RECENT RESULTS FROM FOCUS

Brian O'Reilly

University of Colorado
Boulder, CO 80309

Representing the FOCUS Collaboration

ABSTRACT

Some recent results from the Fermi National Accelerator Laboratory (Fermilab) fixed target experiment FOCUS are presented. In particular we discuss a study of the decay $D^0 \to K^+\pi^-$ and its implications for mixing, a search for direct CP violation and some new measurements of charm particle lifetimes.

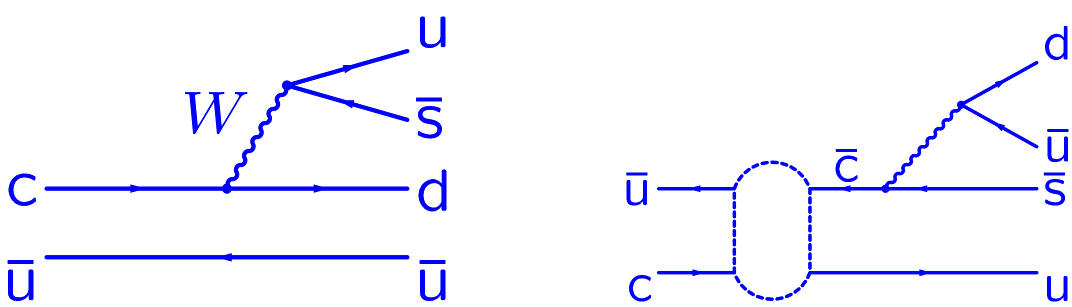

Fig. 1. Feynman diagrams of the DCS and mixing processes for $D^0 \to K^+\pi^-$

1 Introduction

Precise measurements of charmed particle decays challenge existing theoretical methods of calculating the dynamics of heavy quark decays. Additionally mixing and CP violation are expected to be small in this sector making it an ideal place to search for non-Standard Model physics. FOCUS is a photoproduction experiment which took data during the 1996-1997 fixed target run at Fermilab. Bremsstrahlung of electrons and positrons with an endpoint energy of approximately 300 GeV produces a photon beam. These beam photons interact in a segmented beryllium-oxide target and produce charmed particles. The average photon energy for events which satisfy our trigger is $\simeq$ 180 GeV. FOCUS uses an upgraded version of the E687 spectrometer which is described in detail elsewhere.[1] Charged decay products are momentum analyzed by two oppositely polarized dipole magnets. Tracking is performed by a system of silicon vertex detectors in the target region and by multiwire proportional chambers downstream of the interaction. Particle identification is performed by three threshold Čerenkov counters, two electromagnetic calorimeters, an hadronic calorimeter, and by a system of muon detectors.

2 The decay $D^0 \to K^+\pi^-$

The decay $D^0 \to K^+\pi^-$ (throughout this article the charge conjugate mode is implied unless otherwise indicated) may occur either as a doubly Cabibbo suppressed (DCS) decay or through mixing of the D^0 into a $\bar{D}^0$ followed by the Cabibbo Favored (CF) decay $\bar{D}^0 \to K^+\pi^-$. Therefore the wrong-sign (WS) decay rate R_{WS} can have contributions from both DCS and from mixing. The time-dependent rate for WS decays relative to the CF process is:

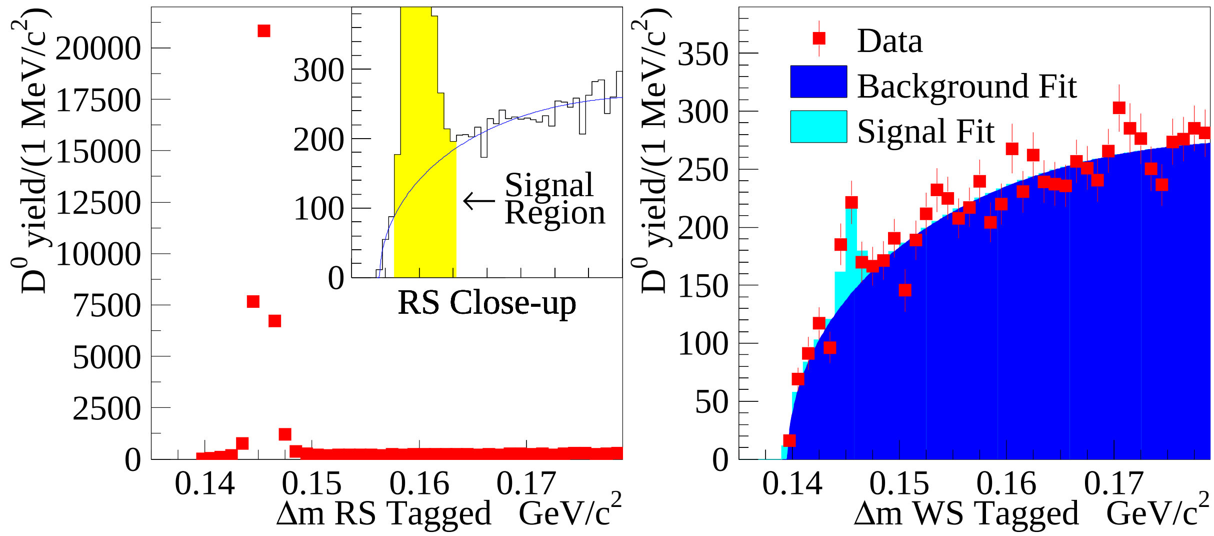

Fig. 2. RS and WS signals for the decay $\bar{D}^0 \to K^+\pi^-$

$$R(t) = \left[R_{DCS} + \sqrt{R_{DCS}}y\prime t + \frac{(x\prime^2 + y\prime^2)}{4}t^2\right] e^{-t} \tag{1}$$

