Upper Limits on the Decay $D^0 \rightarrow \mu^+\mu^-$ and on D^0-$\bar{D}^0$ Mixing

W. C. Louis,[1] C. E. Adolphsen,[2,a] J. P. Alexander,[2,b] K. J. Anderson,[2] C. Biino,[1,c] J. S. Conway,[2] J. F. Greenhalgh,[1,d] J. G. Heinrich,[2] K. T. McDonald,[1] K. W. Merritt,[2,e] S. Palestini,[1,c] J. E. Pilcher,[2] E. I. Rosenberg,[3] F. C. Shoemaker,[1] D. T. Simpson,[3,f] and A. J. S. Smith[1]

[1]*Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544*

[2]*Enrico Fermi Institute and Department of Physics, The University of Chicago, Chicago, Illinois 60637*

[3]*Ames Laboratory and Department of Physics, Iowa State University, Ames, Iowa 50011*

(Received 20 November 1985)

As a by-product to the study of muon pairs produced by 255-GeV/c pions, data from Fermilab yield upper limits on the decay $D^0 \rightarrow \mu^+\mu^-$ and on D^0-$\bar{D}^0$ mixing. An unrestricted sample of 122 630 unlike-sign muon pairs allows a 90%-C.L. (confidence level) upper limit of 1.1×10^{-5} to be placed on the branching ratio of the charm-changing neutral-current decay $D^0 \rightarrow \mu^+\mu^-$. From a sample of 3973 like-sign muon pairs, the ratio $r = \Gamma(\bar{D}^0 \rightarrow \mu^+ X)/\Gamma(\bar{D}^0 \rightarrow \mu^- X)$ is determined to be $r < 5.6 \times 10^{-3}$ at 90% C.L.

PACS numbers: 13.20.Jf, 13.85.Qk, 14.40.Jz

Historically, the suppression of flavor-changing neutral currents has played a major role in shaping the present theory of the weak and electromagnetic interactions and in predicting the existence of new physics. The low rates for K^0-$\bar{K}^0$ mixing and $K_L^0 \rightarrow \mu^+\mu^-$ led to the Glashow-Iliopoulos-Maiani mechanism[1] which in turn predicted the charm quark. As a test of the now-standard $SU(2)_L \times U(1)$ model of electroweak interactions, it is natural to extend the search for flavor-changing neutral currents from the K^0 to the D^0 sector and to look for the decay $D^0 \rightarrow \mu^+\mu^-$ and for D^0-$\bar{D}^0$ mixing. These processes are expected[2,3] to occur at rates below the current experimental limits.[4,5] An additional motivation is the apparent excess of same-sign kaon events found in $D^0\bar{D}^0$ decays by the Mark III group (see Gladding[6]). These events may be due to doubly Cabibbo-suppressed D^0 decays or to D^0-$\bar{D}^0$ mixing. Several models have been proposed[7] which allow a larger mixing rate than the standard model.

The experiment reported here was designed to study muon pairs produced in the forward direction in pion-nucleon interactions. Its principal goal was to explore the structure of the pion, by measurement of $\mu^+\mu^-$ pairs with invariant masses greater than 4 GeV/c^2 which arise from quark-antiquark annihilation.[8] In this Letter we use lower-mass $\mu^+\mu^-$ data to search for the decay $D^0 \rightarrow \mu^+\mu^-$. In addition, we analyze the same-sign muon-pair spectra ($\mu^+\mu^+, \mu^-\mu^-$) to set limits on D^0-$\bar{D}^0$ mixing, where the production of a $D\bar{D}^0$ pair is followed by the semileptonic decays of both mesons to $\mu^+ X$ and the decay $\bar{D}^0 \rightarrow \mu^+ X$ results from D^0-$\bar{D}^0$ mixing.

The experimental apparatus has been described in detail elsewhere.[9] Briefly, the 255-GeV/c pion beam interacted in a tungsten target just upstream of a selection magnet, whose magnetic volume was filled with low-Z material to absorb secondary hadrons. Downstream of the selection magnet was a magnetic spectrometer consisting of sixteen planes of drift chambers, nine planes of multiwire proportional chambers, and four scintillator hodoscopes surrounding an analysis magnet. Candidate track pairs were required to penetrate an additional 2 m of iron at the rear of the apparatus to confirm that they were muons. A hardware processor used hodoscope information to trigger only on muon pairs with an invariant mass above 2.0 GeV/c^2. In addition, there was a prescaled trigger on every thousandth muon pair regardless of mass. Data were obtained in runs of 5.5×10^{13} π^- and 3.8×10^{13} π^+ beam particles at 255 GeV/c.

