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M. Basile et al. :

MEASUREMENT OF ASSOCIATED PRODUCTION OF $D^o\bar{D}$ IN pp INTERACTIONS AT $\sqrt{s}$ = 62 GeV

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Measurement of Associated Production of $D^0\bar{D}$ in pp Interactions at $\sqrt{s} = 62$ GeV (*).

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Summary. — The associated production of charm-meson pairs ($D^0\bar{D}$) has been studied in pp interactions at $\sqrt{s} = 62$ GeV. Total cross-section estimates are given for different hypotheses on the production distributions. The lowest cross-section estimate corresponds to a « central » production model, for both the D^0 and the $\bar{D}$.

1. – Introduction.

The purpose of the present paper is to report evidence for the associated production of « open charm » mesons in pp interactions at $\sqrt{s} = 62$ GeV and to give cross-section estimates.

The reaction studied was

$$\text{pp} \to \bar{D} + D^0 + \text{anything} \tag{1}$$

with the D^0 observed in the decay mode

$$D^0 \to K^-\pi^+ \tag{2}$$

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and the associated $\overline{\mathrm{D}}$ meson, used as a « trigger », via the decay mode

$$\overline{\mathrm{D}} \to \mathrm{e}^- + \mathrm{K}^+ + \text{anything}\,. \tag{3}$$

So far, the production of $\mathrm{D}^0\overline{\mathrm{D}}$ pairs has been observed in π, ν, or γ beam experiments (1) at lower energy.

2. – Experimental set-up.

The experimental apparatus was a large-volume magnetic field, the Split-Field Magnet (SFM) at the CERN Intersecting Storage Rings (ISR), with its powerful system of multiwire proportional chambers (MWPCs) to allow track reconstruction and momentum measurement. A hodoscope of time-of-flight counters (TOF) (2) was also used, providing particle identification up to about 2 GeV/c momentum. In addition, a system of electromagnetic-shower detectors (EMSDs) (3), gas threshold Čerenkov counters and a « dE/dx » chamber (4) (a small MWPC with analog read-out placed very close to the interaction region) was used for electron/positron detection at 90°.

A schematic view of the set-up is shown in fig. 1. Details of detector performances and data-taking conditions have already been reported elsewhere (5-9).

(1) LEBC-EHS COLLABORATION (B. ADEVA *et al.*): preprint CERN-EP/81-28 (1981), and references therein.

(2) M. BASILE, G. CARA ROMEO, L. CIFARELLI, A. CONTIN, G. D'ALÍ, P. DI CESARE, B. ESPOSITO, L. FAVALE, P. GIUSTI, T. MASSAM, F. PALMONARI, G. SARTORELLI, G. VALENTI and A. ZICHICHI: *Nucl. Instrum. Methods*, **179**, 477 (1981).

(3) M. BASILE, G. CARA ROMEO, L. CIFARELLI, A. CONTIN, G. D'ALÍ, P. GIUSTI, T. MASSAM, F. PALMONARI, G. SARTORELLI, G. VALENTI and A. ZICHICHI: *Nucl. Instrum. Methods*, **163**, 93 (1979).

(4) H. FREHSE, F. LAPIQUE, M. PANTER and F. PIUZ: *Nucl. Instrum. Methods*, **156**, 87 (1978); H. FREHSE, M. HEIDEN, M. PANTER and F. PIUZ: *Nucl. Instrum. Methods*, **156**, 97 (1978).

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(6) M. BASILE, G. CARA ROMEO, L. CIFARELLI, A. CONTIN, G. D'ALÍ, P. DI CESARE, B. ESPOSITO, P. GIUSTI, T. MASSAM, F. PALMONARI, G. SARTORELLI, G. VALENTI and A. ZICHICHI: *Nuovo Cimento A*, **62**, 14 (1981).

(7) M. BASILE, G. CARA ROMEO, L. CIFARELLI, A. CONTIN, G. D'ALÍ, P. DI CESARE, B. ESPOSITO, P. GIUSTI, T. MASSAM, F. PALMONARI, G. SARTORELLI, G. VALENTI and A. ZICHICHI: *Lett. Nuovo Cimento*, **30**, 487 (1981).