where t is in units of the D^0 lifetime and we have used the strong phase (δ) rotated convention of CLEO[2] where $y\prime = y\cos\delta - x\sin\delta$ and $x\prime = x\cos\delta + y\sin\delta$. $x = \Delta m/\Gamma$ and $y = \Delta\Gamma/2\Gamma$ are the usual mixing parameters. Using Monte Carlo (MC) generated sample of $\bar{D}^0 \to K^+\pi^-$ decays, (with an input lifetime of 413 fs for the D^0[3]), we can calculate the expected number of WS events by re-weighting each accepted MC event with a weight given by:

$$W_i = \frac{N_{data}}{N_{MC}}\left(R_{DCS} + \sqrt{R_{DCS}}y\prime t_i + \frac{(x\prime^2 + y\prime^2)}{4}t_i^2\right), \tag{2}$$

where t_i is the generated proper time for event i, and $N_{data}(N_{MC})$ is the number of accepted RS events in the data(MC). Summing Equation 2 over all accepted MC events and dividing by N_{data} we obtain:

$$R_{WS} = R_{DCS} + \sqrt{R_{DCS}}y\langle t\rangle + \frac{(x\prime^2 + y\prime^2)}{4}\langle t^2\rangle. \tag{3}$$

The averages $\langle t\rangle$ and $\langle t^2\rangle$ are obtained from the generated lifetime of the accepted MC events. We find $\langle t\rangle = 1.578 \pm 0.008$ and $\langle t^2\rangle = 3.61 \pm 0.03$ where the error is a systematic obtained by comparing the reconstructed MC averages to those obtained in the data. We now have an expression for R_{WS}, which is the quantity we measure experimentally, in terms of R_{DCS} and the mixing parameters $x\prime$ and $y\prime$.

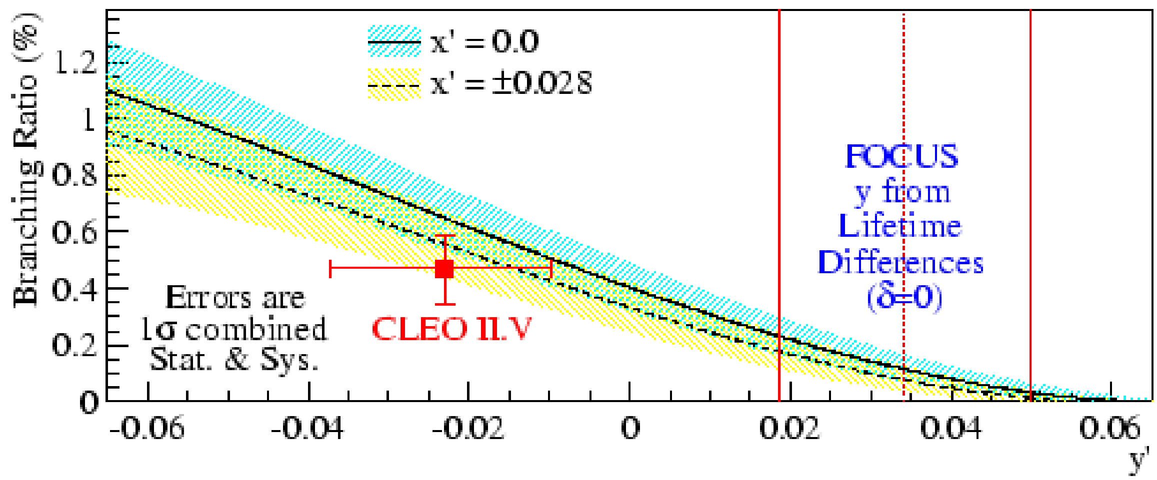

Fig. 3. R_{DCS} vs. $y\prime$. Contours are plotted for two values of $x\prime$ which cover the 95% CL of the CLEO.II.V result.

We identify right sign (RS) and WS decays by "tagging" the soft pion in the decay $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$. In Figure 2 we show the signals obtained. The WS signal is obtained by fitting the D^0 yield in bins of the $D^{*+} - D^0$ mass difference and the fit is a sum of a background contribution and a scaled signal shape from the RS. We measure $R_{WS} = (0.404 \pm 0.085 \pm 0.025)\,\%$ with a WS yield of 149 ± 31 events.

In Figure 3 we use our measured value for R_{WS} to plot R_{DCS} as a function of $y\prime$. The CLEO.II.V and FOCUS[4] results are also included for comparison purposes. The FOCUS result comes from a measurement of y using the lifetime difference between CP even and CP mixed final states. The CLEO.II.V result comes from a direct measurement of R_{DCS}. One can only compare the FOCUS y value to the others by assuming that the strong phase $\delta = 0$.

If charm mixing is sufficiently small then Equation 3 tells us that $R_{WS} \approx R_{DCS}$. In Table 1 we list the existing measurements of this branching ratio under the assumption of no mixing or CP violation. Our analysis of the decay $D^0 \to K^+\pi^-$ has been published in Reference 5.

Table 1. Measurements of R_{DCS} assuming no charm mixing or CP violation.