The decay $D^0 \rightarrow \mu^+\mu^-$ (and $\bar{D}^0 \rightarrow \mu^+\mu^-$), if present, would result in an enhancement at the D^0 mass in the $\mu^+\mu^-$ spectrum. Figure 1(a) shows the raw mass distribution from the 122 630 muon pairs in the prescaled-trigger sample, which is well suited to a search at lower masses because of the absence of a hardware mass cut. The solid line in Fig. 1(a) is a fit to the data using Gaussian distributions for pairs due to J/ψ, ψ', and D^0 decays, and an exponential of a quartic polynomial to describe the continuum mass distribution. The fit was performed in the mass interval $1.0 < M < 5.0$ GeV/c^2 (where the acceptance was slowly varying) and has a χ^2 of 178.6 for 150 degrees of freedom. The χ^2 is 64.9 for 60 degrees of freedom in the mass interval $1.0 < M < 2.75$ Ge/V/c^2. The fitted J/ψ mass, $M_J = 3.080 \pm 0.003$ GeV/c^2, is somewhat low as a result of the energy loss of muons via bremsstrahlung and pair production. The fitted J/ψ mass resolution is 0.165 ± 0.003 GeV/c^2, compatible with the calculation of 0.170 GeV/c^2 made with a Monte Carlo simulation of the apparatus. Figure 1(b) is a plot of the data with the fitted parametrization (except for the D^0 contribution) subtracted. The solid line represents the best fit when D^0 and $\bar{D}^0$ decays are included at 90% confidence level (C.L.). The mass

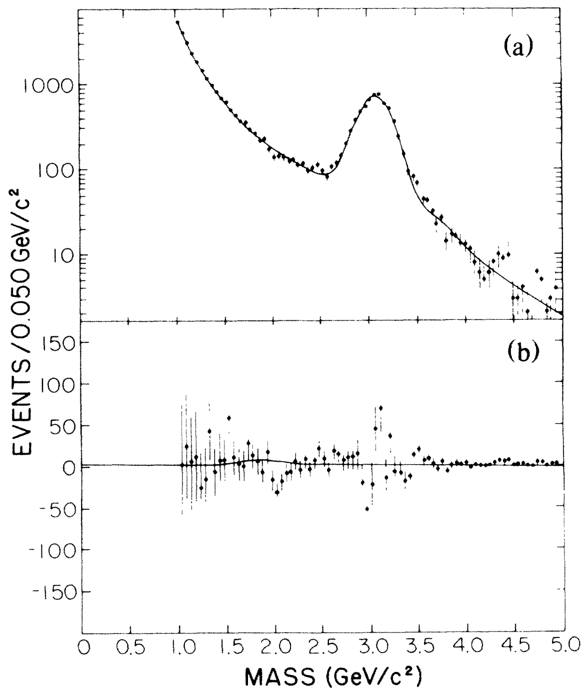

FIG. 1. (a) Raw mass distribution from the prescaled-trigger sample. The solid line is a fit to the data described in the text. (b) Raw mass distribution with the fitted parametrization subtracted. The solid line is the best fit when D^0 and $\bar{D}^0$ decays are included at 90% C.L.

resolution of the $D^0(1865)$ was set to 0.165 GeV/c^2, consistent with the detector resolution.

An upper limit on the decay $D^0 \to \mu^+\mu^-$ was obtained by normalization to J/ψ events according to

$$\frac{\Gamma(D^0 \to \mu^+\mu^-)}{\Gamma(D^0 \to \text{all})} = \frac{\sigma B(J \to \mu^+\mu^-)}{\sigma(D^0)+\sigma(\bar{D}^0)} \frac{N_{D^0}+N_{\bar{D}^0}}{N_J} \frac{A_J}{A_{D^0}},$$

where Γ is the decay rate. The cross section times branching ratio for J/ψ production was measured by our experiment[10] to be $\sigma B(J \to \mu^+\mu^-) = 8.15 \pm 0.76$ nb/nucleon for Feynman x (x_F) > 0. The observed number of J/ψ decays in the prescaled-trigger sample was $N_J = 5584 \pm 200$, and the upper limit on the observed number of D^0 and $\bar{D}^0$ decays at 90% C.L. was $N_{D^0} + N_{\bar{D}^0} \leq 48.6$. The total $J/\psi \to \mu^+\mu^-$ acceptance was calculated to be $A_J = 0.055 \pm 0.003$.

