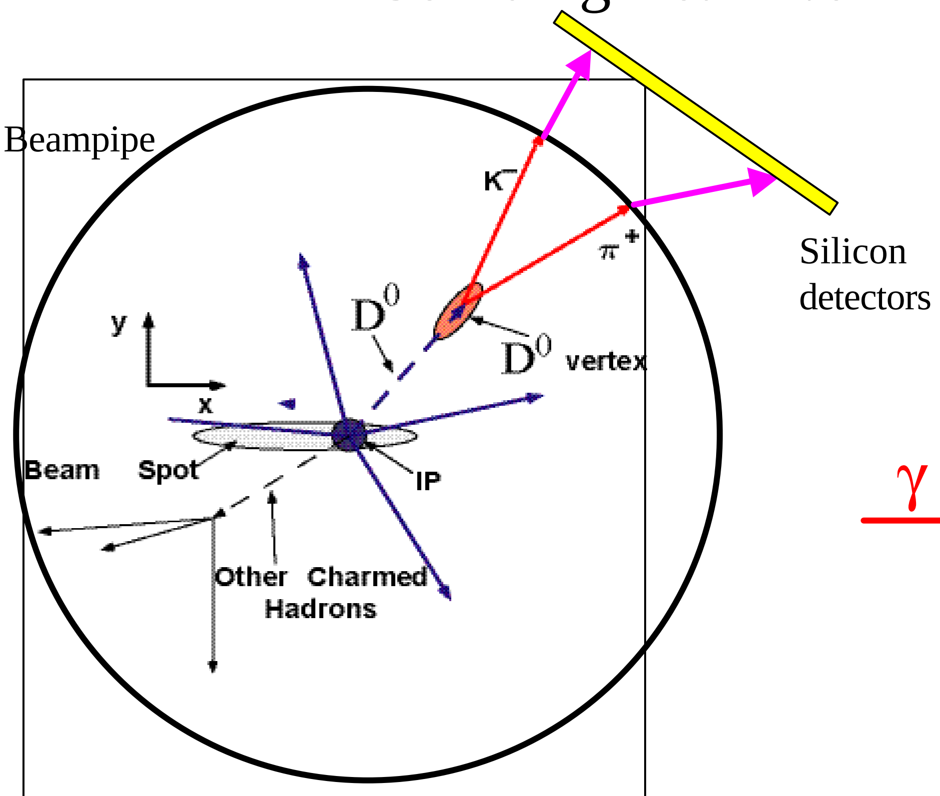
4 baryons (Λ_c, $\Xi_c^{\ +}$, $\Xi_c^{\ 0}$, $\Omega^0{}_c$)

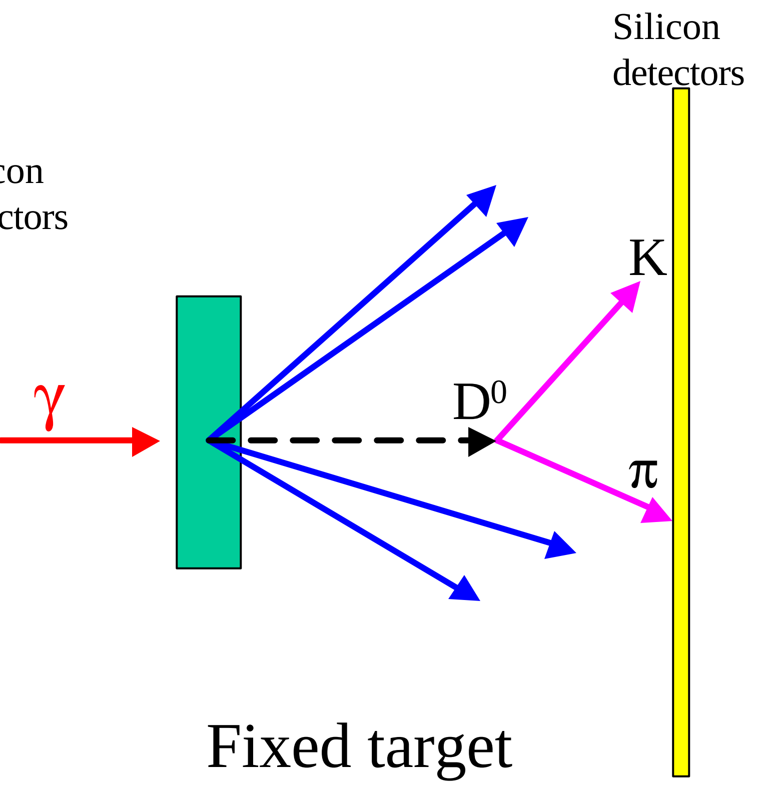
doubly charmed baryons

Interference effects are important: $t_{\Xi_c^+} > t_{\Lambda_c^+} \quad t_{D^+} > t_{D^0}$

