



Charm Hadroproduction Results From Fermilab E-400*

P. Coteus⁽¹⁾, M. Binkley⁽³⁾, F. Bossi⁽⁶⁾, J. Butler⁽³⁾,
J. P. Cumalat⁽¹⁾, M. DiCorato^{(5),(6)}, M. Diesburg⁽²⁾, J. Enagonio⁽¹⁾,
J. Filaseta^{*(2)}, P. L. Frabetti⁽⁴⁾, I. Gaines⁽³⁾, P. Garbincius⁽³⁾,
M. Gormley⁽³⁾, J. Haggerty^{†(3)}, D. J. Harding⁽³⁾, T. Kroc⁽²⁾,
R. Ladbury⁽¹⁾, P. Lebrun⁽³⁾, P. F. Manfredi^{(5),(6)}, J. Peoples⁽³⁾,
A. Sala⁽⁶⁾, C. Shipbaugh⁽²⁾, J. Slaughter^{*(3)}, J. Wiss⁽²⁾

⁽¹⁾University of Colorado
Boulder, Colorado 80303

⁽²⁾University of Illinois at Urbana-Champaign
Urbana, Illinois 61801

⁽³⁾Fermi National Accelerator Laboratory
Batavia, Illinois 60510

⁽⁴⁾Universita di Bologna, Dipartimento di Fisica and I.N.F.N.
Bologna, Italy

⁽⁵⁾Universita di Milano, Dipartimento di Fisica
Milano, Italy

⁽⁶⁾Istituto Nazionale di Fisica Nucleare
Milano, Italy

September 1987

*Presented at the Topical Seminar on Heavy Flavors, San Miniato, Italy, May 25-29, 1987. Submitted to the supplement section of Nucl. Phys. B.



Charm Hadroproduction Results From Fermilab E-400

P. COTEUS⁽¹⁾, M. BINKLEY⁽³⁾, F. BOSSI⁽⁶⁾, J. BUTLER⁽³⁾,
J. P. CUMALAT⁽¹⁾, M. DICORATO^{(5),(6)}, M. DIESBURG⁽²⁾, J. ENAGONIO⁽¹⁾,
J. FILASETA*⁽²⁾, P. L. FRABETTI⁽⁴⁾, I. GAINES⁽³⁾, P. GARBINCIUS⁽³⁾,
M. GORMLEY⁽³⁾, J. HAGGERTY[†]⁽³⁾, D. HARDING⁽³⁾, T. KROC⁽²⁾,
R. LADBURY⁽¹⁾, P. LEBRUN⁽³⁾, P. F. MANFREDI^{(5),(6)}, J. PEOPLES⁽³⁾,
A. SALA⁽⁶⁾, C. SHIPBAUGH⁽²⁾, J. SLAUGHTER*⁽³⁾, J. WISS⁽²⁾

⁽¹⁾ *University of Colorado, Boulder, Colorado 80309*

⁽²⁾ *University of Illinois at Urbana-Champaign, Urbana, Illinois 61801*

⁽³⁾ *Fermilab, Batavia, Illinois 60510*

⁽⁴⁾ *Universita di Bologna, Dipartimento di Fisica and I.N.F.N., Bologna, Italy*

⁽⁵⁾ *Universita di Milano, Dipartimento di Fisica, Milano, Italy*

⁽⁶⁾ *Istituto Nazionale di Fisica Nucleare, Milano, Italy*

Presented by P. Coteus

University of Colorado, Boulder, Colorado 80309 USA

ABSTRACT

Results are presented from Fermilab E-400 on the production of charmed baryons and mesons at a mean energy of 640 GeV. We show evidence for the charm-strange baryon, Ξ_c^+ , and present our measurements of its mass, width, lifetime, cross section and relative branching fractions, and the A, x_f , p_t , and particle/antiparticle dependence of the state. We show evidence for both the Σ_c^{++} and Σ_c^0 , and present measurements of three mass differences, $\Sigma_c^{++} - \Sigma_c^0$, $\Sigma_c^0 - \Lambda_c^+$, and $\Sigma_c^{++} - \Lambda_c^+$. Measurements of the A dependence and particle/antiparticle ratios for Σ_c production are also presented. We show preliminary results on the ratio of two decay modes of the D^0 , $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow K_0\bar{K}_0$. The latter mode has not been previously observed.

* Present address: Northern Kentucky University, Highland Heights, KY 41076

† Present address: Brookhaven National Laboratory, Upton, NY 11973

• Permanent address: Yale University, New Haven, CT 06511

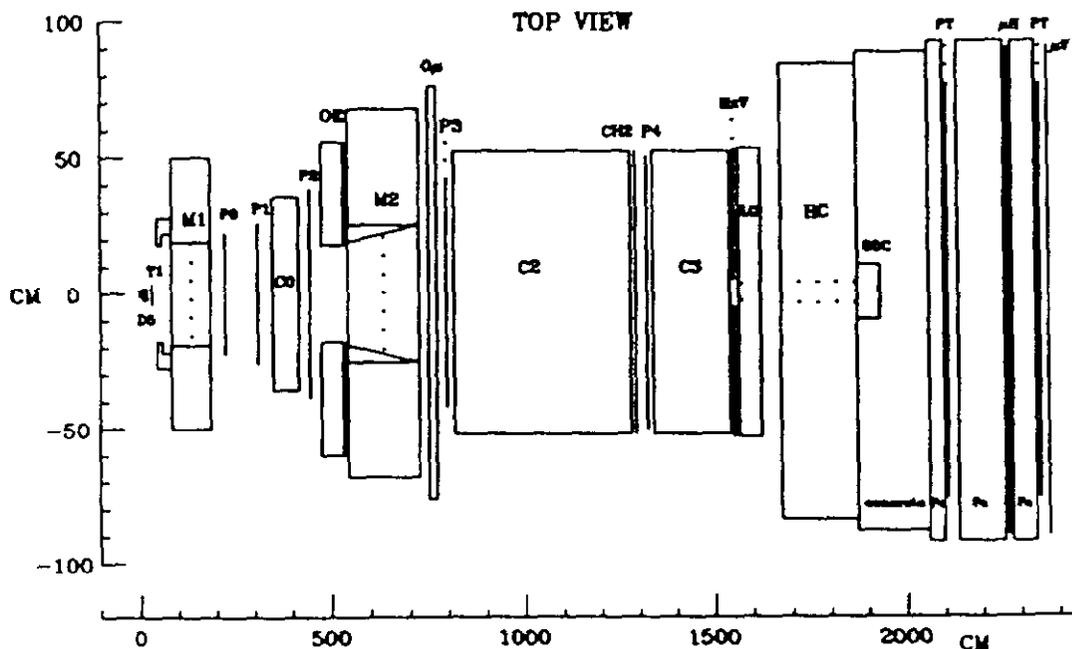
INTRODUCTION

The E-400 spectrometer, shown in figure 1, is a large acceptance spectrometer located in the broadband 0° neutron beam at Fermi National Accelerator Laboratory. The neutron energy spectrum is triangular in shape, with a most probable energy at approximately 640 GeV.