(8) M. BASILE, G. CARA ROMEO, L. CIFARELLI, A. CONTIN, G. D'ALÍ, P. DI CESARE, B. ESPOSITO, P. GIUSTI, T. MASSAM, F. PALMONARI, G. SARTORELLI, G. VALENTI and A. ZICHICHI: *Lett. Nuovo Cimento*, **30**, 481 (1981).

(9) M. BASILE, G. BONVICINI, G. CARA ROMEO, L. CIFARELLI, A. CONTIN, G. D'ALÍ, P. DI CESARE, B. ESPOSITO, P. GIUSTI, T. MASSAM, R. NANIA, F. PALMONARI, G. SARTORELLI, G. VALENTI and A. ZICHICHI: *Lett. Nuovo Cimento*, **31**, 97 (1981).

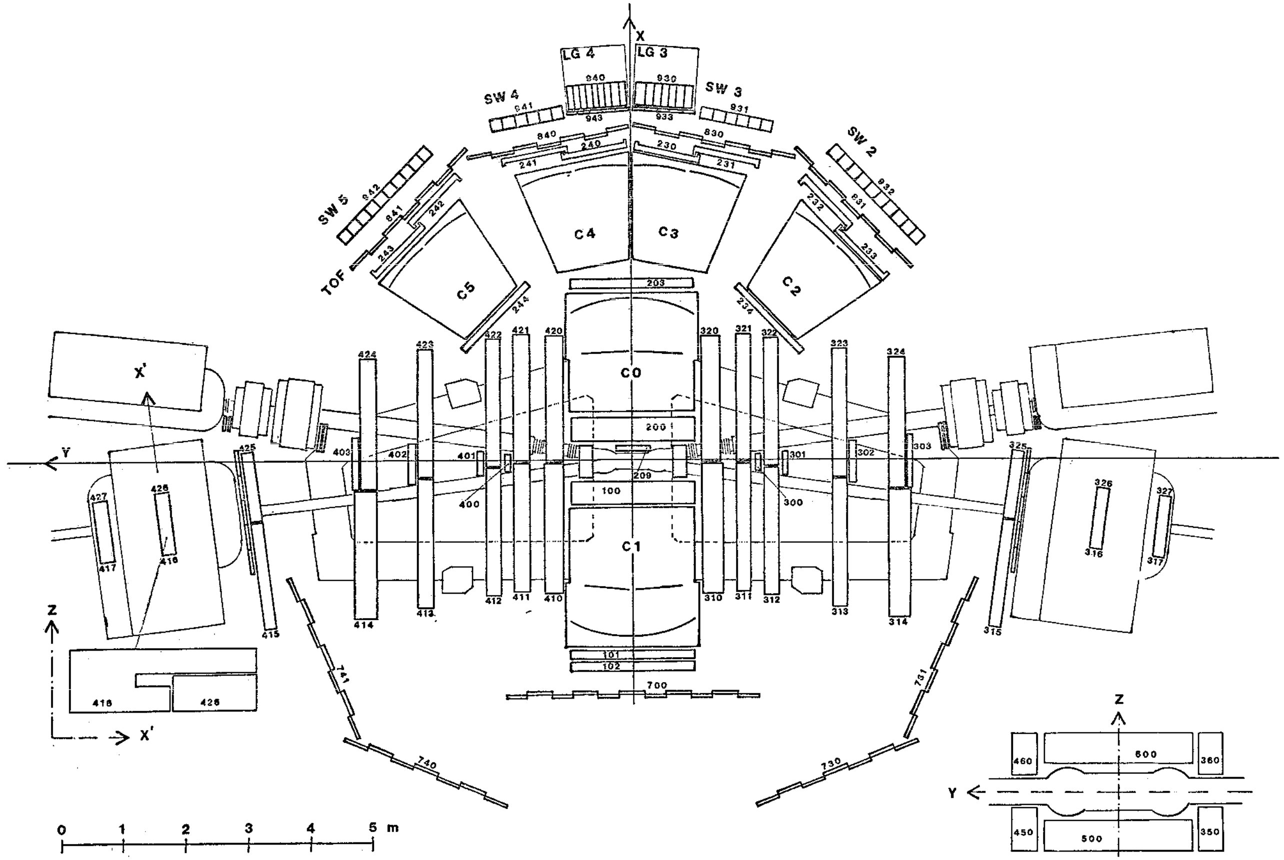


Fig. 1. – Top view of the apparatus showing the SFM and the MWPC system, the Čerenkov counters (C0 to C5), the electromagnetic-shower detectors (EMSDs) (lead-glass array: LG3 and LG4; and lead/scintillator sandwich: SW2 to SW5), the time-of-flight counter hodoscope (TOF) and the « dE/dx » chamber (numbered as 209).