Pattern of lifetimes “predicted” but not exact lifetime values

Colliding Beam vs Fixed Target





Colliding Beam

Better acceptance for short lifetimes

Cleaner environment

Unbinned ML fit

1d or 2d vertex

Fixed target

Better L/σ separation

Large data samples

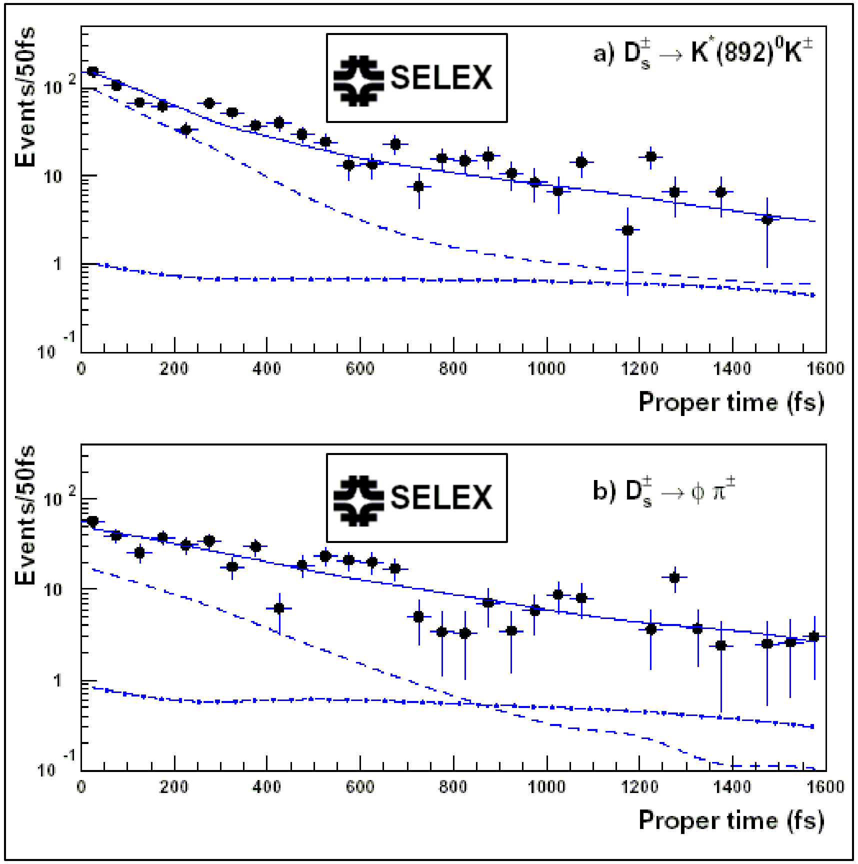
Binned ML fit

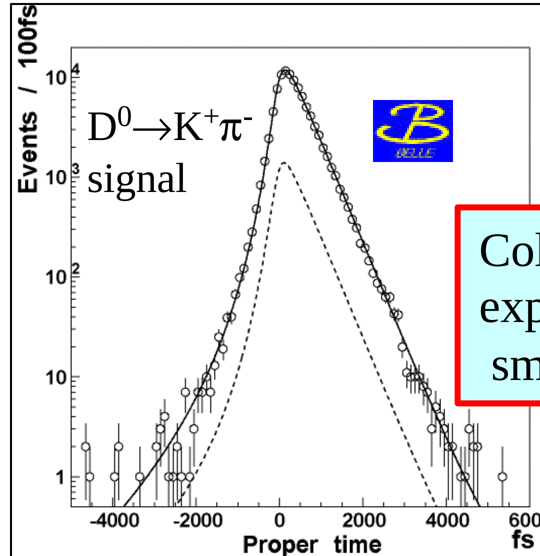
3d vertex

Neither actually “see” the decay as in emulsion and/or bubble chamber

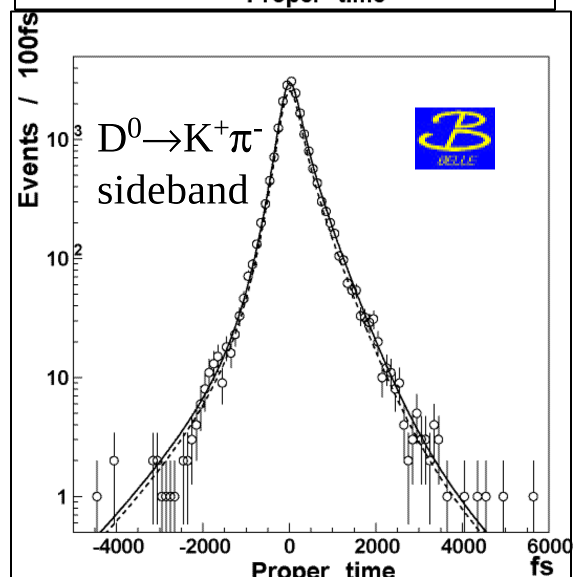
Charmed meson lifetimes

Fixed target: exponential decay



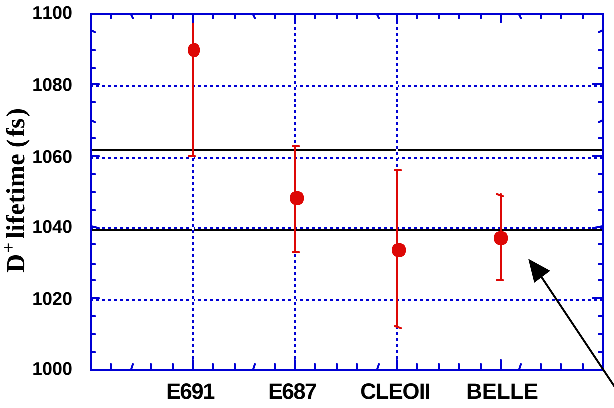


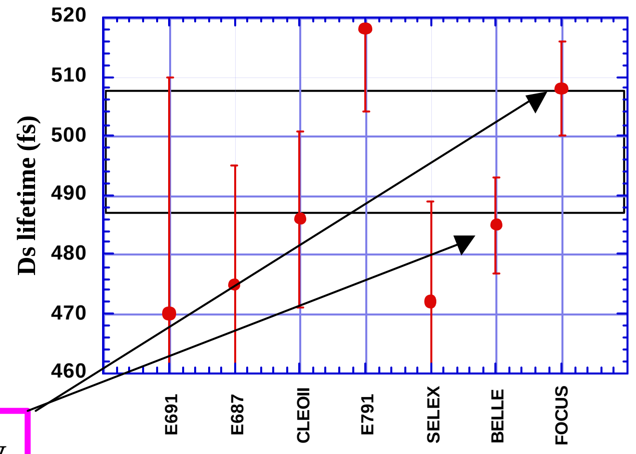
Colliding beam: exponential decay smeared by resolution



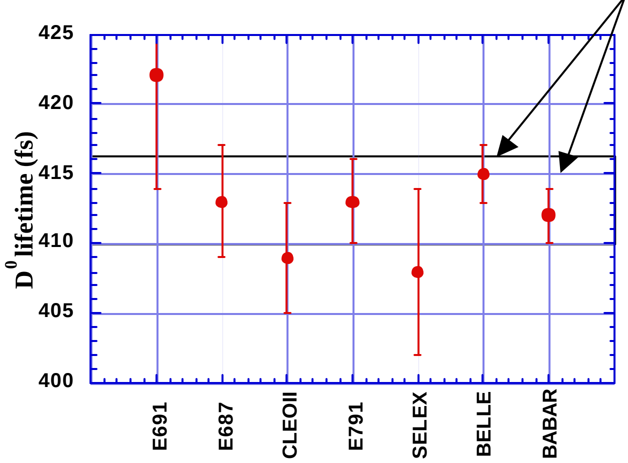
Lifetime results for Charmed Mesons

±1s **PDG2001**





preliminary



Annihilation and exchange diagrams are important for mesons.

PDG 2001: $t_{D_s}/t_{D^0} = 1.20 \pm 0.02$

BELLE: $t_{D_s}/t_{D^0} = 1.17 \pm 0.02 \pm 0.01$

Expect <1.07 without annihilation and exchange.

Bigi & Uraltsev, Z.Phys. C.62, 623, 1994

Richard Kass

Charmed Baryon Lifetimes

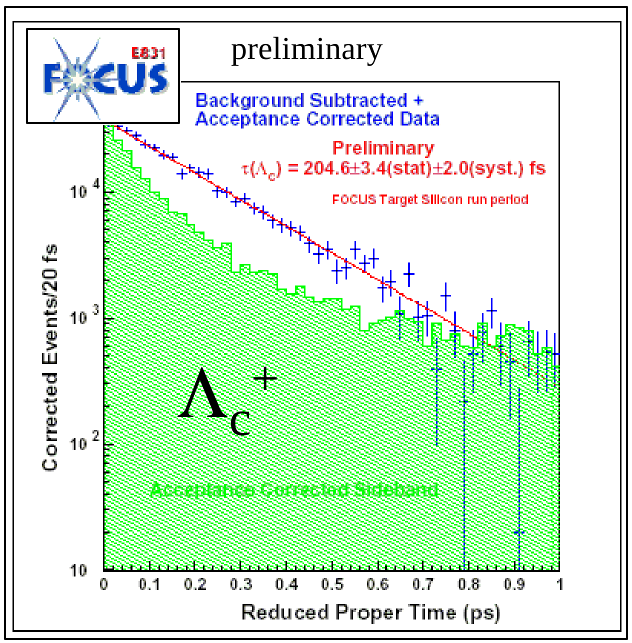
Baryon lifetimes not measured as precisely as mesons: 5-30% vs 1-2%

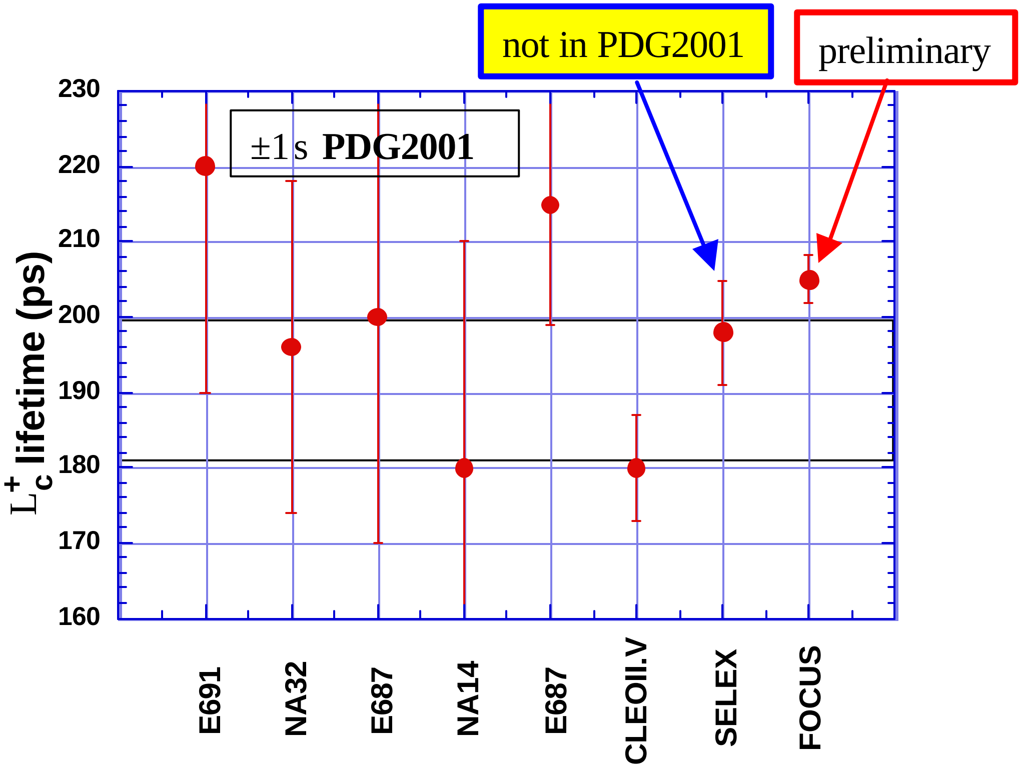
Baryon lifetimes shorter than mesons (e.g. $\tau_{\Omega c}$= 60 fs vs τ_{D0}= 410 fs)

Baryon cross sections are low $\Rightarrow$ samples smaller than mesons

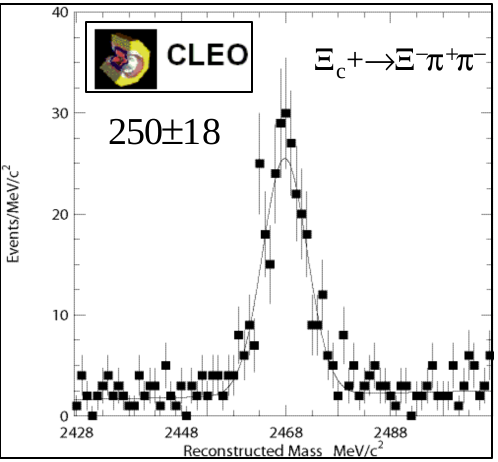
Lifetime calculations more complicated than mesons