Experiment	R_{DCS}(%)	Events
CLEO[6]	$0.77 \pm 0.25 \pm 0.25$	19.1
E791[7]	$0.68^{+0.34}_{-0.33} \pm 0.07$	34
Aleph[8]	$1.77^{+0.60}_{-0.56} \pm 0.31$	21.3
CLEO.II.V[2]	$0.332^{+0.063}_{-0.065} \pm 0.040$	44.8
This Study[5]	$0.404 \pm 0.085 \pm 0.025$	149

3 Search for Direct CP violation in the decays $D^+ \to K_S\pi^+$ and $D^+ \to K_S K^+$

CP is violated when the decay rate of a particle differs from that of its CP conjugate.[9] In the Kobayashi-Maskawa ansatz this arises due to the non-vanishing phase in the Cabibbo-Kobayashi-Maskawa matrix when the decay amplitude has contributions from at least two quark diagrams with differing weak phases. In addition final state interactions (FSI) must provide a strong phase shift. In the Standard Model direct CP violation in the charm meson system is predicted to occur at the level of 10^{-3} or below.[10] The mechanism usually considered is the interference of the tree and penguin amplitudes in singly-Cabibbo suppressed (SCS) decays. In the decay $D^+ \to K_S\pi^+$, (The charge conjugate state is implied unless stated otherwise), the Cabibbo favored (CF) and doubly-Cabibbo suppressed (DCS) amplitudes contribute coherently with, perhaps, a different weak phase. In addition the isospin content of the DCS amplitude differs from that of the CF case so we can expect a non-trivial strong phase shift. Several authors have commented on the effect of K^0 mixing on the CP asymmetry for this decay mode and the possibility of using it to search for new physics.[11,12]

Differences in the weak two-body non-leptonic decay amplitudes of charmed mesons are almost certainly due to FSI. These effects tend to be large in the charmed system making it an ideal laboratory for their study.[13] The isospin amplitudes and phase shifts in $D \to KK$, $D \to K\pi$ and $D \to \pi\pi$ decays can be extracted from measurements of the branching fractions.[14] For example the magnitude of the I=3/2 amplitude can be obtained directly from the $D^+ \to \bar{K}^0\pi^+$ partial width.[15]

Previous studies of $D^+ \to K_S\pi^+$ and $D^+ \to K_S K^+$ have concentrated on measuring relative branching ratios.[16,17] FOCUS has made the first measurement of the CP asymmetry for these decays.

Table 2. Yields and relative efficiencies for $D^+ \to K_S\pi^+$, $D^+ \to K_SK^+$ and $D^+ \to K^-\pi^+\pi^+$. Efficiency numbers are quoted relative to the average of the $D^+ \to K^-\pi^+\pi^+$ and $D^- \to K^+\pi^-\pi^-$ efficiencies. We generated a very large Monte Carlo sample to render the statistical error on the efficiencies negligible.

Decay Mode	$D^+ \to K_S\pi^+$ cuts		$D^+ \to K_SK^+$ cuts	
	Yield	Eff.	Yield	Eff.
$D^+ \to K_S\pi^+$	5080 ±110	0.58	4487 ± 96	0.51
$D^- \to K_S\pi^-$	5518 ±110	0.56	4770 ± 96	0.50
$D^+ \to K_SK^+$	-	-	495 ± 38	0.26
$D^- \to K_SK^-$	-	-	454 ± 42	0.25
$D^+ \to K^-\pi^+\pi^+$	84750 ±512	1.01	84750 ± 512	1.01
$D^- \to K^+\pi^-\pi^-$	91520 ±508	0.99	91520 ± 508	0.99

To correct for production induced asymmetries we make a double ratio using a CF decay where no CP violation is expected to occur. We measure

$$A_{CP} = \frac{\eta\left(D^+\right) - \eta\left(D^-\right)}{\eta\left(D^+\right) - \eta\left(D^-\right)}; \tag{4}$$

where (for example)

$$\eta\left(D^+\right) = \frac{N(D^+ \to K_S\pi^+)}{N(D^+ \to K^-\pi^+\pi^+)} \tag{5}$$

i.e. the ratio of the yields in each decay mode corrected for efficiency and acceptance. This last quantity is equivelant to the relative branching ratio for the decay in question.

The invariant mass signals for the decays $D^+ \to K_S\pi^+$ and $D^+ \to K_SK^+$ can be seen in Figures 4 and 5. The reconstruction efficiencies, relative to that of the $D^+ \to K^-\pi^+\pi^+$ normalizing mode are listed, together with the yields, in Table 2.

In Table 3 we present our relative branching ratio measurements and compare them to the current world average. Finally in Table 4 we show our A_{CP} measurements for the $D^+ \to K_S\pi^+$ and $D^+ \to K_SK^+$ decay modes. This work has now been published in reference [18].

Fig. 4. $D^+ \to K_S\pi^+$ and $D^- \to K_S\pi^-$ signals.