The D cross sections were taken from four experiments which recently measured $D\bar{D}$ production in $\pi^- N$ interactions[11-14] with a variety of targets and beam energies. A summary of the results is shown in Table I. Averaging over the four experiments, we estimate that $\sigma(D) + \sigma(\bar{D}) = 15.4 \pm 1.9$ μb/nucleon for $x_F > 0$, assuming a linear dependence on the atomic number of the target. The data from the Bailey *et al.*[13] (ACCMOR group) and Aguilar-Benitez *et al.*[14] (LEBC-EHS group) suggest that $\sigma(D^0) + \sigma(\bar{D}^0) > \sigma(D^+) + \sigma(D^-)$, which is expected since the D^* decays predominantly to D^0 and $\bar{D}^0$. Nevertheless, we conservatively assume that the charged and neutral cross sections are the same and obtain $\sigma(D^0) + \sigma(\bar{D}^0) = 7.7 \pm 1.0$ μb/nucleon.

The total acceptance for $D^0 \to \mu^+\mu^-$ was calculated to be $A_{D^0} = 0.0462 \pm 0.0046$, on assumption of a distribution of the form

$$d^2\sigma/dx_F\, dP_T^2 \sim (1-x_F)^3 \exp(-1.0 P_T^2)$$

for D production, which is consistent with the measurements of Ritchie *et al.*[12] (CCFRS group) and the LEBC-EHS[14] group. [The total acceptance would be 0.0686 ± 0.0069 for a $(1-x_F)^2$ distribution, which is closer to the measurements of Badertscher *et al.*[11] (BIBC group) and the ACCMOR[13] group.] Finally, it was assumed that the ratio of the cross sections for D and J/ψ production in K-N and p-N interactions is the same as in π-N interactions, even though the J/ψ production cross section by pions is approximately twice that by protons.[15] We therefore counted the kaon and proton contamination in the beam (which averaged 5.2% and 19.6%, respectively) as pions.

Combining the above factors, we find the 90%-C.L. limit on the branching ratio to be

$$\Gamma(D^0 \to \mu^+\mu^-)/\Gamma(D^0 \to \text{all}) < 1.1 \times 10^{-5},$$

where the percentage errors have been added in quadrature. The main uncertainty in the calculation of this limit is the total acceptance A_{D^0} for $D^0 \to \mu^+\mu^-$,

TABLE I. Measurements in $\pi^- N$ interactions of inclusive D production for $x_F > 0$, presented in the form $d^2\sigma/dx_F\, dP_T^2 \sim [A(1-x_F)^{n_1} + B(1-x_F)^{n_2}]e^{-bP_T^2}$.

Ref.	$\sigma(D)+\sigma(\bar{D})$ (μb)	Target	Energy (GeV)	b	A	n_1	B	N_2
11	28 ± 11	C_3F_8	340	~ 1.23	...	~ 0.7	...	...
12	$17.5^{+5.4}_{-3.9}$	Fe	278	0.70 ± 0.15	~ 0.46	~ 0.9	~ 5.2	~ 5.9
13	$24 \pm 7.5 \pm 12$	Be	175/200	1.1 ± 0.5	...	0.8 ± 0.4	...	...
14	15.8 ± 2.7	H	360	1.18 ± 0.18	~ 0.34	~ 0.7	~ 6.8	~ 7.5

which depends on the D-production distribution. Although there is some disagreement among the experiments concerning the x_F distribution, we have conservatively chosen a relatively central x_F spectrum to estimate A_{D^0}. Aubert *et al.*[4] have set an upper limit of 3.4×10^{-4} on this branching fraction.

As mentioned above, the $\mu^+\mu^+$ spectrum[16] might contain a component due to the production and semileptonic decay of a $D\bar{D}^0$ pair in which the decay $\bar{D}^0\rightarrow\mu^+X$ occurs via D^0-$\bar{D}^0$ mixing. To search for mixing we found it most effective to examine the $|\cos\theta|$ distribution of the pairs, where θ is the angle between the direction of the incident pion and a μ^+ in the muon-pair rest frame. Figure 2 shows the $|\cos\theta|$ distribution of the 3973 $\mu^+\mu^+$ pairs with mass > 2.0 GeV/c^2 belonging to the full data sample, for which the hardware mass cut was enforced. Pairs in the full data sample were required to have muon tracks at angles of at least 8 mrad relative to the incident pion beam, to avoid contamination by muons from beam-particle decays.