The key points of the experiment were

i) the detection of a single electron e^- or of a single positron e^+ (via EMSD, Čerenkov and « dE/dx »),

ii) the identification of a negative or a positive K-meson (via TOF),

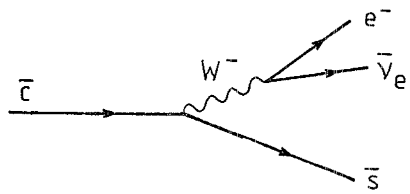
iii) the momentum measurement of all charged tracks, no matter whether they are identified as « e » or « K ».

3. – Data analysis.

The logic of the experiment, in order to study reaction (1), was as follows.

The $\bar{D}$-meson could be either a negatively charged D^- or a neutral $\bar{D}^0$. However, its decay mode had to follow the pattern illustrated below, in terms of antiquark transition states:

(4)



In terms of physical particles, reaction (4) produces the final state of reaction (3), *i.e.* an e^- and a K^+. These particles were used as a « trigger ». This means that the semi-leptonic decay mode of the D state was taken as a « signature » for the production of an anticharm particle.

The identification of the e^- was done via the study of the energy release in the EMSDs, of the Čerenkov counters' response and of the pulse height in the « dE/dx » chamber [5-9]. Furthermore, the reconstructed e^- track was required to have a transverse momentum $p_T \geqslant 0.5$ GeV/c and a momentum uncertainty $\Delta p/p \leqslant 15\%$. The residual charged-hadron contamination in the e^- sample was $\sim 2\%$, whilst the background from neutral-hadron conversion amounted to $\leqslant 50\%$.

The K^+ identification was done by the TOF system with better than 90% C.L. [2]. The momentum cuts were $p < 1.5$ GeV/c and $\Delta p/p \leqslant 30\%$. The π^+ and proton contamination in the K^+ sample was about 10%.

The charmed meson D^0 was searched for via its decay mode (2). For this purpose, the $K^-\pi^+$ invariant mass was studied, where the K^- was any negative track not identified by TOF as a $\bar{p}$ or a π^-, and the π^+ was any positive track not identified by TOF as a p or a K^+. In addition, the π^+ had to satisfy the condition $|x_L| < 0.3$ (where $x_L = 2p_L/\sqrt{s}$), since above this value the « leading » proton contamination was not negligible ([10]).

In order to enter the $K^-\pi^+$ mass plot, a track had to have a momentum error $\Delta p/p \leqslant 30\%$.

Finally, all e^-, K^+, K^- and π^+ tracks were required to fit the event vertex within ± 5 cm.