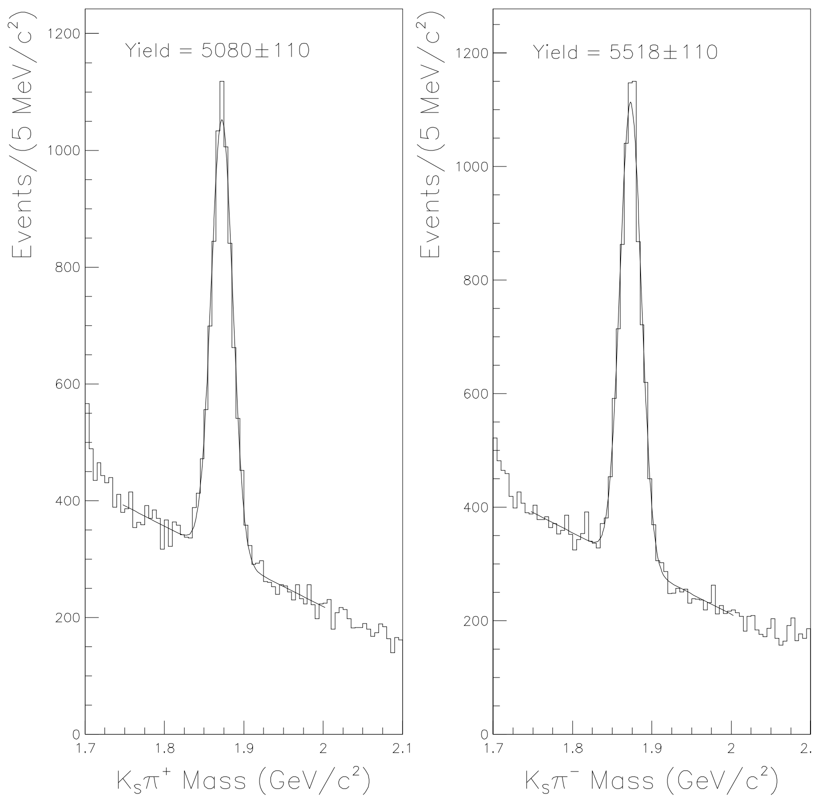

Table 3. Relative branching ratio results. The first error is statistical and the second is systematic. We account for the decay chain $\bar{K}^0 \to K_S \to \pi^+\pi^-$ by multiplying our K_S numbers by a factor of 2.91 assuming that $\Gamma(D^+ \to \bar{K}^0\pi^+) = 2 \times \Gamma(D^+ \to K_S\pi^+)$; we then quote these results in terms of $\bar{K}^0$.

Measurement	Result	PD G Average [3]
$\frac{\Gamma(D^+\to\bar{K}^0\pi^+)}{\Gamma(D^+\to K^-\pi^+\pi^+)}$	$(30.60 \pm 0.46 \pm 0.32)\%$	$(32.0 \pm 4.0)\%$
$\frac{\Gamma(D^+\to\bar{K}^0K^+)}{\Gamma(D^+\to K^-\pi^+\pi^+)}$	$(6.04 \pm 0.35 \pm 0.30)\%$	$(7.7 \pm 2.2)\%$
$\frac{\Gamma(D^+\to\bar{K}^0K^+)}{\Gamma(D^+\to\bar{K}^0\pi^+)}$	$(19.96 \pm 1.19 \pm 0.96)\%$	$(26.3 \pm 3.5)\%$

Fig. 5. $D^+ \to K_S K^+$ and $D^- \to K_S K^-$ signals.

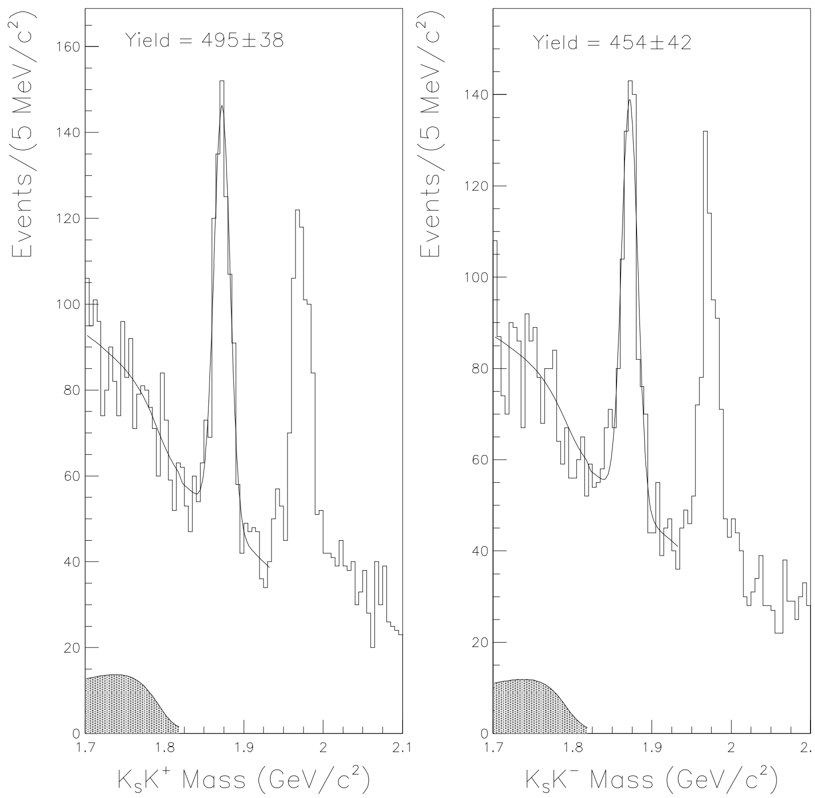

Table 4. CP asymmetry measurements. The first error is statistical and the second is systematic.

Measurement	Result
$A_{CP}(K_S\pi^+)$ w.r.t. $D^+ \to K^-\pi^+\pi^+$	$(-1.6 \pm 1.5 \pm 0.9)\%$
$A_{CP}(K_S K^+)$ w.r.t. $D^+ \to K^-\pi^+\pi^+$	$(+6.9 \pm 6.0 \pm 1.5)\%$
$A_{CP}(K_S K^+)$ w.r.t. $D^+ \to K_S\pi^+$	$(+7.1 \pm 6.1 \pm 1.2)\%$

4 Charm Lifetimes

Precise measurements of the lifetimes of charmed mesons and baryons provide an important test of our theoretical understanding of the dynamics of heavy quarks. Heavy Quark Effective theory relies on expansions in the heavy quark mass, extensions to the charm sector may be complicated by the lower mass of the charm quark. Lifetime differences between mesons and baryons in the beauty sector tend to be significantly scaled down relative to those of charm. Thus it has been said that “the decays of charm hadrons act as nature’s microscope into the decays of beauty hadrons”.[19]

Historically, FOCUS is the only collaboration to have measured all of the weakly decaying charm particle lifetimes. Our excellent lifetime resolution (on the order of 30fs for some decays), and high statistics ensure that our new measurements will once again dominate the world average. Only with the advent of high statistics charm analyses from the e^+e^- factories will more precise measurements be forthcoming. In that event our precision measurements with tightly controlled systematics should serve as a benchmark by which to evaluate and control systematic effects unique to the collider regime.