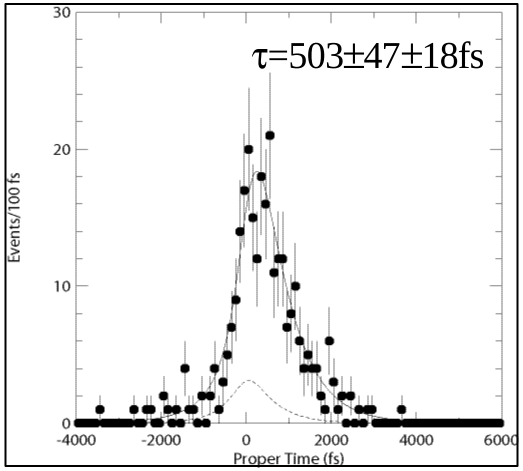
New results for Λ_c^+, Ξ_c^+, Ξ_c^0

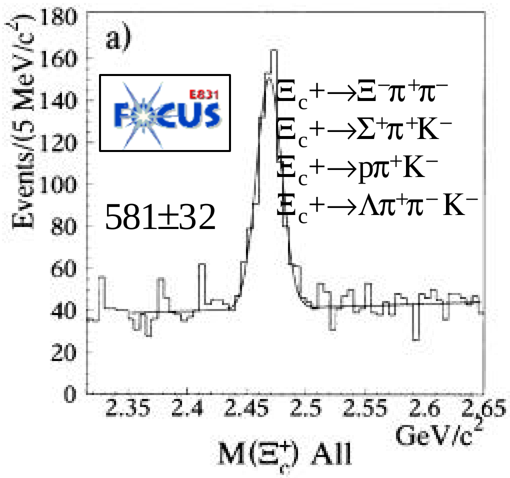


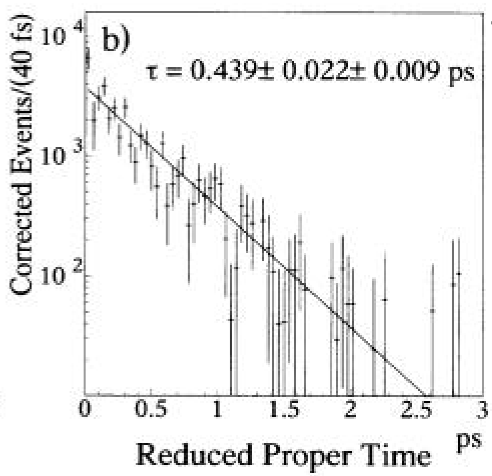


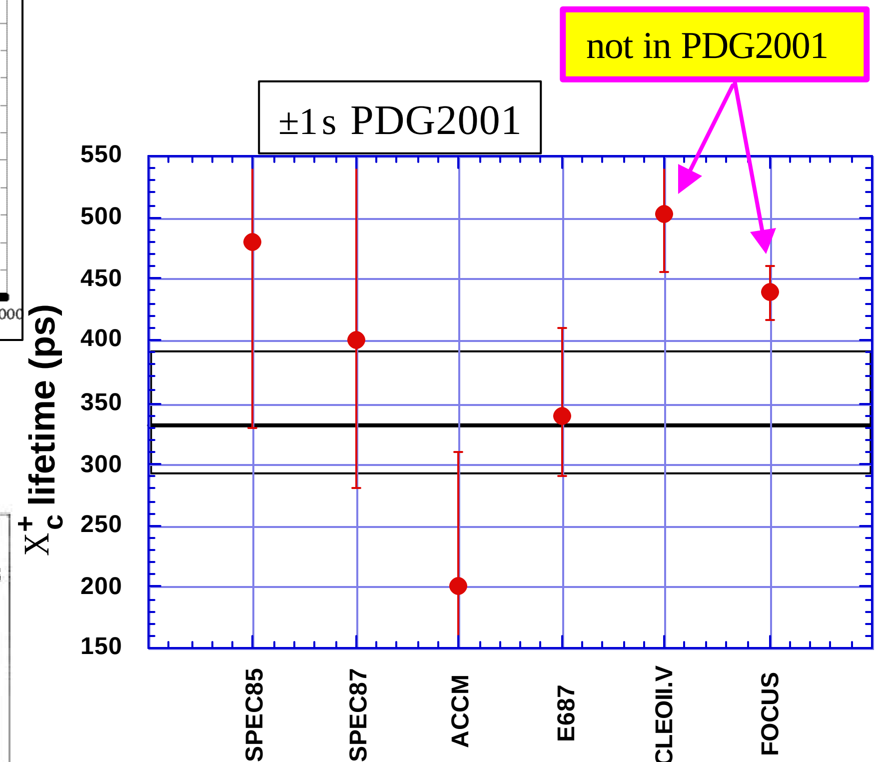
Recent Ξ_c^+ lifetime Results











Charmed Baryons Lifetimes

Preliminary Ξ_c^0 result from FOCUS:

$\tau=109^{+10}_{-9}$ fs (PDG2001: $\tau=98^{+23}_{-15}$ fs)

Based on a total of 137±19 events ($\Xi_c^0 \to \Omega^- K^+$, $\Xi^-\pi^+$)

Comments:

Measured lifetime ratio for Ξ_c^+ / Λ_c^+ larger than theory:

$$\text{CLEOII.V}: \frac{t_{\Xi_c^+}}{t_{\Lambda_c^+}} = 2.8 \pm 0.3 \qquad \text{FOCUS}: \frac{t_{\Xi_c^+}}{t_{\Lambda_c^+}} = 2.1 \pm 0.1$$

Theory ranges from:

1.3 Blok and Shifman, proceedings of 3rd workshop on physics of a tau charm factory, (1993)

1.2-1.7 Guberina and Melic, Eur. Phys. J. C2, 697 (1998)

At some point in the future lifetime analyses may have to correct for:

- $\Omega_c^0 \to \Xi_c^+\pi^-$ contamination of Ξ_c^+ sample
- $\Xi_c^0 \to \Lambda_c^+\pi^-$ contamination of Λ_c^+ in sample
- Doubly charmed baryons

Cabibbo suppressed $s \to u$ instead of $c \to s$

No Calculations available

Why is D^0-$\bar{D}^0$ mixing interesting?

Only meson system where mixing has not been observed
Only meson system where mixing is generated by *down* quarks
Mixing in D sector expected to be small in Standard Model
doubly Cabibbo Suppressed (DCS)
vanishes the limit of SU(3) flavor symmetry

If D mixing is large:

$\Delta\Gamma \geq \Delta M$: large flavor SU(3) breaking ?
$\Delta M >> \Delta\Gamma$: new physics ?

D mixing only involves the first two generations:

CPV >> $10^{-3} \Rightarrow$ New Physics

Can make measurements to look for mixing !

D mixing Phenomenology

$$|D_H\rangle = p|D_0\rangle + q|\overline{D}_0\rangle \qquad |D_L\rangle = p|D_0\rangle - q|\overline{D}_0\rangle$$

Usual definitions:

$$\Delta m = m_H - m_L$$

$$\Delta\Gamma = (\Gamma_H - \Gamma_L)$$

$$\Gamma = \frac{1}{2}(\Gamma_H + \Gamma_L)$$

→

$$x = \frac{\Delta m}{\Gamma}$$

$$y = \frac{\Delta\Gamma}{2\Gamma}$$

Phases:

δ is the strong phase between Cabibbo allowed and doubly Cabibbo suppressed amplitudes

ϕ is the CP violating phase in mixing (very small in SM)

CP Violation:

CPV in mixing due to $|p/q| \neq 1$

CPV in interference between decay with and without mixing $\propto \sin\phi \neq 0$

Assume no direct CPV

Ways to Observe D mixing

Measure lifetime difference between CP+ and/or CP- states and with flavor specific (CP mixed) states.