The histogram in Fig. 2 was obtained from the "random-pair sample." This was generated by taking a muon in the prescaled-trigger sample which was not part of an in-time opposite-sign muon pair and randomly combining it with another such muon. The excellent agreement between the directly observed $\mu^+\mu^+$ data and the random-pair sample suggests that the like-sign muon pairs were essentially all due to uncorrelated background, probably from separate pion and/or kaon decays. Since the average pion multiplicity in an rf "bucket" was about 5, the muons from uncorrelated background came mostly from different pion interactions.

We used a Monte Carlo simulation to calculate the $|\cos\theta|$ distribution of $\mu^+\mu^+$ pairs from $D\bar{D}^0$ decay with D^0-$\bar{D}^0$ mixing. To perform this simulation we needed to know the differential cross section for the associated production of $D\bar{D}^0$ pairs, as well as the muon spectra from the semileptonic decays of the D mesons. The latter were taken from the work of Ali,[17] with the assumption of contributions from $d\rightarrow K\mu\nu$, $D\rightarrow K^*(890)\mu\nu$, and $D\rightarrow\pi\mu\nu$ of 55%, 39%, and 6%, respectively.[18] For $D\bar{D}$ associated production we considered four different parametrizations: (A) Uncorrelated $D\bar{D}$ production with each D generated by

$$d^2\sigma/dx_F\,dP_T^2\sim(1-x_F)^3e^{-1.0P_T^2}$$

for $x_F>0$. (B) Uncorrelated $D\bar{D}$ production with each D generated by

$$d^2\sigma/dx_F\,dP_T^2\sim(1-x_F)^2e^{-1.0P_T^2}$$

for $x_F>0$. (C) Uncorrelated $D\bar{D}$ production with each D generated by

$$d^2\sigma/dx_F\,dP_T^2\sim[0.46(1-x_F)^{0.9}+5.2(1-x_F)^{5.9}]e^{-0.7P_T^2}$$

for $x_F>0$. (D) Correlated $D\bar{D}$ production with the D's produced from the decay of a heavier state M generated by

$$d^3\sigma/dM\,dx_f\,dP_T^2\sim e^{-0.55M}M^{-3}(1-x_F)^1e^{-1.0P_T^2}.$$

This yields a distribution $\sim(1-x_F)^3$ for each D.

Parametrization A is consistent with the measurements of the CCFRS[12] and LEBC-EHS[14] groups while B is closer to the measurements of the BIBC[11] and ACCMOR[13] groups. Parametrization C comes directly from the CCFRS[12] group, which had a beam energy and target material similar to ours. Parametrization D is representative of correlated $D\bar{D}$ production.[14]

The dashed and solid curves in Fig. 2 are the $\mu^+\mu^+$ spectra predicted by combining D^0-$\bar{D}^0$ mixing with parametrizations A and D, respectively. They have a completely different shape from the data. To determine quantitatively what fraction of the $\mu^+\mu^+$ data could be due to D^0-$\bar{D}^0$ mixing, the data were fitted by a sum of random-pair sample and Monte Carlo–generated D^0-$\bar{D}^0$ mixing events. The results of the fit are shown in Table II for the four different parametrizations. The χ^2 is 25.6 for 18 degrees of freedom for each fit. Not more than 63 events are consistent with D^0-$\bar{D}^0$ mixing at 90% C.L.

The upper limit on D^0-$\bar{D}^0$ mixing (normalized to J/ψ events) is given by

$$r=\frac{\Gamma(\bar{D}^0\rightarrow\mu^+X)}{\Gamma(\bar{D}^0\rightarrow\mu^-X)}=\frac{\sigma B(J\rightarrow\mu^+\mu^-)}{\sigma(D\bar{D}^0)B_DB_{\bar{D}^0}}\frac{N_{D\bar{D}^0}}{N_J}\frac{A_J}{A_{D\bar{D}^0}}.$$