Currently we have published results for the Ξ_c^+ and are in the process of finalizing the Λ_c^+,D^+,D^0,D_s^+,Ξ_c^0 and Ω_c^0 lifetime analyses.

4.1 Ξ_c^+ Lifetime

We have measured the Ξ_c^+ lifetime using five different decay modes which occur in eight distinct topologies. In Figure 6 we show the signal distributions and the lifetime fit is shown in Figure 7. Our analysis was based on a yield of 532.4 ± 30.4 events. We measured a lifetime of $439 \pm 22 \pm 9$ fs where the first error is statistical and the second is systematic. In Figure 8 we compare this result to previous experimental measurements. The improvement over previous results is obvious as is the fact that the world average for the Ξ_c^+ lifetime will increase. Several authors[20–23] predict that $\tau(\Xi_c^+) > \tau(\Lambda_c^+)$ where the inequality represents a factor of about 1.3. Using the Λ_c^+ lifetime average of PDG, CLEO and SELEX,[3,24,25] $(0.1916 \pm 0.0054$ ps) and the Ξ_c^+ lifetime reported in this paper, one obtains a ratio $\tau(\Xi_c^+)/\tau(\Lambda_c^+) = 2.29 \pm 0.14$, which differs significantly from the prediction. This work is now published in reference [26].

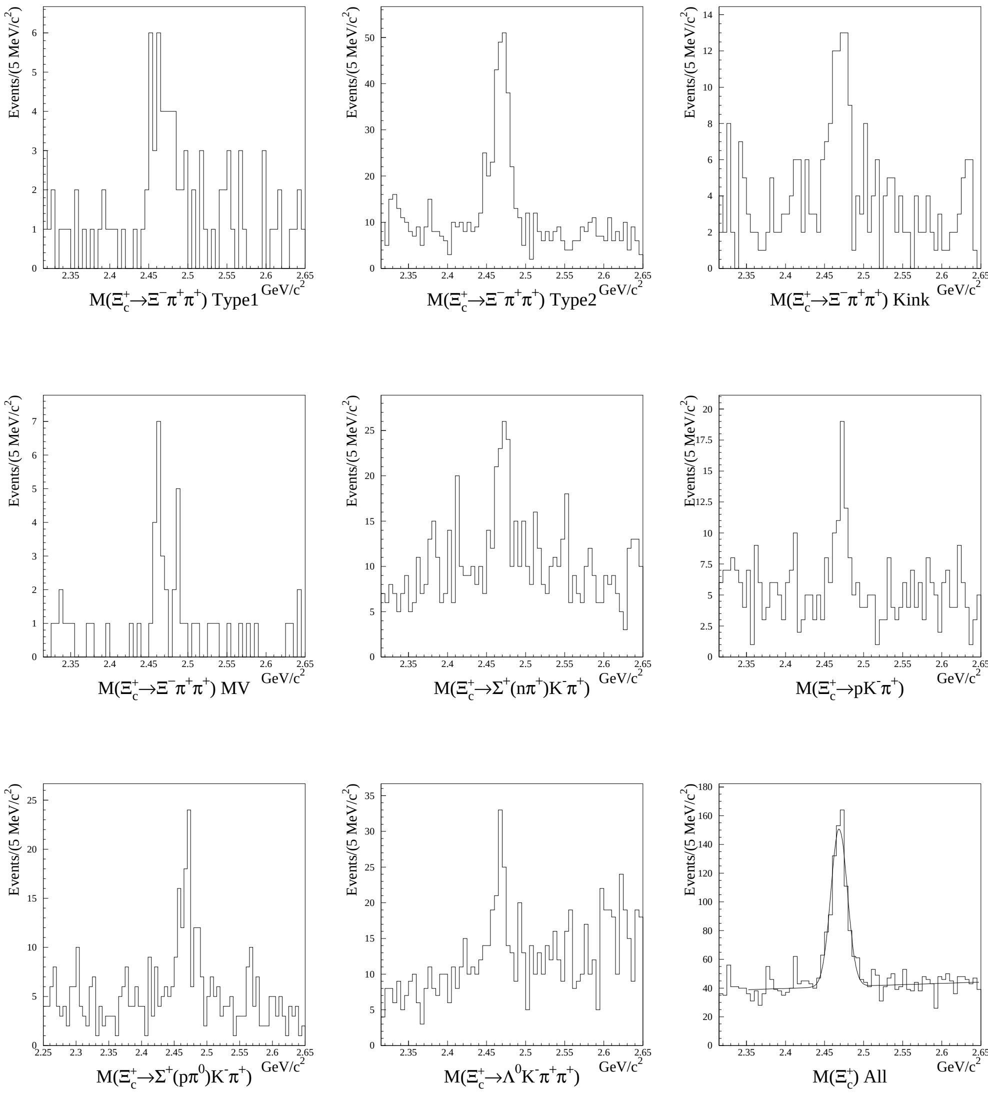

Fig. 6. Signals for the five different decay modes used in our determination of the Ξ_c^+ lifetime. The bottom right plot is the sum of all the modes.