CP+:	$D^0 \rightarrow K^+K^-, \pi^+\pi^-$
CP-:	$D^0 \rightarrow K_s^0\rho^0, K_s^0\omega$
Mixed:	$D^0 \rightarrow K^-\pi^+$

Gives info on y:

$$y_{CP} = \frac{\Gamma_{CP+} - \Gamma_{CP-}}{\Gamma_{CP+} + \Gamma_{CP-}} = y\cos\phi - \frac{(|q|/|p|)^2 - 1}{2} x \sin\phi$$

$y_{cp} \approx y$ if no CPV

$$y_{CP} = \frac{\tau_{D \rightarrow K\pi}}{\tau_{D \rightarrow KK}} - 1$$

Requires good time (vertex) resolution

Measure "Wrong" sign Decays.

hadronic decays: $D^0 \rightarrow K^+\pi^-$

semi-leptonic decays: $D^0 \rightarrow K^+ l^- \bar{\nu}$

Don't have to measure time dependence

“Wrong” sign D^0 decays

These decays can originate from:

a) Double Cabibbo suppression (DCS) (hadronic decays only)

$$R_{DCS} = \left| \frac{< K^+ X^- | H | D^0 >}{< K^- X^+ | H | D^0 >} \right|^2 \qquad X^- = p^-, p^- p^- p^+, p^- p^0, \; etc.$$

b) Mixing

Wrong sign rate (R_{WS}) has interesting time dependence due to mixing+decay:

$$R_{WS} \propto [R_{DCS} + (y\cos d - x\sin d)(\Gamma t)\sqrt{R_{DCS}} + \frac{x^2 + y^2}{4}(\Gamma t)^2]e^{-\Gamma t}$$

Usual assumptions:
CP conserved $\Rightarrow |p/q|=1$
$|x|, |y|, R_{DCS} << 1$

δ=strong phase difference between CF and DCS decays

Convenient to rotate away δ: $x' = x\cos\delta + y\sin\delta$, $y' = y\cos\delta - x\sin\delta$

$$R_{WS} \propto [R_{DCS} + y'(\Gamma t)\sqrt{R_{DCS}} + \frac{x'^2 + y'^2}{4}(\Gamma t)^2]e^{-\Gamma t}$$

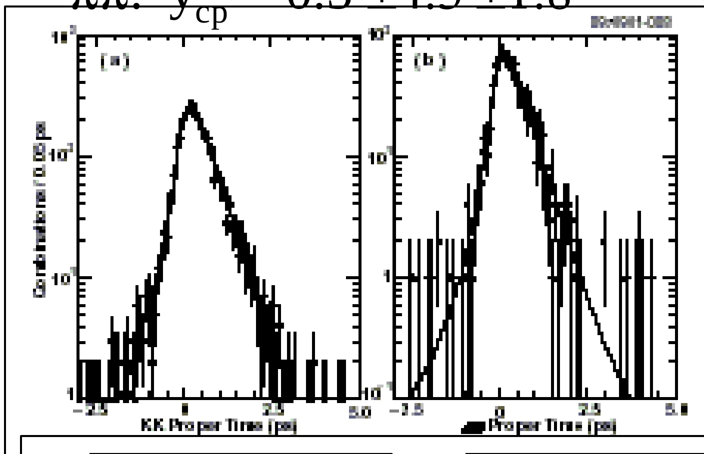
NO DCS for semi-leptonic decays:

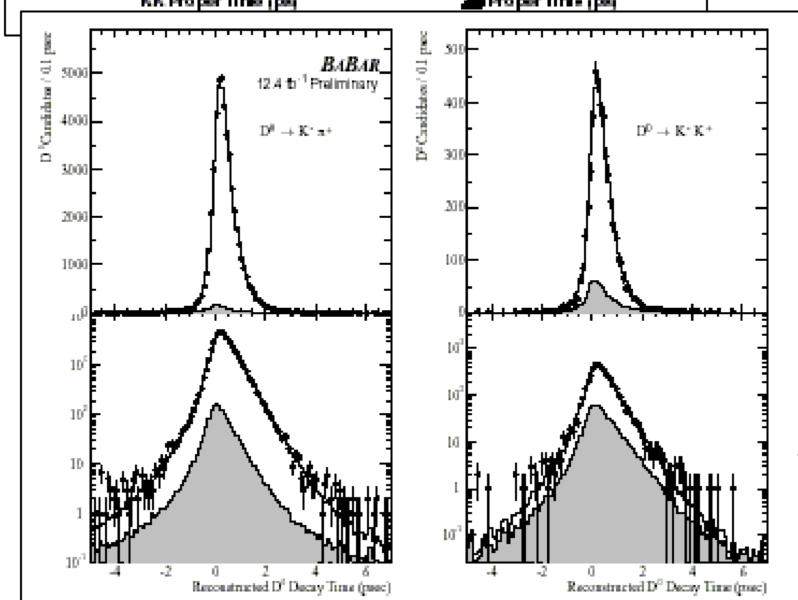
$$R_{WS} \propto (x'^2 + y'^2)(\Gamma t)^2 e^{-\Gamma t}$$

Some Recent y_{cp} Lifetime Results

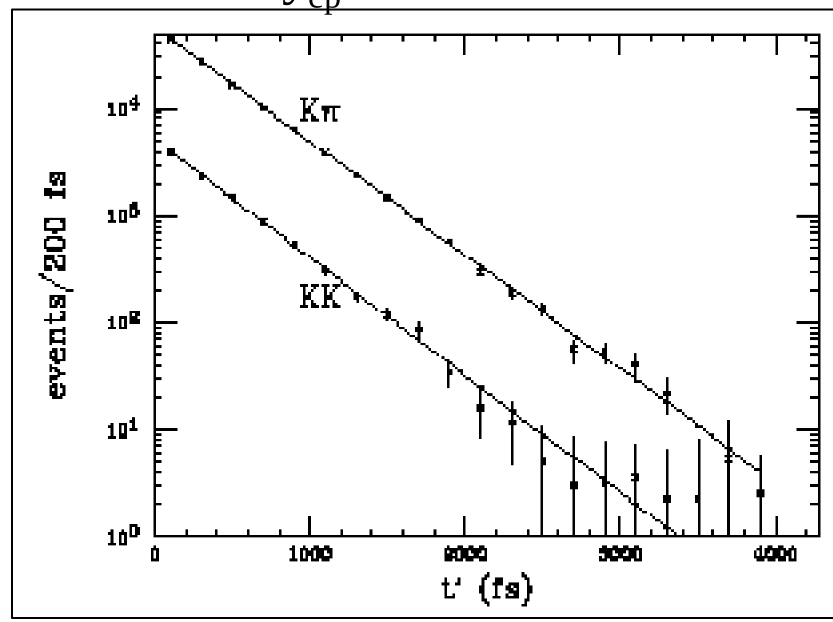
Not a full blown lifetime analysis
Looking for lifetime differences

CLEO: sub. PRD
KK: y_{cp} =-1.9 ±2.9 ±1.6
ππ: y_{cp} = 0.5 ±4.3 ±1.8



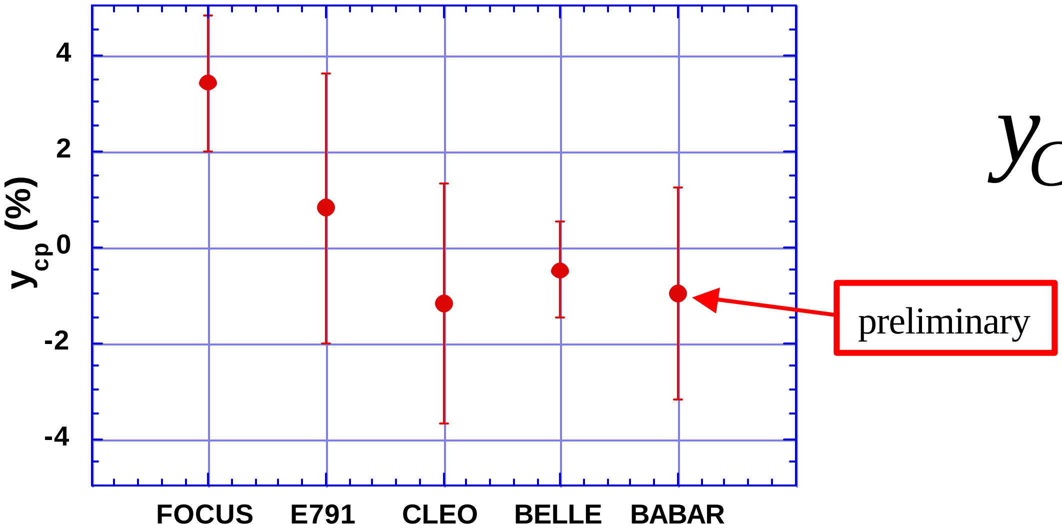


FOCUS: PLB485, 62 (2000)
y_{cp} =3.4 ±1.4 ±0.7



BABAR: preliminary
y_{cp} =-1.0 ±2.2 ±1.7

Recent Mixing Results via y_{cp}



$$y_{CP} = \frac{t_{D \to K\pi}}{t_{D \to KK}} - 1 \approx y$$

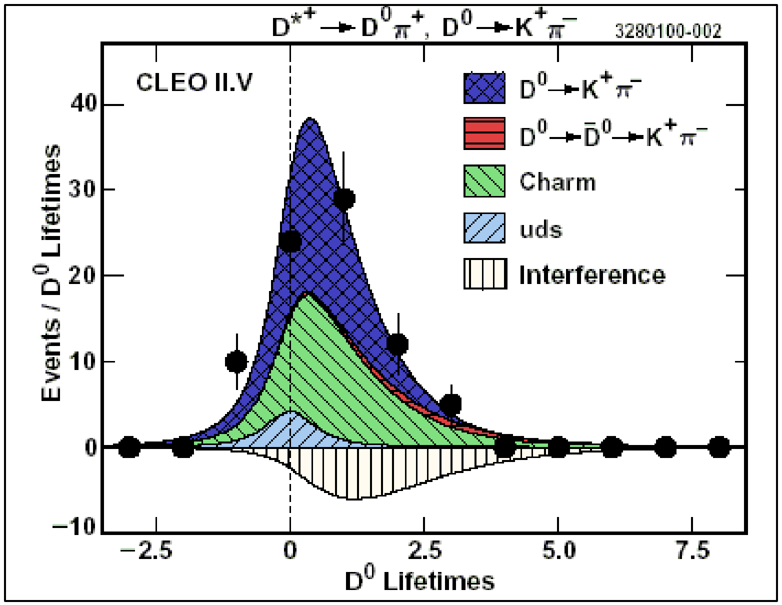
experiment	y_{cp}(%)	comments
FOCUS	3.4 ±1.4 ±0.7	Fixed target, K^+K^-
E791	0.8 ±2.8 ±1.0	Fixed target, K^+K^-
CLEO	-1.2 ±2.5 ±1.4	e^+e^-, K^+K^-,$\pi^+\pi^-$
BELLE	$-0.5 \pm 1.0 ^{+0.7}_{-0.8}$	e^+e^-, K^+K^-
BABAR	-1.0 ±2.2 ±1.7	e^+e^-, K^+K^-