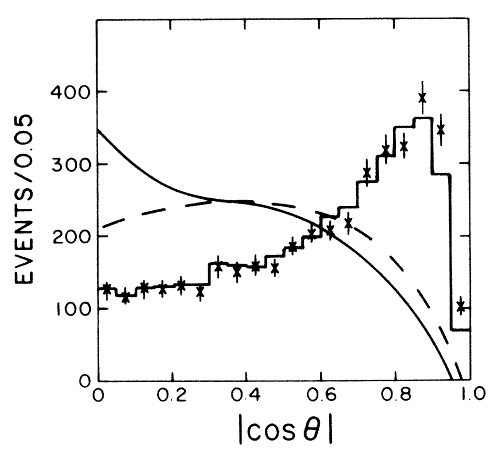

FIG. 2. $|\cos\theta|$ distribution for like-sign muon pairs (points with error bars). The histogram is from the random-pair sample. The dashed and solid lines are predictions arising from D^0-$\bar{D}^0$ mixing in parametrizations A and D, respectively, described in text.

TABLE II. Total acceptances, limits on the number of mixing events, and limits on $r=\Gamma(\bar{D}^0\rightarrow\mu^+X)/\Gamma(\bar{D}^0\rightarrow\mu^-X)$ for the four parametrizations of $D\bar{D}$ production described in the text.

Parametrization	Total acceptance	Limit on mixing events	Limit on r
A	$(3.3\pm0.3)\times10^{-5}$	52.1	5.6×10^{-3}
B	$(4.6\pm0.5)\times10^{-5}$	43.6	3.4×10^{-3}
C	$(4.5\pm0.5)\times10^{-5}$	62.9	5.0×10^{-3}
D	$(6.8\pm0.7)\times10^{-5}$	43.8	2.3×10^{-3}

The cross section times branching ratio for J/ψ production is given above. The number of J/ψ decays observed in the full data sample was $N_J=(2.20\pm0.10)\times10^6$. The total $J/\psi\rightarrow\mu^+\mu^-$ acceptance was calculated to be $A_J=0.0307\pm0.0016$, with account taken of the more restrictive trigger and analysis requirements of the full data sample. For the $D\rightarrow\mu X$ semileptonic branching ratios we used measurements by Baltrusaitis *et al.*[19] of $B_D=(11.7\pm1.1)\%$ and $B_{\bar{D}^0}=(7.5\pm1.2)\%$. We assumed that a $\bar{D}^0$ was always accompanied by a D^+ or D^0 with equal probability. A neutral-D cross section larger than the charged-D cross section, or significant $\Lambda_c^+\bar{D}$ production,[20] would imply a lower semileptonic branching ratio; however, this would be offset by a relatively larger $\bar{D}^0$ cross section. Hence, the cross section for a $D\bar{D}^0$ pair was taken to be $\sigma(D\bar{D}^0)=\sigma(\bar{D}^0)=3.8\pm0.5$ μb/nucleon. The total acceptance $A_{D\bar{D}^0}$ for $D(\rightarrow\mu^+X)\bar{D}^0(\rightarrow\mu^+X)$, the number $N_{D\bar{D}^0}$ of possible D^0-$\bar{D}^0$ mixing events at 90% C.L. and the resulting limits are shown in Table II for the four different parametrizations.

To set a limit we take the $D\bar{D}$ production parameters from parametrization A and conclude that at 90% C.L.,

$$r=\Gamma(\bar{D}^0\rightarrow\mu^+X)/\Gamma(\bar{D}^0\rightarrow\mu^-X)<5.6\times10^{-3},$$

where the percentage errors have been added in quadrature. A possible source of systematic error is the estimate of the total acceptance, $A_{D\bar{D}^0}$. Our acceptance is greater for correlated $D\bar{D}^0$ production at high x_F and lower for uncorrelated production at low x_F. To be conservative we have based our limit on parametrization A which produces an uncorrelated $D\bar{D}^0$ pair with a central x_F spectrum. The previous best limit[5] is $r<1.2\times10^{-2}$. Predictions[3] of r lie in the range 10^{-4} to 10^{-12}. Analysis of D^0-$\bar{D}^0$ mixing indicates that

$$r=(4\Delta M^2+\Delta\Gamma^2)/(8\Gamma^2+4\Delta M^2-\Delta\Gamma^2),$$

where ΔM and $\Delta\Gamma$ are the differences in the masses and widths of the two CP eigenstates of the D^0, and Γ is the average width.[21] For $\Gamma=2.27\times10^{12}$/sec,[22] and $r<5.6\times10^{-3}$, we obtain $\Delta M<1.6\times10^{-4}$ eV/c^2 and $\Delta\Gamma/\Gamma<0.21$.