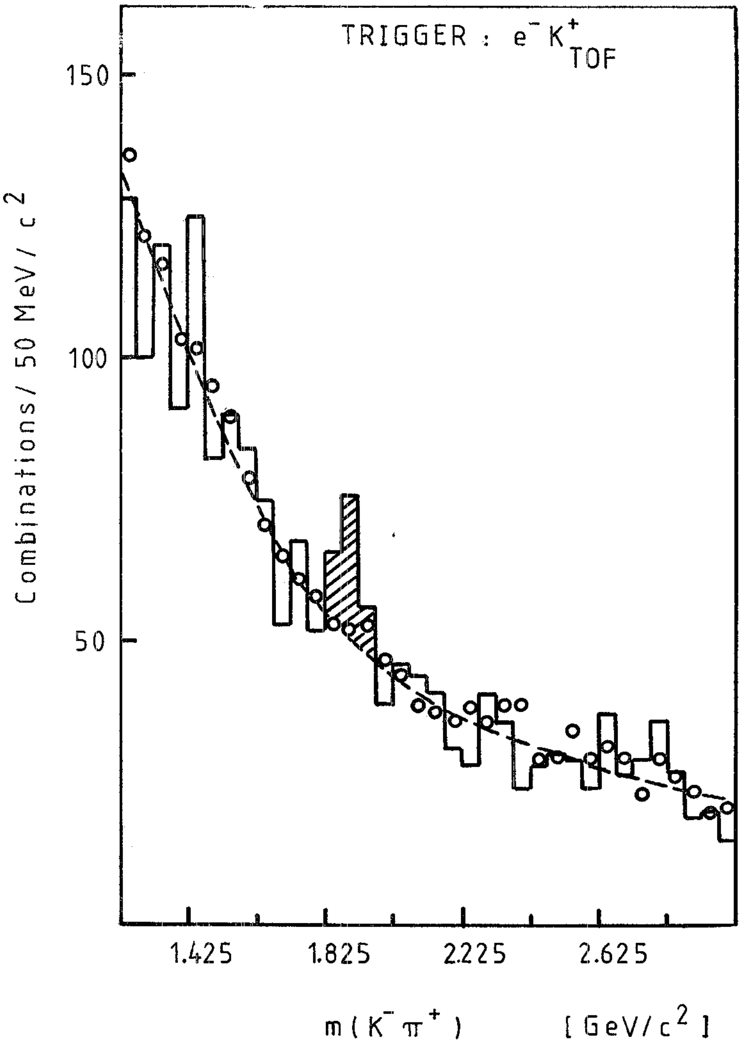


Fig. 2. – $K^-\pi^+$ invariant-mass spectrum obtained with $(e^-K^+_{TOF})$ trigger. The circles and the dashed curve superimposed show the « event mixing » background spectrum and fit, respectively.

([10]) P. Capiluppi, G. Giacomelli, A. M. Rossi, G. Vannini, A. Bertin, A. Bussière and E. J. Ellis: *Nucl. Phys. B*, **79**, 189 (1974).

4. – Results.

4'1. *The mass spectrum.* – We have studied the $K^-\pi^+$ mass spectrum in two ways.

The first is shown in fig. 2, where the D^0 enhancement is present with 47 ± 13 mass combinations and about 4 standard-deviation significance. This result is obtained by means of the $(e^-K^+_{TOF})$ trigger described above, without any further condition on the $K^-\pi^+$ system.