The detector's strengths are its ability to reconstruct events with high multiplicity (up to 20 charged tracks) with good pion/kaon/proton identification (3 Cerenkov counters with 34 cells each) and with an extended K_s and Λ decay volume. Protons are uniquely identified from 20 to 80 GeV, while unique kaon identification extends from 10 to 40 GeV/c. Neutral kaons and lambdas are reconstructed if they decay at least 15 cm downstream of the target and upstream of the center of the second analyzing magnet.

The experiment was run with three different targets (thin wafers of W, Si, and Be in a common vacuum) separated along the beam by 2.5 cm. A thin instrumented Si target wafer followed the target stack. Long-lived charm decays which occurred primarily in the space between target segments were detected by a high resolution vertex MWPC consisting of 9 planes of wires with a 250μ pitch in 3 views.¹

There were three calorimeters. The summed response of the first two calorimeters (made respectively of leaded glass and steel-scintillator and containing a small beam hole) comprised our minimum energy trigger. A third calorimeter was used to measure energy passing through the beam hole. The entire system provided a resolution of $\sigma_E/E = 14\%$.



1. E-400 spectrometer

DATA SET

The results to be discussed come from a sample of approximately 45 million events. The primary trigger was a coincidence between a target region scintillation counter and two coincidences in a downstream scintillator hodoscope (HxV). Ninety percent of the data was recorded with additional requirements: a) A minimum neutron energy of 265 GeV. b) A minimum multiplicity of 4 charged tracks. c) A deposited charge in the most downstream silicon target equivalent to 2 or more charged tracks. d) At least 1 charged kaon with momentum over 21 GeV/c traversing the entire detector.^{3,4} For these triggers we found all charged tracks and a common vertex, then performed a Cerenkov counter analysis and searched for all K_s and Λ candidates. Finally all tracks were traced through the vertex detector. An acceptable fit to all chamber hits and timing information (our MWPC's had recorded drift times) was required for a successful link (about 90% efficient).

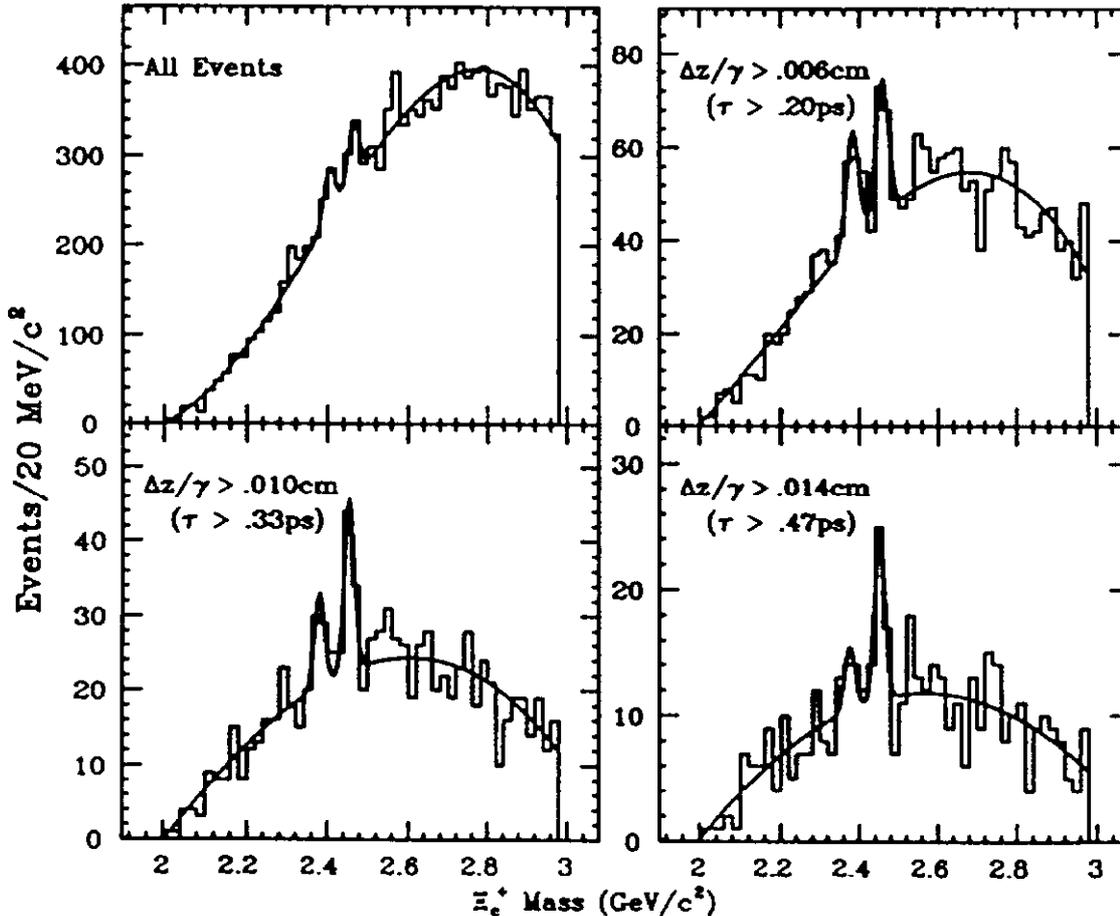
THE Ξ_c^+

The CERN Hyperon Group² has previously reported on the observation of a long-lived, narrow state in the reaction (135 GeV) $\Sigma^- + \text{Be} \rightarrow \Lambda K^- \pi^+ \pi^+ + X$ at a mass of $2460 \pm 15 \text{ MeV}/c^2$ with quark content (csu). We confirm this observation.