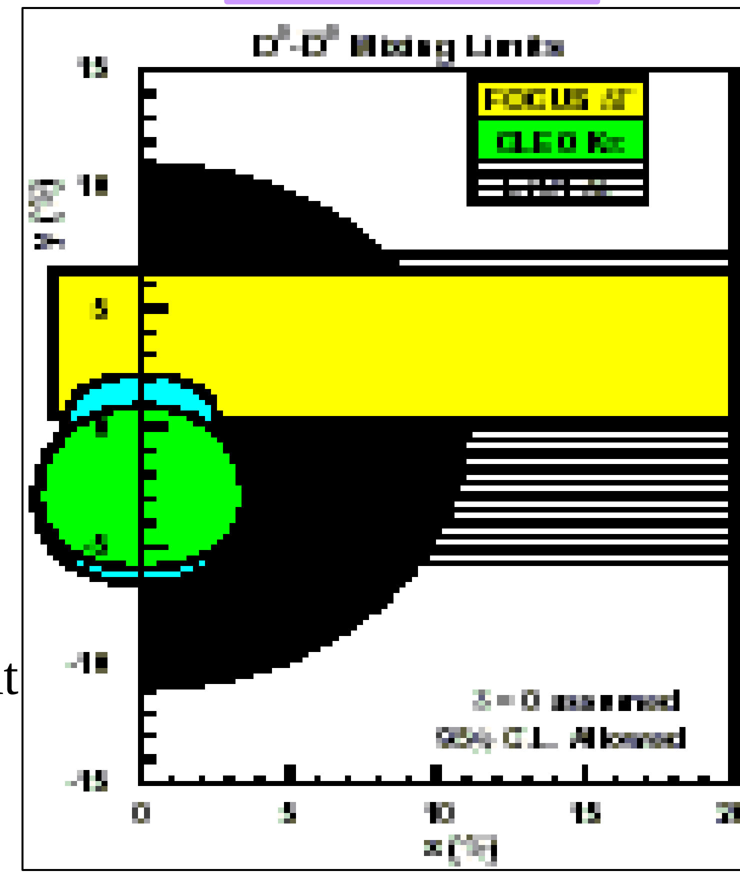
Mixing Limits using "wrong" sign and y_{cp} measurements

♦ CLEO's Time dependence of $\Gamma(D^0 \to K^+\pi^-)/\Gamma(D^0 \to K^-\pi^+)$

$$R_{WS} \propto [R_{DCS} + y'(\Gamma t)\sqrt{R_{DCS}} + \frac{x'^2 + y'^2}{4}(\Gamma t)^2]e^{-\Gamma t}$$

Published Data





♦E791 Semi-leptonic $\Gamma(D^0 \to K^+l^-\nu)/\Gamma(D^0 \to K^-l^+\nu)$ limit

$\Gamma(D^0 \to K^+l^-\nu)/\Gamma(D^0 \to K^-l^+\nu) < 0.5\%$@ 90%CL

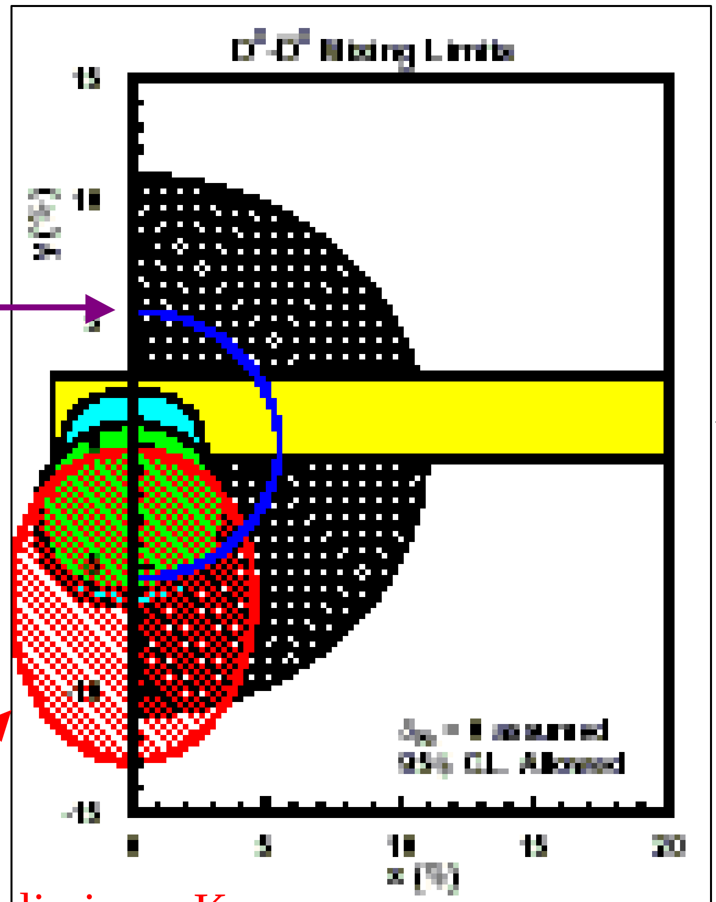
♦ y_{cp} measurements (FOCUS, E791)

Mixing Limits using "wrong" sign and y_{cp} measurements

What will this plot look like in the near future?

New results expected soon from CLEO, FOCUS, BABAR, BELLE

FOCUS, CLEO
SL sensitivity



average y_{cp}

FOCUS preliminary $K\pi$

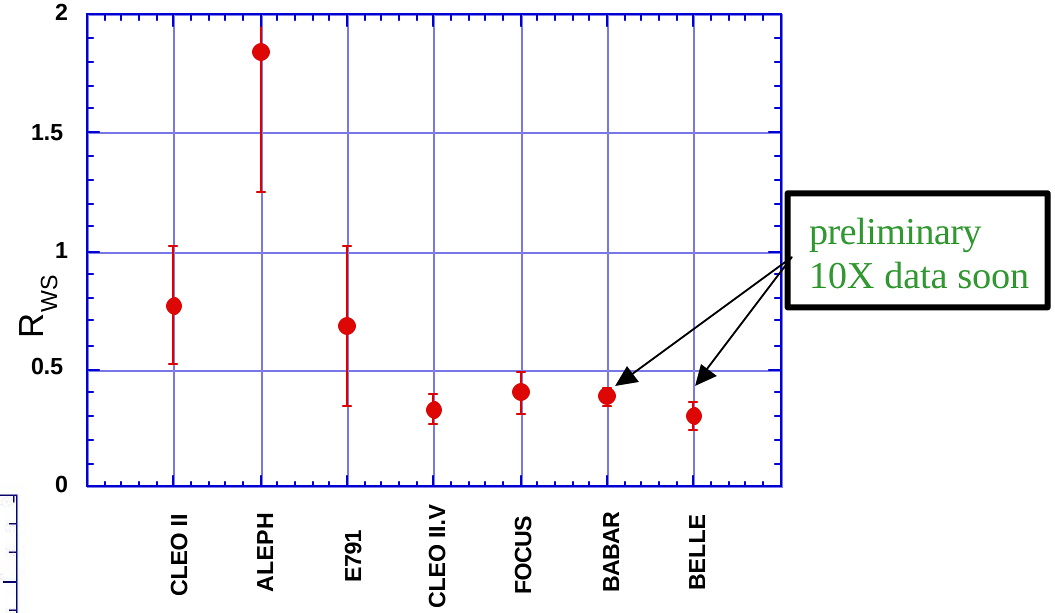
"Wrong" sign D^0 Decay rates

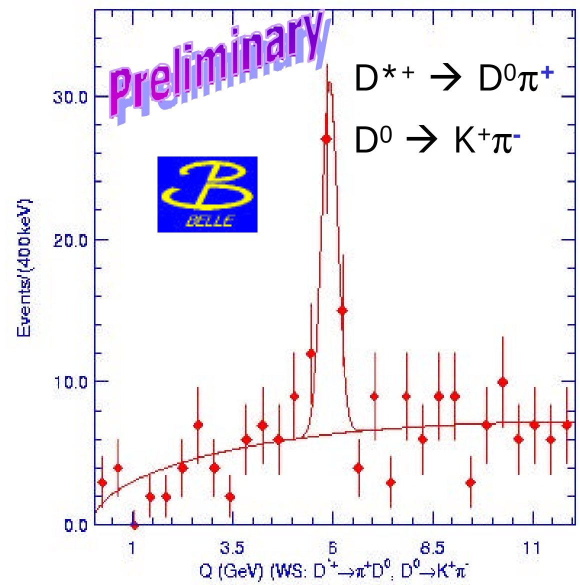
Improved measurements of $\Gamma(D^0 \to K^+\pi^-)/\Gamma(D^0 \to K^-\pi^+)$:

$R_{WS} = \Gamma(D^0 \to K^+\pi^-)/\Gamma(D^0 \to K^-\pi^+)$ (%)

CLEO II	0.77 ± 0.25 ± 0.25
ALEPH	1.84 ±0.59 ±0.34
E791	0.68 ±0.34 ±0.07
CLEO II.V	0.33 ±0.06 ± 0.04
FOCUS	0.40 ±0.09 ±0.03
BABAR	0.38 ±0.04 ±0.02
BELLE	0.30 ±0.06 ±0.08

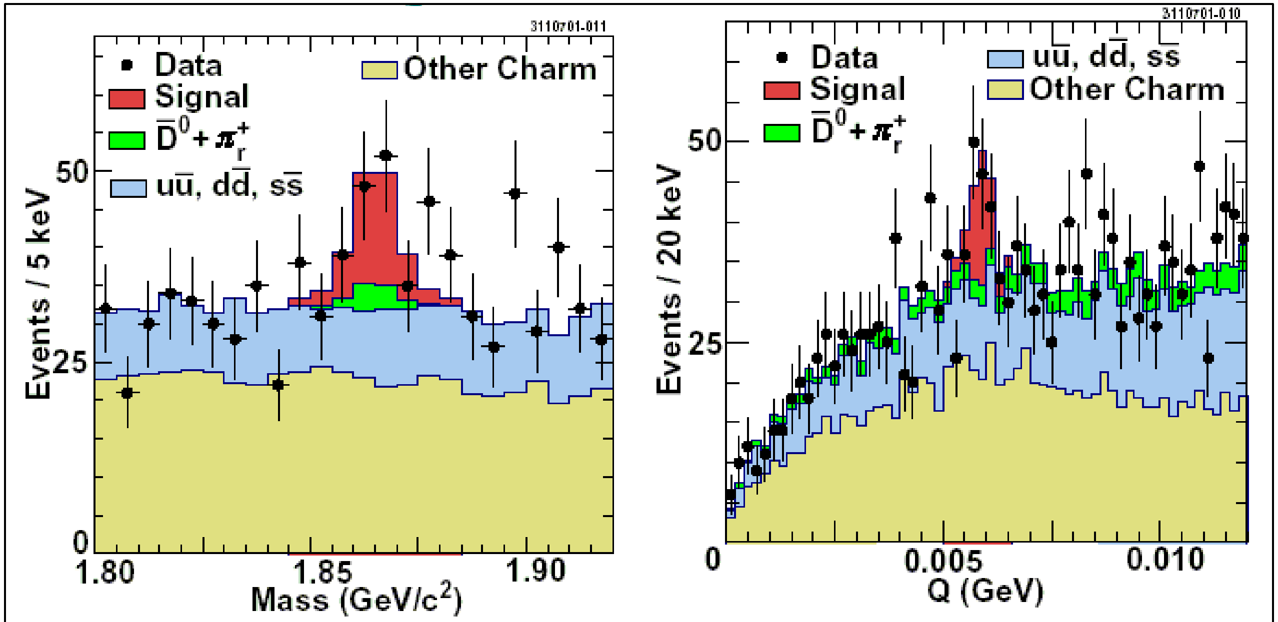
preliminary





More "wrong" sign D^0 Decay rates

CLEO II.V result for $D^0 \to K^+\pi^-\pi^+\pi^-$



9fb^{-1} of data used in analysis

54 ± 14 WS events from 2D binned ML fit

$$R_{WS} = \frac{(D^0 \to K^+p^-p^+p^-)}{(D^0 \to K^-p^+p^-p^+)} = [0.41^{+0.12}_{-0.11}\text{ (stat) } \pm 0.04\text{(sys)}] \times (1.07 \pm 0.10)\text{(phase space)(\%)}$$

CLEO II.V result consistent with previous E791 result:

$$R_{WS} = 0.25\ ^{+0.36}_{-0.34}\text{ (stat) } \pm 0.03\text{ (sys) (\%)} \quad \text{(phase space=1)}$$

But cannot tell if this result is from DSC or mixing since:

$$R_{WS} = R_{DCS} + y'\sqrt{R_{DCS}}+) + 0.5(y'^2 + x'^2)$$

Only other WS D^0 result: CLEO's $R_{WS} = \frac{(D^0 \to K^+p^-p^0)}{(D^0 \to K^-p^+p^0)} = 0.43^{+0.11}_{-0.10} \pm 0.07\%$

$D^0 \longrightarrow K_L^0 \pi^0$ and $K_S^0 \pi^0$

Preliminary result from BELLE

Interference between the Cabibbo allowed decay $D^0 \rightarrow \bar{K}^0 \pi^0$ and the DCS decay $D^0 \rightarrow K^0 \pi^0$ can lead to a rate difference between $D^0 \rightarrow K_L \pi^0$ and $K_S \pi^0$.

Expect a 5% ($\approx \tan^2\theta_c$) asymmetry in:

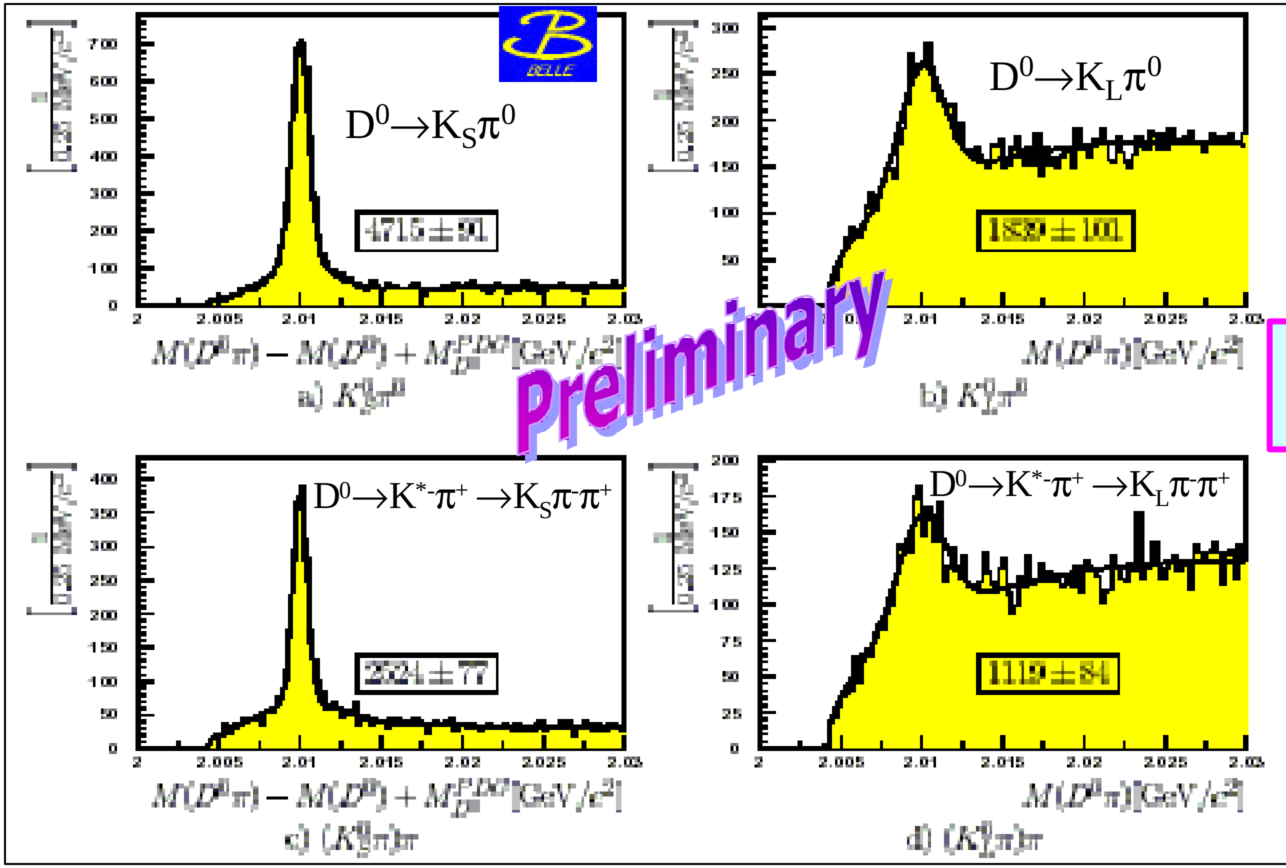
$$A = \frac{\Gamma(D^0 \rightarrow K_S^0 \boldsymbol{p}^0) - \Gamma(D^0 \rightarrow K_L^0 \boldsymbol{p}^0)}{\Gamma(D^0 \rightarrow K_S^0 \boldsymbol{p}^0) + \Gamma(D^0 \rightarrow K_L^0 \boldsymbol{p}^0)}$$

The magnitude and sign of *A* provides info the strong phase difference (δ) between $D^0 \rightarrow K^+ \pi^-$ and $D^0 \rightarrow K^- \pi^+$.