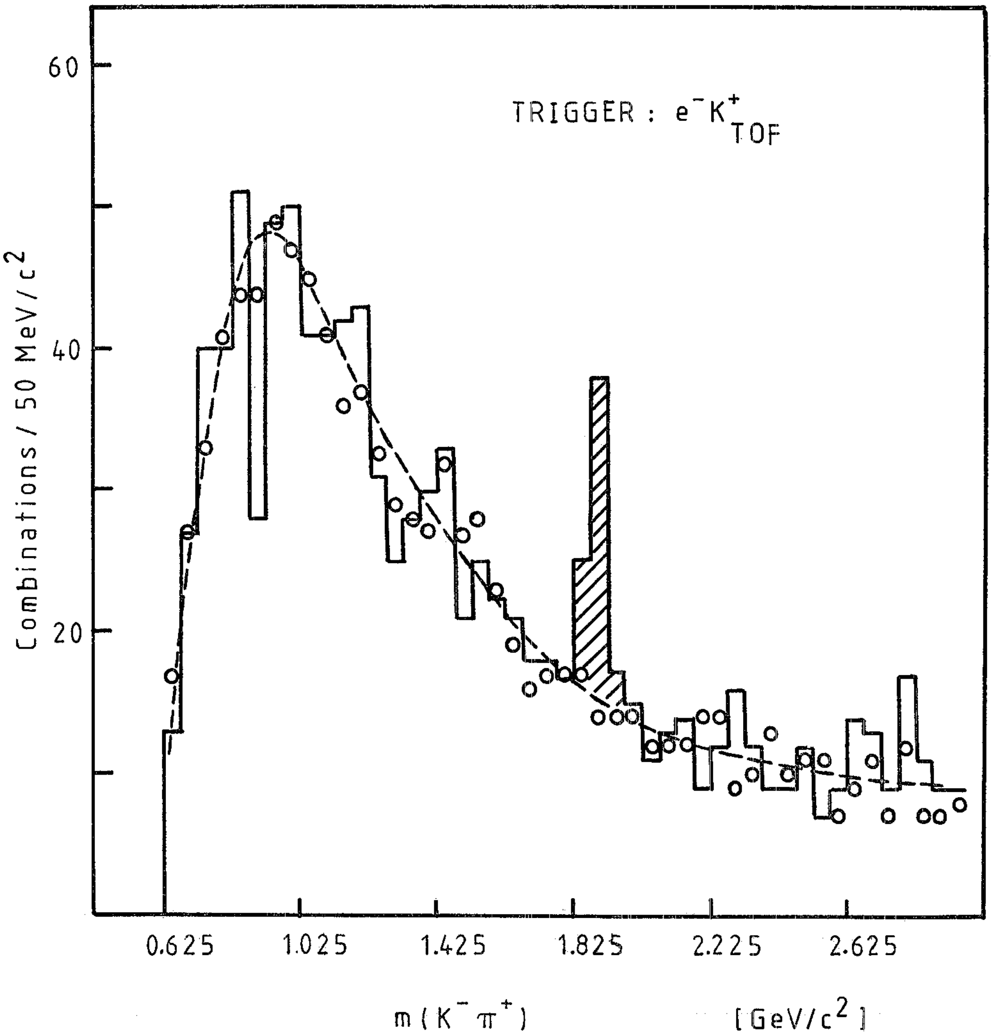


Fig. 3. – Same as fig. 2 with the further high-p_T requirement $p_T(K^-\pi^+) \geqslant 0.7$ GeV/c.

The second way is illustrated in fig. 3, where a transverse-momentum cut is applied to the $K^-\pi^+$ system, *i.e.* $p_T(K^-\pi^+) \geqslant 0.7$ GeV/c. The number of combinations is reduced to 34 ± 7. However, the statistical significance increases: it is now at the 5 standard-deviation level.

The D^0 is observed in the mass interval

$$(1.825 \leqslant m_{D^0} < 1.975)\ \text{GeV}/c^2\,,$$

and its width is compatible with the expected mass resolution. The events/combinations ratio in the D^0 peak is $\sim 75\%$.

The background shape in fig. 2 and 3 is obtained by using the « event mixing » technique: take an $(e^-K^+_{TOF})$-triggered event and combine the K^- from this event with the π^+ from the next one. The background shape follows quite well the natural background of the $K^-\pi^+$ mass spectrum.

Now comes a crucial test to check the validity of our starting hypothesis:

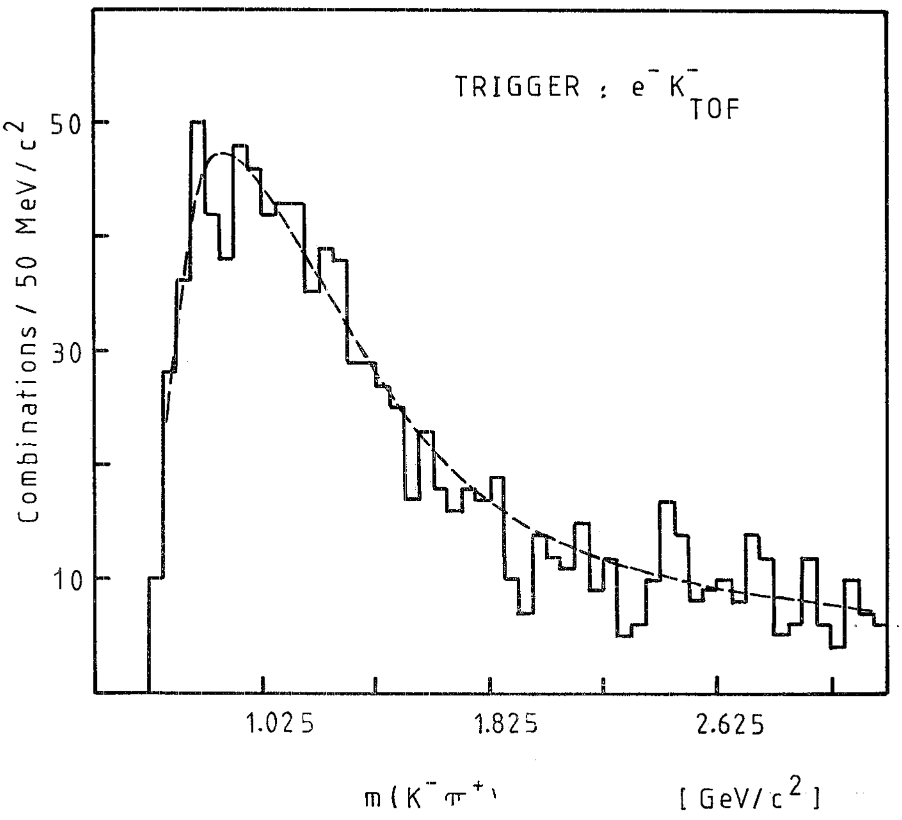


Fig. 4*a*. – $K^-\pi^+$ mass spectrum obtained when $p_T(K^-\pi^+) \geqslant 0.7$ GeV/c with the trigger $(e^-K^-_{TOF})$. The dashed curve is a fit to this spectrum.

Is the $(e^-K^+_{TOF})$ trigger the signature of an anticharm semi-leptonic decay? In order to verify this point, we have studied the $K^-\pi^+$ mass plot using data with the following triggers:

i) $(e^-K^-_{TOF})$, ii) $(e^+K^+_{TOF})$, iii) $(e^+K^-_{TOF})$.

Trigger i) has the « correct » e^- but the « wrong » K^-_{TOF}, trigger ii) has the « correct » K^+_{TOF} but the « wrong » e^+, and trigger iii) has both the e^+ and the

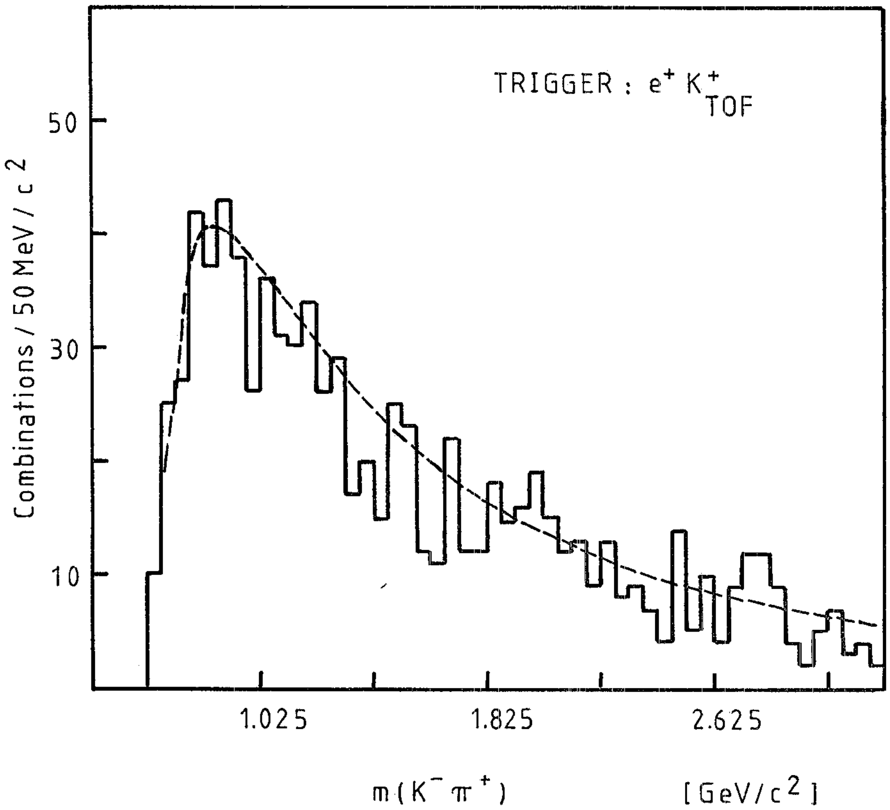


Fig. 4*b*. – Same as fig. 4*a*, but for the trigger $(e^+K^+_{TOF})$.