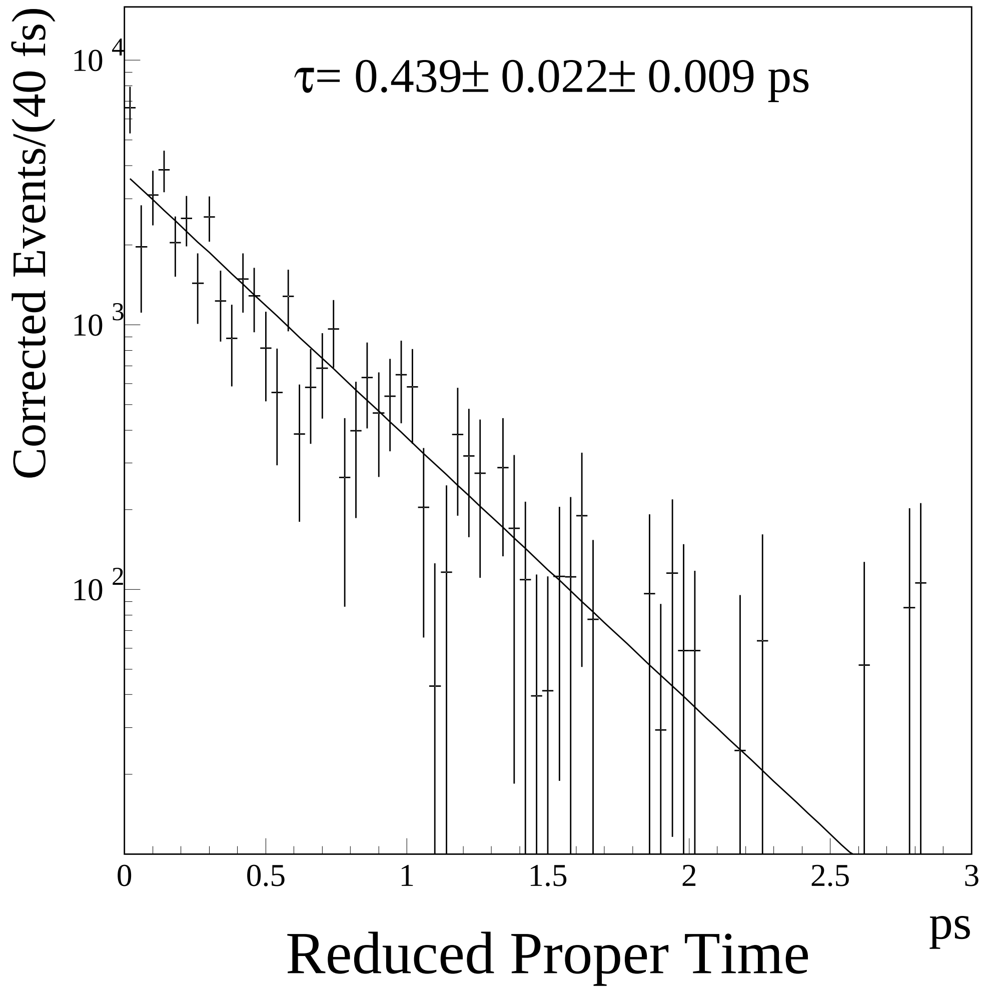

Fig. 7. The combined lifetime fit to the background subtracted, Monte Carlo corrected, reduced proper time distribution obtained from all the studied decay modes.

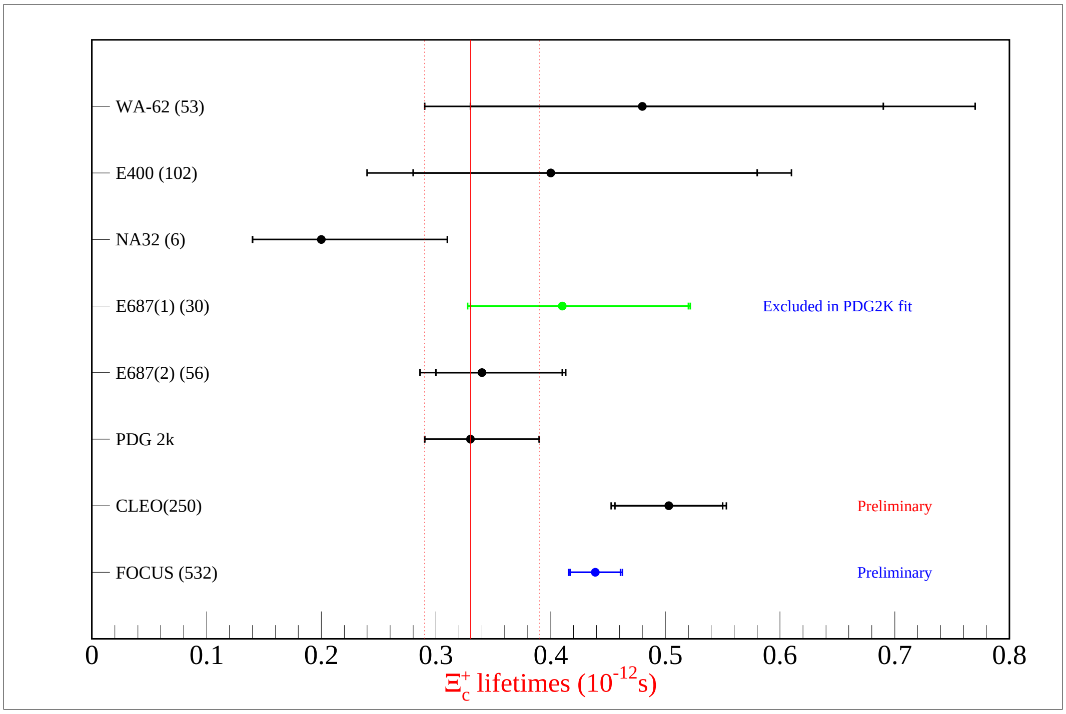

Fig. 8. Comparison of experimental measurements of the Ξ_c^+ lifetime. Note that the CLEO and FOCUS numbers are no longer preliminary. The number in parentheses after each experiment's name represents the number of events they used to make their measurement.