Experimentally very challenging !
Difficult to reconstruct K_L's in an e^+e^- experiment

BELLE calibrates K_L efficiency using $D^0 \rightarrow K^{*-} \pi^+$, with $K^{*-} \rightarrow K_L \pi^-$.

$D^0 \longrightarrow K_L^0\pi^0$ and $K_S^0\pi^0$



First reconstruction of D's using K_L's!

Using 23 fb^{-1} of data BELLE measures:

$$A = \frac{\Gamma(D^0 \to K_S^0 p^0) - \Gamma(D^0 \to K_L^0 p^0)}{\Gamma(D^0 \to K_S^0 p^0) + \Gamma(D^0 \to K_L^0 p^0)} = 0.06 \pm 0.05 \pm 0.05$$

CP Violation in D^0 Decay

CPV expected to be small in the charm sector

SM predictions $O(0.1\%)$

CPV > 1% evidence for non-SM processes

Look for particle ⇔ anti-particle rate differences

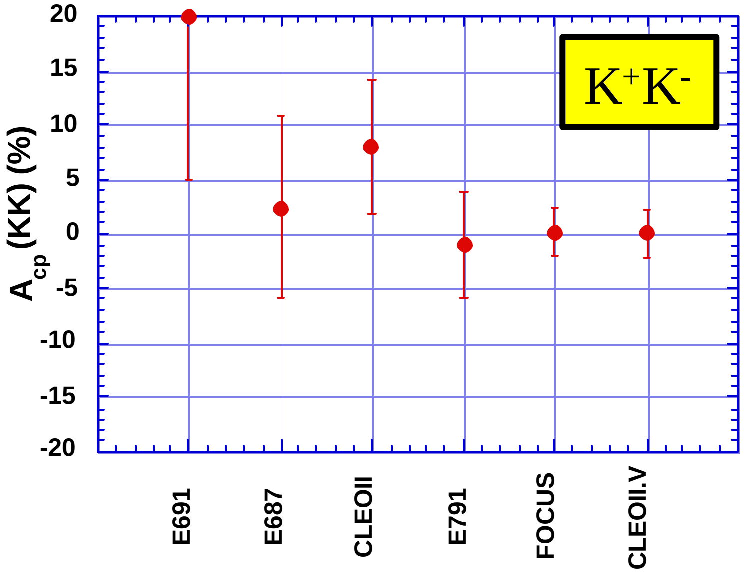
$$A_{CP} = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$

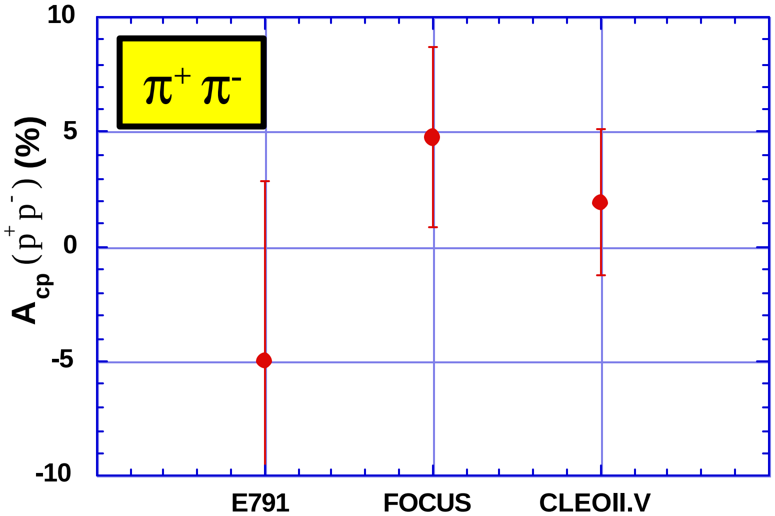
Use D* tag to distinguish D^0 from $\bar{D}^0$.

Measure: $$A'_{CP} = \frac{\Gamma(D^{*+} \to p^+ f) - \Gamma(D^{*-} \to p^- f)}{\Gamma(D^{*+} \to p^+ f) + \Gamma(D^{*-} \to p^- f)}$$

Where *f* is: K^+K^-, $\pi^+\pi^-$, $K_s\phi$, $K_s\pi^0$, $\pi^0\pi^0$, and K_sK_s

CP Violation in D^0 Decay





CLEO also has the following results:

$A_{CP}(K_s\phi)=-2.8\pm9.4\%$ $A_{CP}(\pi^0\pi^0)=0.1\pm4.8\%$

$A_{CP}(K_s\pi^0)=0.1\pm1.3\%$ $A_{CP}(K_sK_s)=23\pm19\%$

CLEO "wrong" sign $D^0\rightarrow K^+\pi^-$ analysis yields:

$A_{CP}(K^+\pi^-)=2^{+19}_{-20}\pm1.0\ \%$ No mixing in fit

No evidence for CP violation in D^0 decay

CP Violation in D^+ Decay

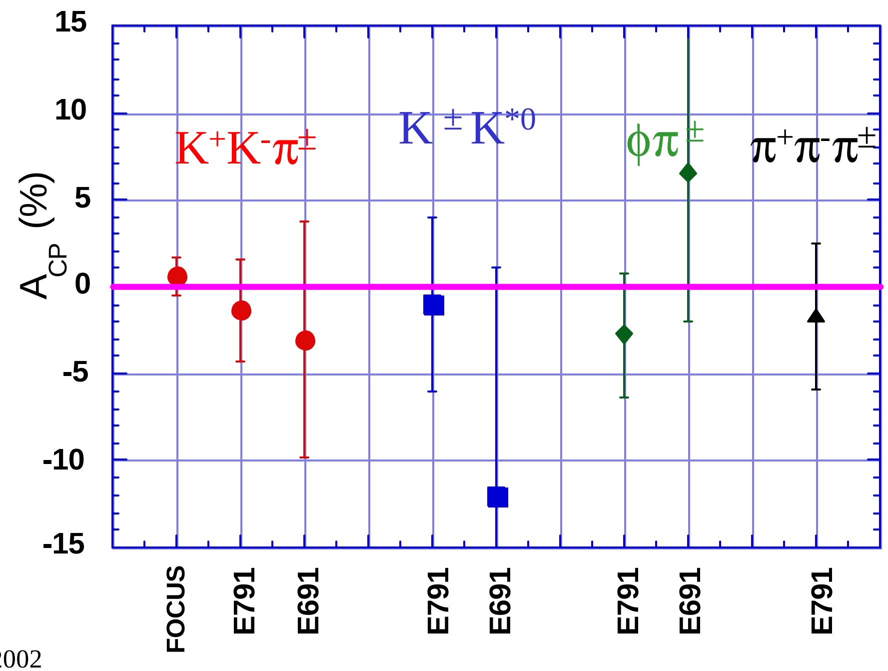
For charged D's measure the following:

$$A_{CP} = \frac{\Gamma(D^+ \to f^+) - \Gamma(D^- \to f^-)}{\Gamma(D^+ \to f^+) + \Gamma(D^- \to f^-)}$$

Look for direct CP violation, no mixing.

Not much new since 2000

All results are from fixed target experiments.



No evidence for CPV

CLEO Measurement of $B(D^+ \to \bar{K}^{*0} l^+ \nu_l)$

This decay is sensitive to P $\to$V form factor

These form factors are related to *ff*'s in b$\to$ulν and b$\to$sll.