We first selected a clean sample of Λ 's ($\pm 14 \text{ MeV}/c^2$ of nominal mass). Charged kaons were required to be uniquely identified, while pions were defined as any track which was not an electron, kaon, or proton. If no particle identification was possible, the pion hypothesis was assumed. Lastly, we formed Ξ_c^+ candidates by requiring the sign combination $\Lambda K^- \pi^+ \pi^+$, requiring these tracks to link to the vertex detector, and requiring the Λ to have a larger momentum than either of the pions. In our Monte Carlo simulation of the production and (phase space) decay of the Ξ_c^+ , this last condition was satisfied for all geometrically accepted decays.

For each combination, all other tracks in the event were used to form the primary vertex. To remove the effects of other long-lived decays in the event, the primary vertex was constrained in z to the center of the nearest target module. (The target thicknesses range from 300μ for W to 4000μ for Be.) The $K\pi\pi$ of the Ξ_c were fit simultaneously to a vertex constrained to a line following the Ξ_c momentum vector and fixed at one end to the primary vertex. The free parameters were the $K\pi\pi$ track parameters and the z of the decay point. Candidates with unacceptable fits were removed from the analysis. We then computed the proper decay distance $z_p = \text{decay distance} / \gamma$. Except for error in the primary vertex, z_p would be momentum independent, since the decay vertex error scales with the decay candidate momentum. For low momentum (low x_f) Ξ_c^+ candidates, the primary vertex error dominates the error of the decay vertex; a large component of the background satisfying a minimum cut on z_p comes from non-charm candidates with $x_f < .15$.

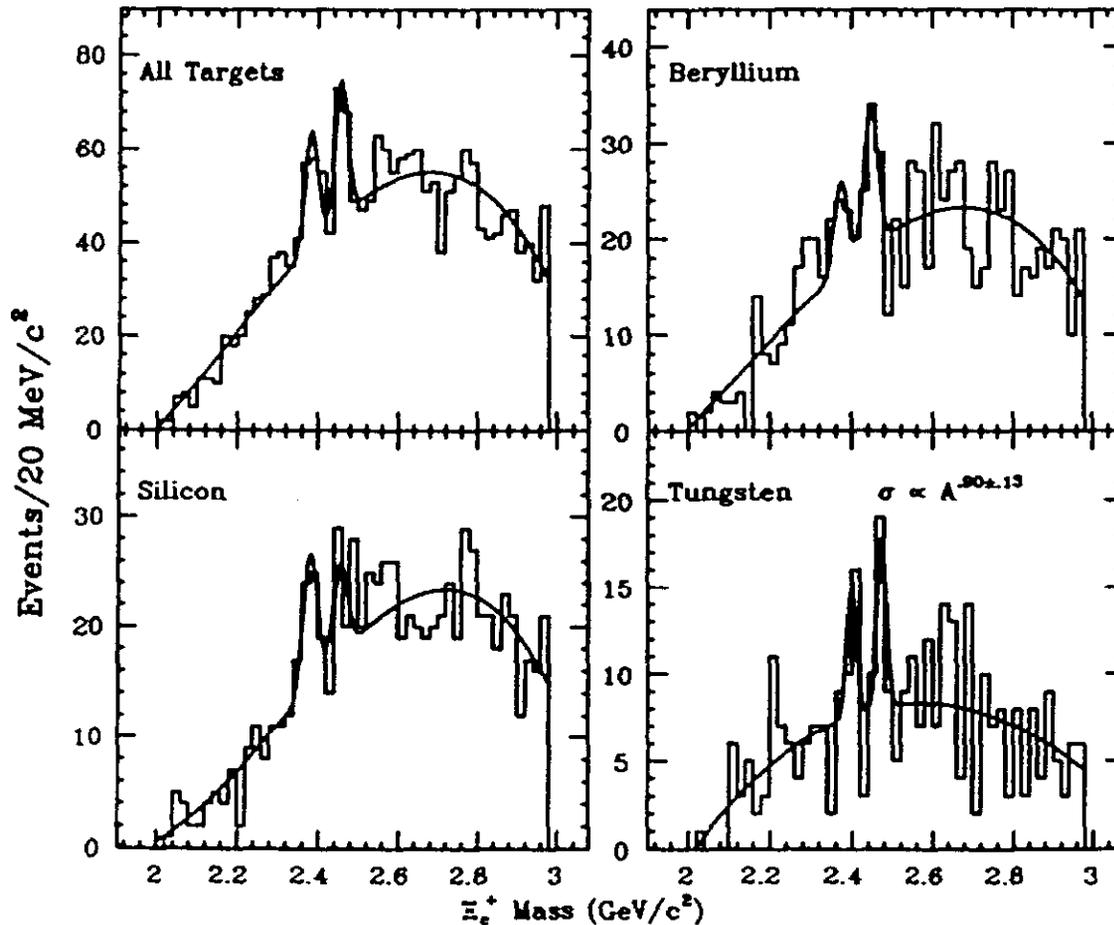
Figure 2 shows the mass spectrum for Ξ_c^+ candidates with $x_f > .15$ for increasing values of the minimum proper decay distance. As x_p is increased, two narrow peaks emerge above a smoothly varying background. We interpret this as two Cabibbo favored decays of the charm strange baryon: $\Xi_c^+ \rightarrow \Delta K^- \pi^+ \pi^+$ and $\Xi_c^+ \rightarrow \Sigma^0 K^- \pi^+ \pi^+$; $\Sigma^0 \rightarrow \gamma \Delta$. We have checked by Monte Carlo simulation that the effect of our detector resolution ($\sigma \sim 15 \text{ MeV}/c^2$) is to make the width of the two $\Delta K^- \pi^+ \pi^+$ states nearly identical. The separation in mass should be $75 \text{ MeV}/c^2$, corresponding to the energy of the missing gamma in the Ξ_c^+ center of mass frame. These expectations are confirmed by the superimposed fits, composed of two independent gaussians and a second order polynomial background. Referring to the upper right plot a maximum likelihood fit yields a mass of $2459 \pm 5 \text{ MeV}/c^2$ for the higher mass peak and a mass separation of $76 \pm 8 \text{ MeV}/c^2$ between the peaks. We estimate a systematic uncertainty in the mass scale (checked by reconstruction of $K_s, \Lambda, \Xi^-, \Omega^-$, and D^0) of $30 \text{ MeV}/c^2$. The significance of the double peak system is 5.5 standard deviations. Our acceptance for the two decay modes is nearly identical, hence a ratio of the areas of the two peaks yields the branching ratio $B(\Xi_c^+ \rightarrow \Sigma^0 K^- \pi^+ \pi^+) / B(\Xi_c^+ \rightarrow \Delta K^- \pi^+ \pi^+) = .84 \pm .36$.