4.2 Λ_c^+ Lifetime

We have also measured the lifetime of the Λ_c^+ from the decay mode $\Lambda_c^+ \to \mathrm{p}K^-\pi^+$. We reconstructed 8034 ± 122 events and determined the lifetime to be $204.6 \pm 3.4 \pm 2.5$ fs. This result has been submitted for publication.[27]

We are analysing two decay modes for the Ξ_c^0 which occur in five separate topologies. In Figure 11 the signals used in our preliminary determination of this lifetime are plotted. Using 137 ± 18.8 events we measure the lifetime to be 109^{+10}_{-9} fs.

In addition to these analyses we are also working on the lifetime measurements for the D^0, D^+ and Ω_c^0.

5 Summary

We have presented some recent results from FOCUS on mixing, direct CP violation limits and charm lifetimes. Many of these analyses are soon to be, or have already been

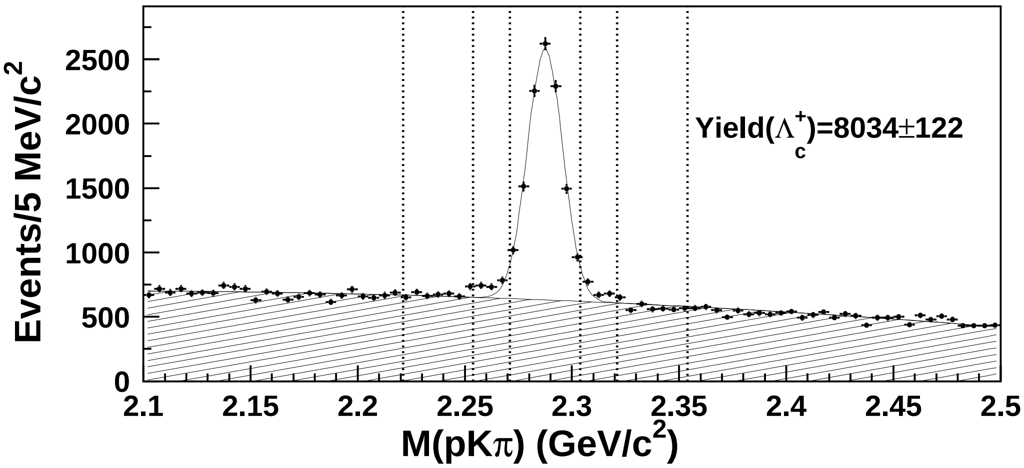

Fig. 9.

published. In addition we are working on a wide variety of other topics such as Dalitz analyses, $D\bar{D}$ production, semileptonic branching ratios and form factors, five-body hadronic decays and the spectroscopy of excited charm mesons.

References

[1] P. L. Frabetti *et al.*, Nucl. Instrum. Meth. **A320**, 519 (1992).

[2] R. Godang *et al.*, Phys. Rev. Lett. **84**, 5038 (2000).

[3] D. E. Groom *et al.*, Eur. Phys. J. **C15**, 1 (2000).

[4] J. M. Link *et al.*, Phys. Lett. **B485**, 62 (2000).

[5] J. M. Link *et al.*, Phys. Rev. Lett. **86**, 2955 (2001).

[6] D. Cinabro *et al.*, Phys. Rev. Lett. **72**, 1406 (1994).

[7] E. M. Aitala *et al.*, Phys. Rev. **D57**, 13 (1998).

[8] R. Barate *et al.*, Phys. Lett. **B436**, 211 (1998).

[9] I. Bigi and A. Sanda, *CP Violation* (Cambridge University Press, The Edinburgh Building, Cambridge CB2 2RU, UK, 2000).

[10] F. Buccella, M. Lusignoli, G. Miele, A. Pugliese, and P. Santorelli, Phys. Rev. **D51**, 3478 (1995).

[11] I. I. Bigi and H. Yamamoto, Phys. Lett. **B349**, 363 (1995).