Can help reduce uncertainty in extraction of $|V_{ub}|$

CLEO Method:

Use D* tag, reconstruct ν using jet direction for D^+ direction

2-fold ambiguity, choose solution closest to $\delta m = M_{D^*} - M_D = 140.6$ MeV

fit K* mass in bins for δm then fit resulting δm with K*+data to extract signal

$$R_l = \frac{B(D^+ \to \bar{K}^{*0} l^+ n)}{B(D^+ \to K^- p^+ p^+)}$$

$R_e = 0.74 \pm 0.04 \pm 0.06$

$R_\mu = 0.72 \pm 0.104 \pm 0.06$

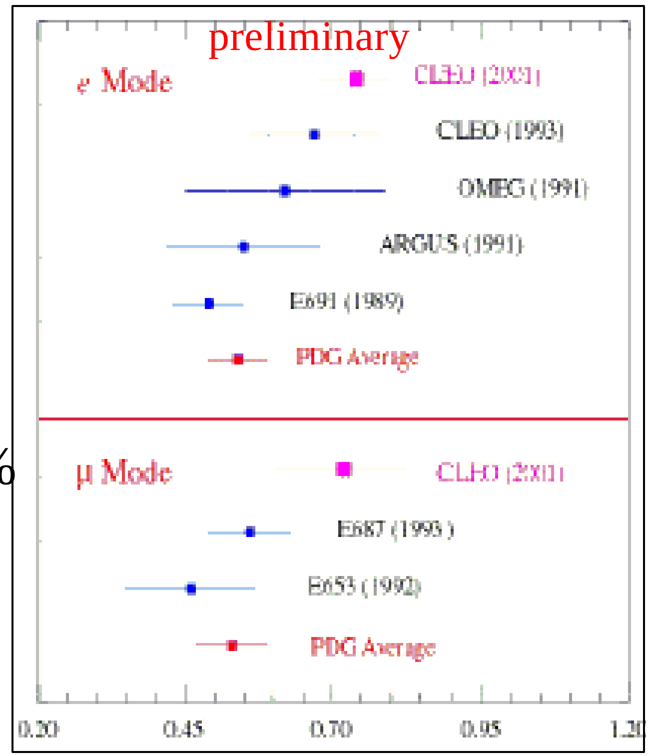
$R = 0.73 \pm 0.04 \pm 0.05$

PDG: $B(D^+ \to K^- \pi^+ \pi^+) = (9.0 \pm 0.6)\%$

$BR_e = (6.7 \pm 0.4 \pm 0.5 \pm 0.4)\%$

$BR_\mu = (6.5 \pm 0.9 \pm 0.5 \pm 0.4)\%$

$BR = (6.6 \pm 0.4 \pm 0.5 \pm 0.4)\%$



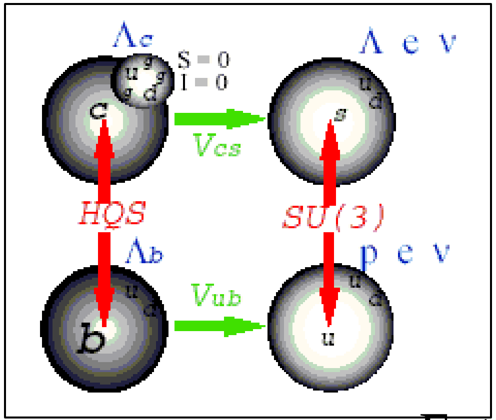
CLEO's form factor ratio measurement in $\Lambda_c \to \Lambda e^+ \nu$

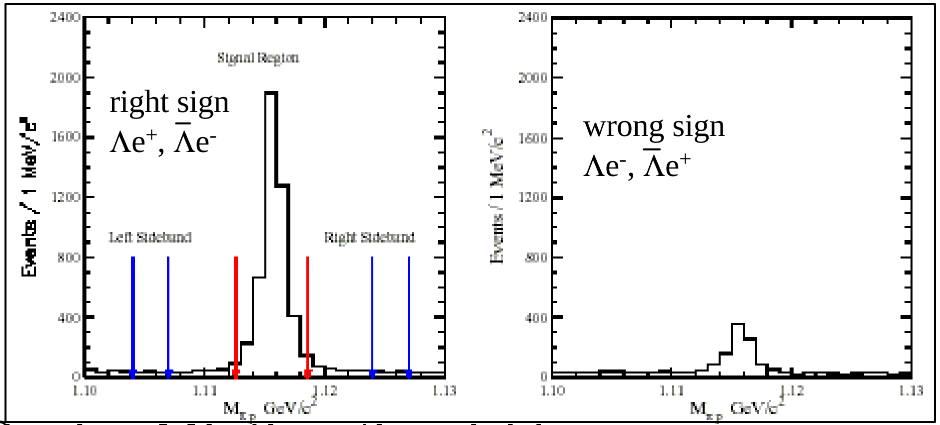
Motivation: Alternative method for extracting $|V_{ub}|$ and $|V_{cb}|$

Same set of form factors in both decays: $f_1(q^2)$, $f_2(q^2)$

$$f_i(q^2) = \frac{f_i(q^2_{\max})}{(1-q^2/m^2_{D_s^*})^2}(1-q^2_{\max}/m^2_{D_s^*})^2$$

Korner&Kramer predict: $R = f_2(q^2)/f_1(q^2) = -0.25$ (PL B275,495 (1992))





Extract R using ML fit to 3 variables:

- $t = (q/q_{\max})^2$
- $\cos\theta_W$ = angle between e and W in cm of W
- $\cos\theta_\Lambda$ = angle between p and Λ in cm of Λ

Preliminary Result: $R = -0.31 \pm 0.06 \pm 0.06$

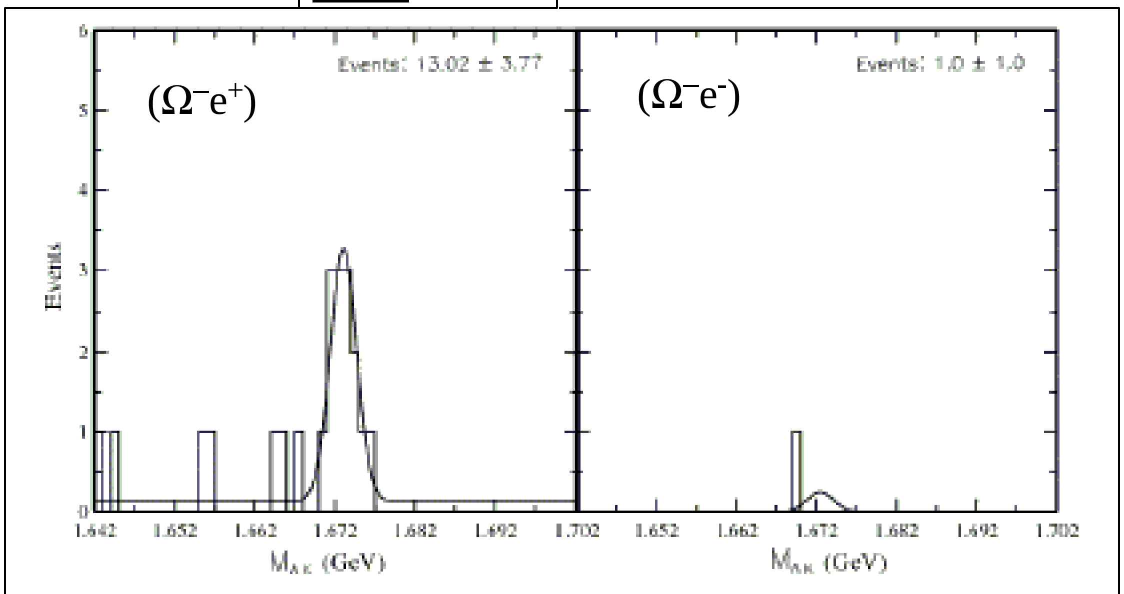
Improvement over previous CLEO result: $R = -0.25 \pm 0.14 \pm 0.08$, (PRL 75,624 (1995))

Consistent with Korner&Kramer

$\Omega_c^0 \to \Omega^- e^+ \nu$

Search for $\Omega_c^0 \to \Omega^- e^+ \nu$ by comparing "right" ($\Omega^- e^+$) sign and "wrong" sign ($\Omega^- e^-$) event yields.

CLEO preliminary



Probability of background fluctuation < 9×10^{-4}

$B(\Omega_c^0 \to \Omega^- e^+ \nu)\sigma(e^+e^- \to \Omega_c X) = 42.2 \pm 14.1 \pm 11.9$ fb

10X smaller than ARGUS result $520 \pm 230 \pm 130$ fb

First observation of baryon β decay with no *u* or *d* in parent particle

Charm Review Summary

Lifetimes: mesons: lifetimes measured to 1- 2%

baryons: lifetimes measured ~2 - 30%

theory may need a tune up: $\tau_{\Xi_c^+}/\tau_{\Lambda_c}|_{exp}>2$ *vs* $\tau_{\Xi_c^+}/\tau_{\Lambda_c}|_{th}< 1.7$

D Mixing: Exciting times ahead

new results expected from BELLE & BABAR soon

CP Violation: Keep looking !

Semileptonic Decays: Progress measuring rates and form factors

"The future of charm physics lies ahead of us !"

Yogi Berra? George W.?

b-factories are charm factories too

CLEO-c