2. Ξ_c^+ lifetime development

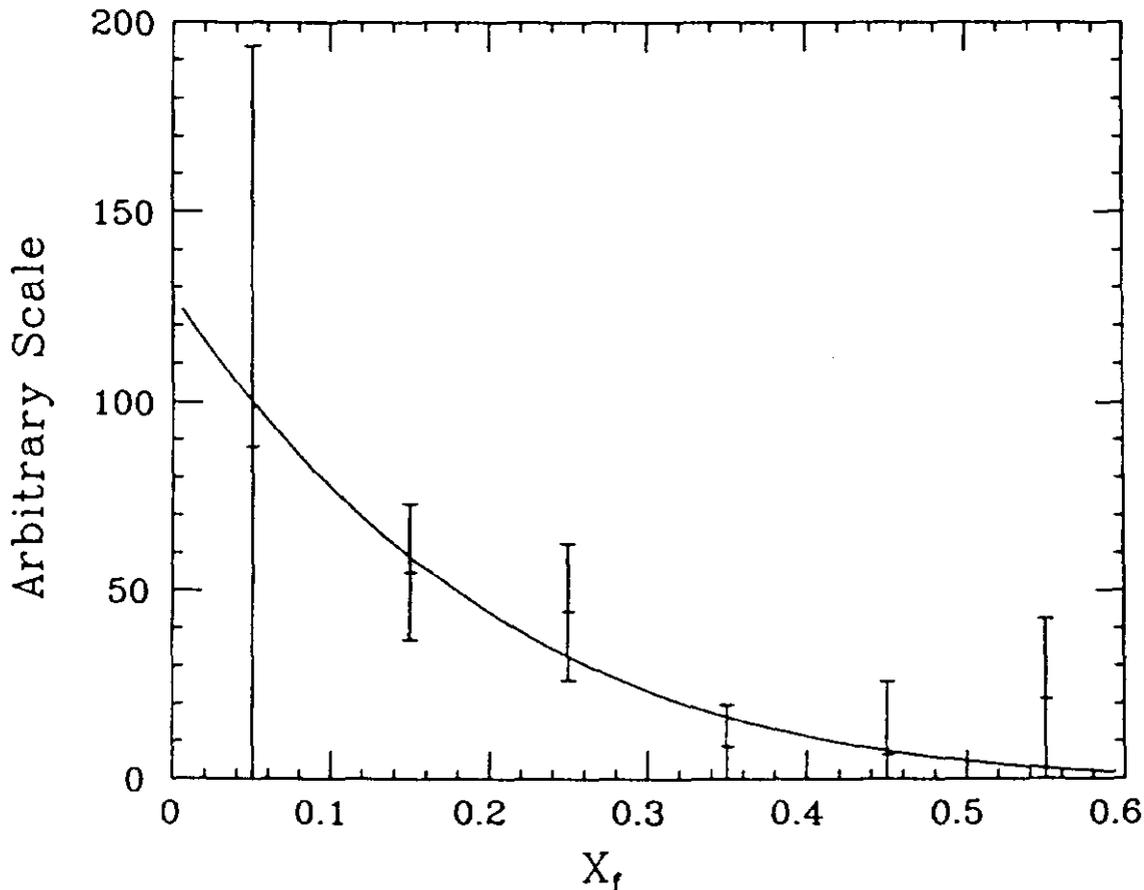
To increase the data sample, we elected to determine the Ξ_c^+ lifetime without use of the x_f cut used in figure 2. Data were grouped into five bins of z_p beginning at .012 cm (.40 ps). After extracting the signal and correcting for resolution we find the two decay modes yield consistent values for the lifetime; the combined lifetime measurement for both decay modes is $.40_{-.12}^{+.18}$ ps where the errors are statistical only. As a test of systematic errors we made a second determination of lifetime by fitting the proper time (measured from our minimum time of .40 ps) of Ξ_c^+ candidates within ± 15 MeV/ c^2 of the Ξ_c^+ mass to a pure exponential plus a time distribution for background events (determined from mass sidebands) appropriately normalized. This method yields a combined lifetime of $.46_{-.12}^{+.17}$ ps, or over twice the time evolution of the background events. We quote the lifetime value from the first method with an additional systematic error of $\pm .10$ ps.

The event sample of figure 2 with $z_p > .006$ cm is shown in figure 3 divided into three groups, depending on the atomic number of the target. After extracting the number of Ξ_c^+ decays we form the ratio $\sigma(n + A_i \rightarrow \Xi_c^+ + X) / \sigma(n + A_j \rightarrow \Xi_c^+ + X) = (A_i / A_j)^\alpha$ and find $\alpha = .90 \pm .13$. Our data suggests that Ξ_c^+ production has a stronger dependence on A than does the total inelastic neutron cross section, and is consistent with $A^{1.0}$ dependence.