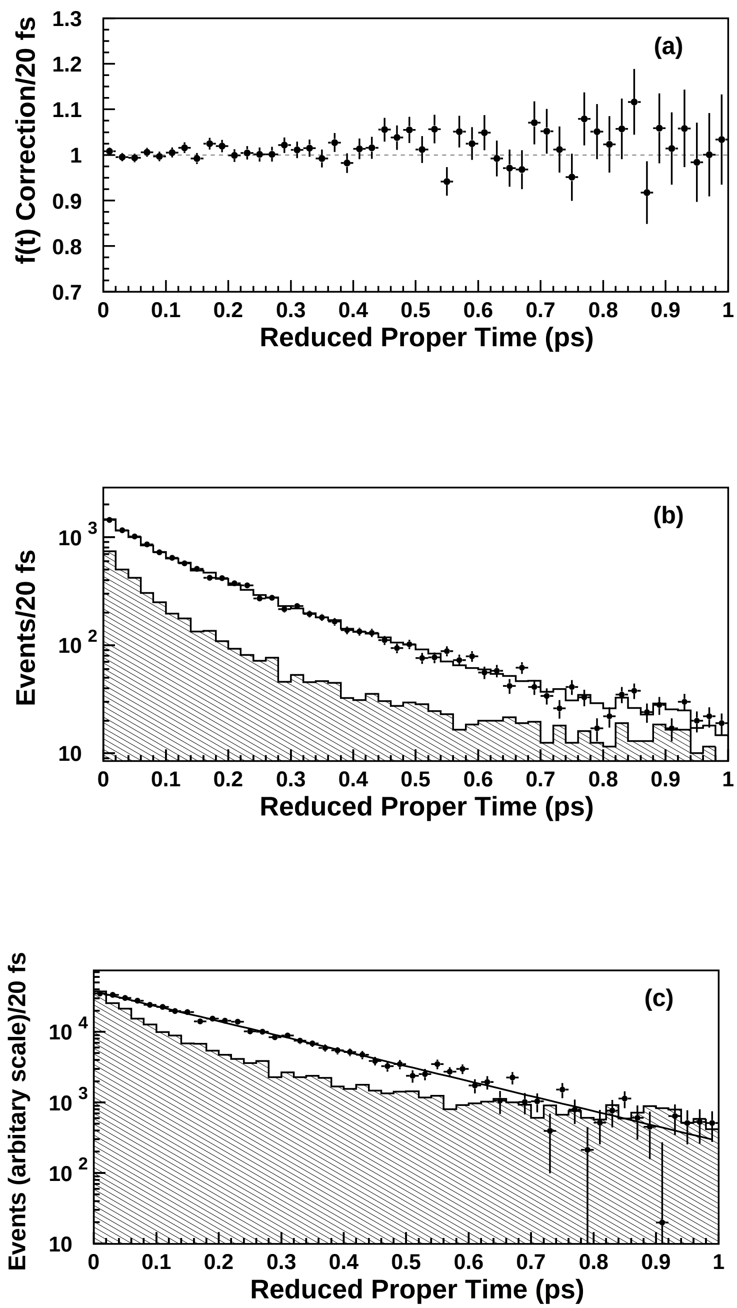

Fig. 10. (a) The f(t′) correction function. Deviation from a flat line indicates the correction from a pure exponential; (b) the lifetime distribution for all decays in the data signal region (points) and the fit (histogram). The shaded distribution shows the lifetime distribution of the background component in the signal region; (c) The lifetime distribution for Λ_c^+ decays (points), *i.e.* the sideband subtracted and f(t′) corrected yield. The line is a pure exponential with the fitted lifetime and the shaded region gives the background. An arbitrary yield scale is used because of the particular normalization of f(t′).

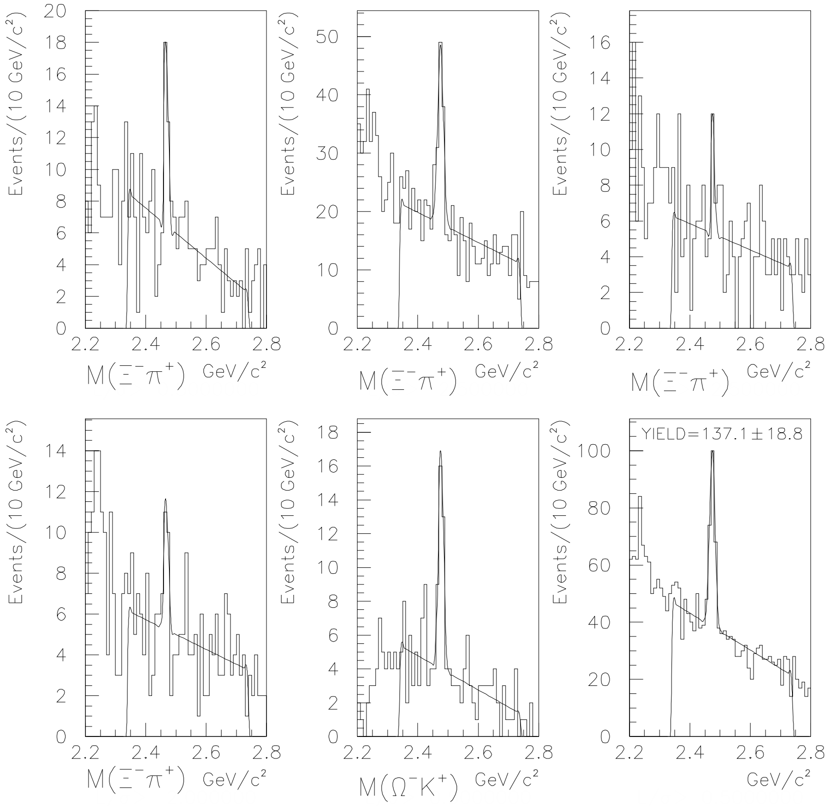

Fig. 11. Signals for the two decay modes used in our determination of the Ξ_c^0 lifetime. The bottom right plot is the sum of all the modes.

[12] H. J. Lipkin and Z.-Z. Xing, Phys. Lett. **B450**, 405 (1999).

[13] J. L. Rosner, Phys. Rev. **D60**, 114026 (1999).

[14] M. Bishai *et al.*, Phys. Rev. Lett. **78**, 3261 (1997).

[15] M. Bauer, B. Stech, and M. Wirbel, Z. Phys. **C34**, 103 (1987).

[16] J. C. Anjos *et al.*, Phys. Rev. **D41**, 2705 (1990).

[17] P. L. Frabetti *et al.*, Phys. Lett. **B346**, 199 (1995).

[18] J. M. Link *et al.*, Phys. Rev. Lett. **88**, 041602 (2002).

[19] G. Bellini, I. I. Y. Bigi, and P. J. Dornan, Phys. Rept. **289**, 1 (1997).

[20] B. Blok and M. A. Shifman, (1991).

[21] B. Guberina and B. Melic, Eur. Phys. J. **C2**, 697 (1998).

[22] I. I. Y. Bigi, (1996), talk given at Workshop on Heavy Quarks at Fixed Target (HQ 96) , St. Goar, Germany, 3-6 Oct 1996 (UND-HEP-96-BIG06).

[23] H.-Y. Cheng, Phys. Rev. **D56**, 2783 (1997).

[24] A. H. Mahmood *et al.*, Phys. Rev. Lett. **86**, 2232 (2001).

[25] A. Kushnirenko *et al.*, Phys. Rev. Lett. **86**, 5243 (2001).

[26] J. M. Link *et al.*, Phys. Lett. **B523**, 53 (2001).

[27] J. M. Link *et al.*, Submitted to Phys. Rev. Lett., hep-ex/0202001 (2002).