This work was supported in part by the U. S. Department of Energy under Contracts No. DE-AC02-76ER03072 and No. W-7405-ENG-82-KA-01-01 and by the National Science Foundation under Grant No. 83-03203.

(a)Present address: University of California at Santa Cruz, Santa Cruz, Cal. 95064.

(b)Present address: Stanford Linear Accelerator Center, Stanford, Cal. 94305.

(c)Present address: Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Torino, Italy.

(d)Present address: FONAR Corp., Melville, N.Y. 11747.

(e)Present address: Fermilab, Batavia, Ill. 60510.

(f)Present address: IBM, Endicott, N.Y. 13760.

[1]S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D **2**, 1285 (1970).

[2]S. L. Glashow and S. Weinberg, Phys. Rev. D **15**, 1958 (1977); E. A. Paschos, Phys. Rev. D **15**, 1966 (1977).

[3]L. Wolfenstein, Phys. Lett. **164B**, 170 (1985); A. Datta and D. Kumbhakar, Z. Phys. C **27**, 515 (1985); L.-L. Chau, Phys. Rep. **95**, 1 (1983); E. A. Paschos, B. Stech, and U. Türke, Phys. Lett. **128B**, 240 (1983); A. Pais and S. B. Treiman, Phys. Rev. D **12**, 2744 (1975).

[4]J. J. Aubert *et al.*, Phys. Lett. **155B**, 461 (1985).

[5]A. C. Benvenuti *et al.*, Phys. Lett. **158B**, 531 (1985); H. Yamamoto *et al.*, Phys. Rev. Lett. **54**, 522 (1985); A. Bodek *et al.*, Phys. Lett. **113B**, 82 (1982); J. J. Aubert *et al.*, Phys. Lett. **106B**, 419 (1981); P. Avery *et al.*, Phys. Rev. Lett. **44**, 1309 (1980); G. J. Feldman *et al.*, Phys. Rev. Lett. **38**, 1313 (1977); G. Goldhaber *et al.*, Phys. Lett. **69B**, 503 (1977).

[6]G. Gladding, in Proceedings of the Fifth International Conference on Physics in Collision, Autun, France, 1985 (to be published).

[7]A. Datta, Phys. Lett. **154B**, 287 (1985); A. M. Hadeed and B. Holdom, Phys. Lett. **159B**, 379 (1985); R. L. Kingsley, F. Wilczek, and A. Zee, Phys. Lett. **61B**, 259 (1976).

[8]S. Palestini *et al.*, Phys. Rev. Lett. **55**, 2649 (1985).

[9]C. Biino *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **243**, 323 (1986).

[10]C. E. Adolphsen, Ph.D. dissertation, University of Chicago, 1985 (unpublished).

[11]A. Badertscher *et al.*, Phys. Lett. **123B**, 471 (1983).

[12]J. Ritchie *et al.*, Phys. Lett. **138B**, 213 (1984). We have reduced the cross section from 20.2 μb, using the D semileptonic branching ratio from R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **54**, 1976 (1985).

[13]R. Bailey *et al.*, Phys. Lett. **132B**, 230, 237 (1983).

[14]M. Aguilar-Benitez *et al.*, Phys. Lett. **123B**, 98 (1983), and **146B**, 266 (1984), and **164B**, 404 (1985), and Phys. Lett. B (to be published).

[15]J. Badier *et al.*, Z. Phys. C **20**, 101 (1983); K. J. Anderson *et al.*, Phys. Rev. Lett. **36**, 237 (1976).

[16]The $\mu^+\mu^+$ spectrum includes $\mu^+\mu^+$ pairs produced by the π^- beam and $\mu^-\mu^-$ pairs produced by the π^+ beam.

[17]A. Ali, Z. Phys. C **1**, 25 (1979).

[18]W. Bacino *et al.*, Phys. Rev. Lett. **43**, 1073 (1979).

[19]Baltrusaitis, Ref. 12.

[20]We estimated that if $\Lambda_c^+\bar{D}^0$ production is comparable to $D^0\bar{D}^0$ and $D^+\bar{D}^0$ production, our limit would increase by about 10%.

[21]R. L. Kingsley, Phys. Lett. **63B**, 329 (1976).

[22]C. G. Wohl *et al.*, (Particle Data Group), Rev. Mod. Phys. **56**, S1 (1984).