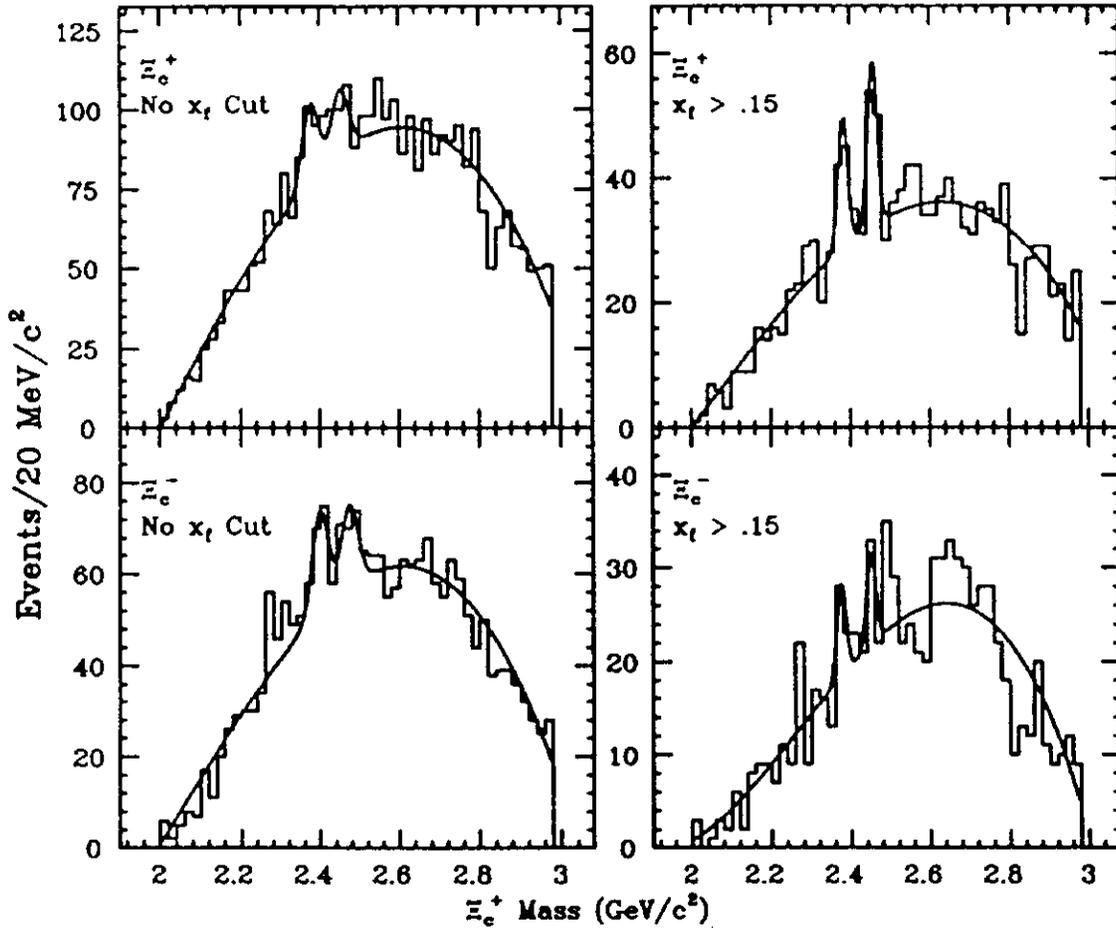
3. Ξ_c^+ target A dependence

To determine the functional form of dN / dx_f we show in figure 4 the efficiency corrected event yields for both decay modes with $x_p > .006$ cm assuming a lifetime of .40 ps. Also shown is a fit to the data, using the functional form $dN / dx_f = (1 - x_f)^n$. The fit gives $n = 4.7 \pm 2.3$ with a χ^2 of 1.8 for 4 DoF. The neutron luminosity was determined from the number of minimum bias triggers, corrected for scintillation counter efficiencies and final state topologies (all neutral or 1 charged track) which would not fire the trigger. The product of cross section times branching fraction ($\sigma \cdot B$) for both decay modes of the Ξ_c^+ is $4.8 \mu\text{b}$ per nucleon for the $0. < x_f < .6$ interval. The statistical error is 33%. We have ascribed a systematic error of 25%, to cover uncertainties in our corrections of acceptance and luminosity. We of course use an A dependence of $A^{.90 \pm .13}$, but the exponent error introduces yet another uncertainty in the Ξ_c^+ cross section of +50% or -35%, where the correction is negative for a positive error in the exponent of A . We add the two statistical errors in quadrature to obtain a total error of $\frac{+2.9+1.2}{-2.3-1.2} \mu\text{b}$. To determine the p_t dependence of Ξ_c^+ production we require $x_f > .15$, divide the remaining candidates into three bins of p_t , and extract the number of Ξ_c^+ decays. After a modest (15%) efficiency correction we find a good fit to the form $dN / dp_t^2 = N_0 \exp(-bp_t^2)$ with $b = 0.97 \pm .21 (\text{GeV}/c)^{-2}$.



4. dN / dx_f vs x_f for Ξ_c^+

We have also searched for the charge conjugate state Ξ_c^- . As figure 5 suggests, there is some evidence that the antiparticle is produced with a softer momentum spectrum (i.e., is attenuated more by a minimum x_f cut) than is the Ξ_c^+ , although our measurement errors are large. We find $R = \Xi_c^+ / \Xi_c^- = 1.1 \pm .5$ for $0 < x_f < .6$, and $R = 2.6 \pm 1.6$ for $.15 < x_f < .6$.



5. Comparison of Ξ_c^+ and Ξ_c^-

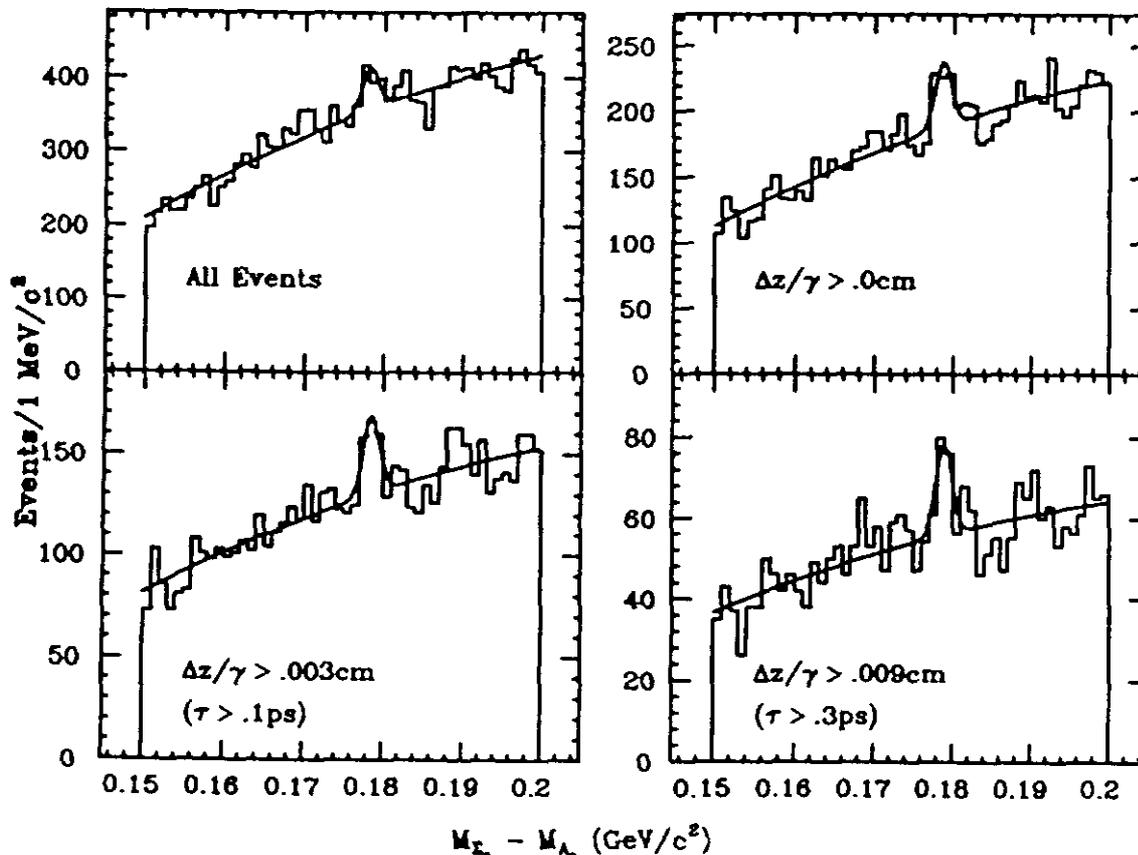
Σ_c^0 AND Σ_c^{++}

Several models^{5,6} exist where the mass differences within the Σ_c Family arise from such effects as constituent quark masses, the color hyperfine interaction, and the QCD coulomb quark force. These models predict the $\Sigma_c^{++} - \Sigma_c^0$ mass differences varying from $+6.5 \text{ MeV}/c^2$ to $-18 \text{ MeV}/c^2$. We report on a measurement of three mass differences, $\Sigma_c^{++} - \Sigma_c^0$, $\Sigma_c^0 - \Lambda_c^+$, and $\Sigma_c^{++} - \Lambda_c^+$, using essentially the same lifetime tagging techniques as just described. The latter two transitions arise from the strong decay of the charm baryon state Σ_c , namely; $\Sigma_c^0 \rightarrow \Lambda_c^+ + \pi^-$ and $\Sigma_c^{++} \rightarrow \Lambda_c^+ + \pi^+$ where $\Lambda_c^+ \rightarrow pK^- \pi^+$. (Note: from here on we use the convention that reference to a particle state implies the charge conjugate

state also.) Because of the small mass difference between the Σ_c and the Λ_c , the mass resolution on the splitting is excellent, approximately $2 \text{ MeV}/c^2$, and is very insensitive to systematic errors in the mass scale.

Particle identification was performed as follows. Protons were required to be uniquely identified as such. To extend the momentum range for kaon identification, they were accepted as either uniquely identified as kaons or ambiguous with a proton hypothesis. With this criterion kaons were identified from 2.8 to 40 GeV/c . As before, all tracks not explicitly identified as kaons or protons were considered as pion candidates.

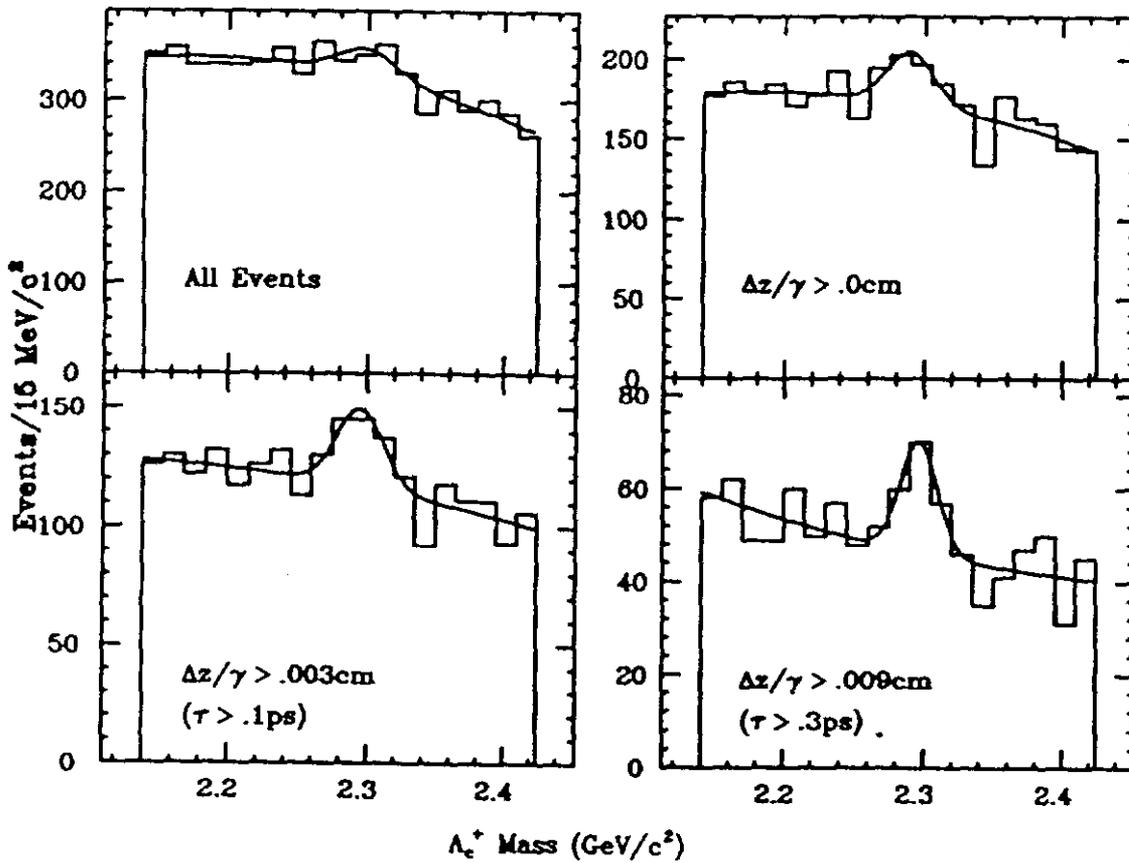
Candidates for the Δ_c were formed by requiring the sign combination $pK^-\pi^+$, and requiring all three tracks to link through the vertex detector. As before we fit these tracks to a common vertex, constrained to lie on a line along the Δ_c momentum vector and fixed at one end to the (z constrained) primary vertex of all other tracks. The proper decay length z_p was then computed. Σ_c candidates were formed by adding a pion to the Δ_c candidates just described. In order to increase our efficiency, there was no requirement that the additional pion linked thru the vertex detector. Finally, to reduce the combinatoric background we required the charged multiplicity to be less than 12.



6. $\Sigma_c^0 \rightarrow \Delta_c^+ + \pi^-$; $\Delta_c^+ \rightarrow pK^-\pi^+$ lifetime development of $M_{\Sigma_c^0} - M_{\Lambda_c^+}$

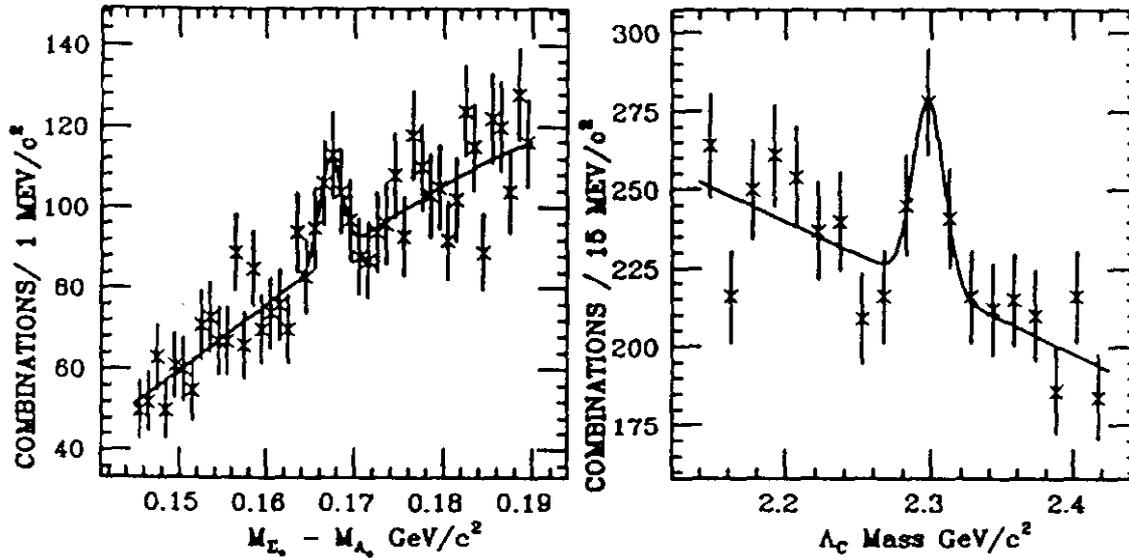
Figure 6 shows the mass difference $M_{\Sigma_c^0} - M_{\Lambda_c^+}$ in the Λ_c mass region ($2.280 < M_{\Lambda_c} < 2.310$) for increasing minimum proper decay lengths. A narrow peak with a width consistent with our resolution appears above a smooth background. The behavior of the state under these lifetime cuts implies an upper limit of .28 ps for the lifetime of the Λ_c , while the background fits a lifetime of about .17 ps. Also shown is a fit to the data. The fitting function consists of a gaussian signal plus a polynomial background. All four fits give the consistent result $M_{\Sigma_c^0} - M_{\Lambda_c^+}$ of $178.2 \pm .5 \pm 2$ MeV/c² where the first error is statistical and the second systematic. The statistical significance of the fits range from 3.7 to 4.5 standard deviations.

In figure 7 we show a similiar lifetime development, this time for the Λ_c with $M_{\Sigma_c^0} - M_{\Lambda_c^+} = 177 \pm 1.5$ MeV/c². A clear Λ_c enhancement is seen, with a mass of $2295 \pm 5 \pm 30$ MeV/c². The event yields as a function of minimum lifetime match the yields of figure 6.



7. $\Sigma_c^0 \rightarrow \Lambda_c^+ + \pi^-$; $\Lambda_c^+ \rightarrow pK^- \pi^+$ lifetime development of M_{Λ_c} .

In figure 8 we show similar plots for the Σ_c^{++} , where the softer momentum spectrum of the Σ_c^{++} required us to remove the constrained vertex cut. Again clear enhancements in both the $\Sigma_c^{++} - \Lambda_c^+$ mass difference (at $167.4 \pm 6 \pm 2$ MeV/c²) and the Λ_c (at $2298 \pm 4 \pm 30$ MeV/c²) are observed.



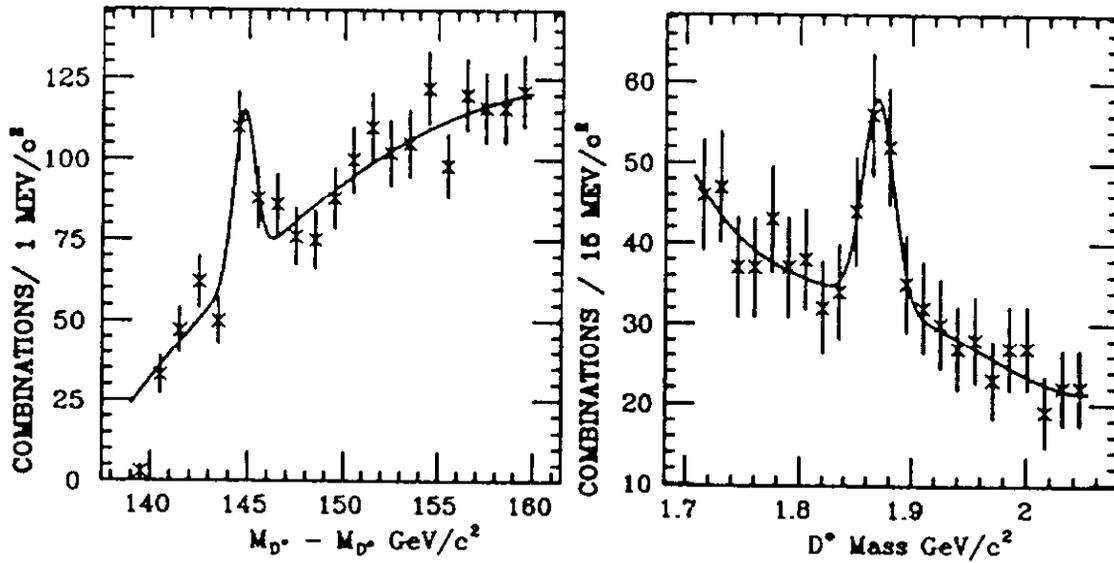
8. $\Sigma_c^{++} \rightarrow \Lambda_c^+ + \pi^+$; $\Lambda_c^+ \rightarrow pK^-\pi^+$; $M_{\Sigma_c^{++}} - M_{\Lambda_c^+}$ and $M_{\Lambda_c^+}$

We can use these two mass splittings to calculate the theoretically interesting mass difference $\Sigma_c^{++} - \Sigma_c^0$, which we find to be -10.8 ± 2.9 MeV/c², outside the range of most theoretical calculations and also outside the range recently determined by the ARGUS collaboration⁷.

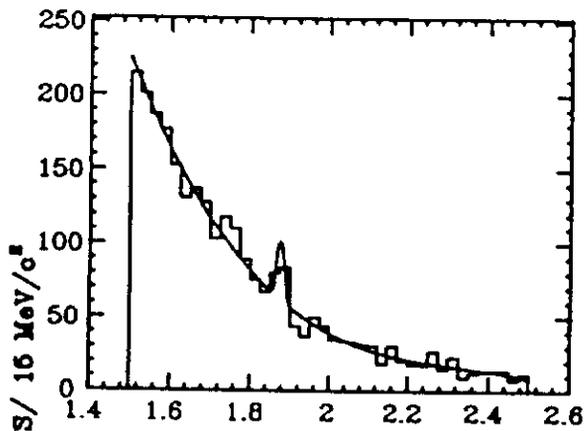
We have also determined the event yields for the Σ_c^0 and Σ_c^{++} as a function of A and find Σ_c^0 production fits $A^{.90 \pm .19}$ while Σ_c^{++} is produced as $A^{1.00 \pm .22}$. The particle/antiparticle yields are $\Sigma_c^{++} / \overline{\Sigma_c^{--}} = 1.38 \pm .80$ and $\Sigma_c^0 / \overline{\Sigma_c^0} = 1.30 \pm .60$. The A dependence and particle/antiparticle yields agree qualitatively with our observations of Ξ_c production.

DECAYS OF THE D^0

We turn now to the hadroproduction of charm mesons. We have new information on D and F charm meson production which for lack of time (and space!) I will be unable to report. I will restrict myself to a comparison of two decay modes of the D^0 (observed through decay of the D^* into $D^0\pi$), $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow K_0\overline{K}_0$. The latter diagram is a forbidden decay at the quark level, and can only decay through hadronic final-state interactions.⁸ These final state interactions may mix the K^+K^- and $K_0\overline{K}_0$ final states, hence the comparison. We show in figure 9 unambiguous evidence for the cabbibo suppressed decay of the D^0 into 2 charged kaons.



9. $D^* \rightarrow D\pi; D \rightarrow K^+K^-$: $M_{D^*} - M_{D^0}$ and M_{D^0}



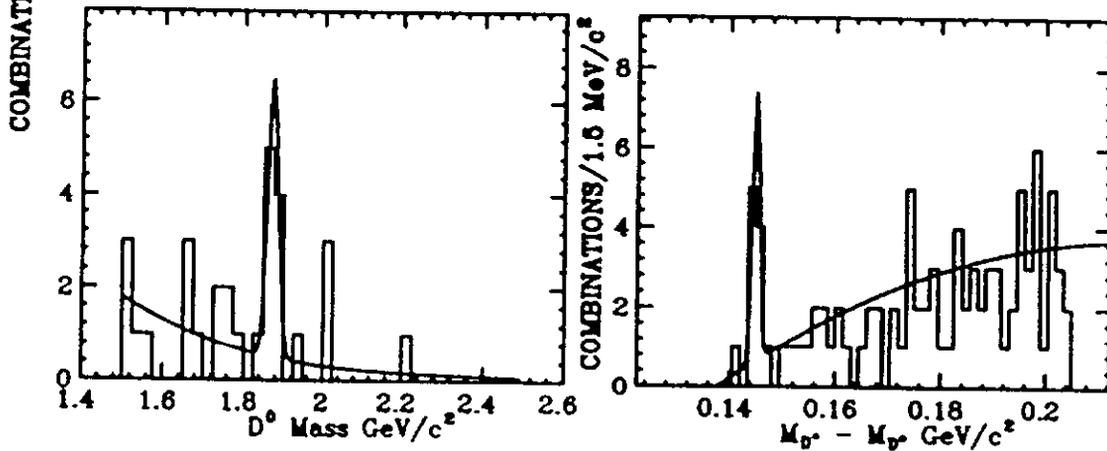
$D^* \rightarrow D^*\pi; D^0 \rightarrow K^0K^0$

D^0 Mass = 1872 ± 6 MeV

Area = 8.3 ± 2.7

$M_{D^*} - M_{D^0} = 145 \pm .2$ MeV

Significance: 4.4 S.D.



10. a) $D^0 \rightarrow K_s K_s$ inclusive; b) $D^0 \rightarrow K_s K_s$ with $143 < M_{D^*} - M_{D^0} < 147$ MeV/c²; c) $M_{D^*} - M_{D^0}$ with a D^0 mass cut

Figure 10 shows evidence for a similar decay into $K_s K_s$. You can count the events from the plot (there are about 10), the significance is 4.4 standard deviations. The two decay modes yield D^0 masses of respectively 1871 ± 6 and 1872 ± 6 MeV/ c^2 . Similar agreement exists for the D^* masses. The acceptances and detection efficiencies for the two states are very different; our analysis at this point suggests that the branching fraction for $D^0 \rightarrow K^0 \overline{K^0}$ is approximately half that of $D^0 \rightarrow K^+ K^-$, or about .3%. This is approximately the level expected.

ACKNOWLEDGEMENTS

We gratefully acknowledge the assistance we received from the Fermilab staff and the support staffs at the University of Illinois, at the University of Colorado, and at INFN in Milan. This research was supported by the U.S. Department of Energy and by the Instituto Nazionale di Fisica Nucleare of Italy.

REFERENCES

1. P. Coteus et al., IEEE Trans. on Nucl. Sci. 32 1 (1984) 585
2. S .F. Biagi et al., Phys. Lett. 122B (1983) 455;
S .F. Biagi et al., Phys. Lett. 150B (1985) 230;
S .F. Biagi et al., Z. Phys. 28C (1985) 175.
3. D. Harding et al., IEEE Trans. Nucl. Sci. 30 5 (1983)
4. P. Coteus, in Proceedings of Physics in Collision 3, Como, Italy, August 1983, edited by G. Bellini, A. Bettini, and L. Perasso (editions Frontieres)
5. W. Kwong, J. L. Rosner, and C. Quigg, Fermilab-Pub-87/15-T
6. W-Y. P. Hwang and D. B. Lichtenberg, Phys Rev. 35D (1987) 3526 and many references within.
7. D. Macfarlane, in Proceedings of the Twenty-Third International Conference of High Energy Physics, Berkeley, California, 1986, edited by S. Loken (World Scientific, Singapore).
8. Xuan-Yem Pham, PAR LPTHE 87-16, Mar (1987)