K^-_{TOF} « wrong ». The results are shown in fig. 4*a*-4*c*, where there is clearly no evidence for any effect in the $K^-\pi^+$ invariant-mass spectrum. Figure 4*d* is the sum of all the triggers.

4·2. *Cross-section estimates.* – In order to evaluate the production cross-section for reaction (1), the following quantities are needed:

a) the branching ratio

(5) $$B(\overline{\mathrm{D}} \to \mathrm{e}^-\mathrm{K}^+ + \text{anything}) = \frac{\overline{\mathrm{D}} \to \mathrm{e}^-\mathrm{K}^+ + \text{anything}}{\overline{\mathrm{D}} \to \text{all}}\,,$$

b) the branching ratio

(6) $$B(\mathrm{D}^0 \to \mathrm{K}^-\pi^+) = \frac{\mathrm{D}^0 \to \mathrm{K}^-\pi^+}{\mathrm{D}^0 \to \text{all}}\,;$$

c) the production distributions for the D^0 and the $\overline{\mathrm{D}}$,

d) the acceptances and the efficiencies of the experimental apparatus,

e) the total luminosity.

The branching ratios are known, although with large uncertainties. In order to derive the semi-leptonic decay of the $\overline{\mathrm{D}}(=\frac{1}{2}\overline{\mathrm{D}}^0+\frac{1}{2}\mathrm{D}^-)$, we have

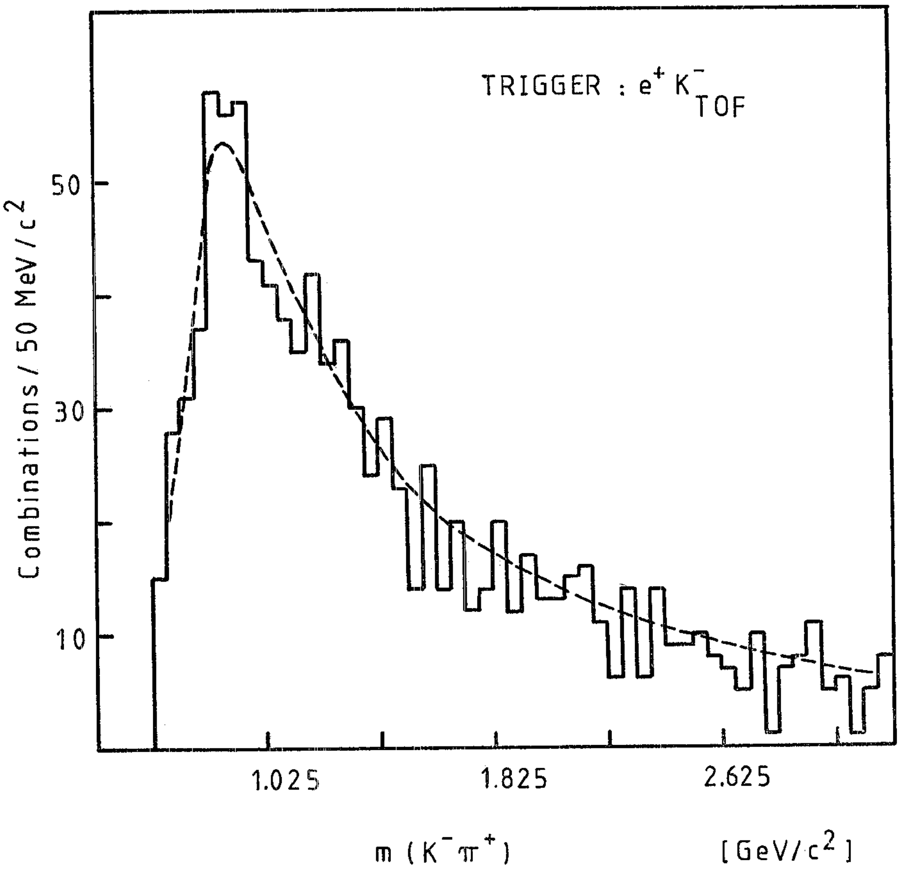


Fig. 4*c*. – Same as fig. 4*a*, but for the trigger ($\mathrm{e}^+\mathrm{K}^-_{\mathrm{TOF}}$).

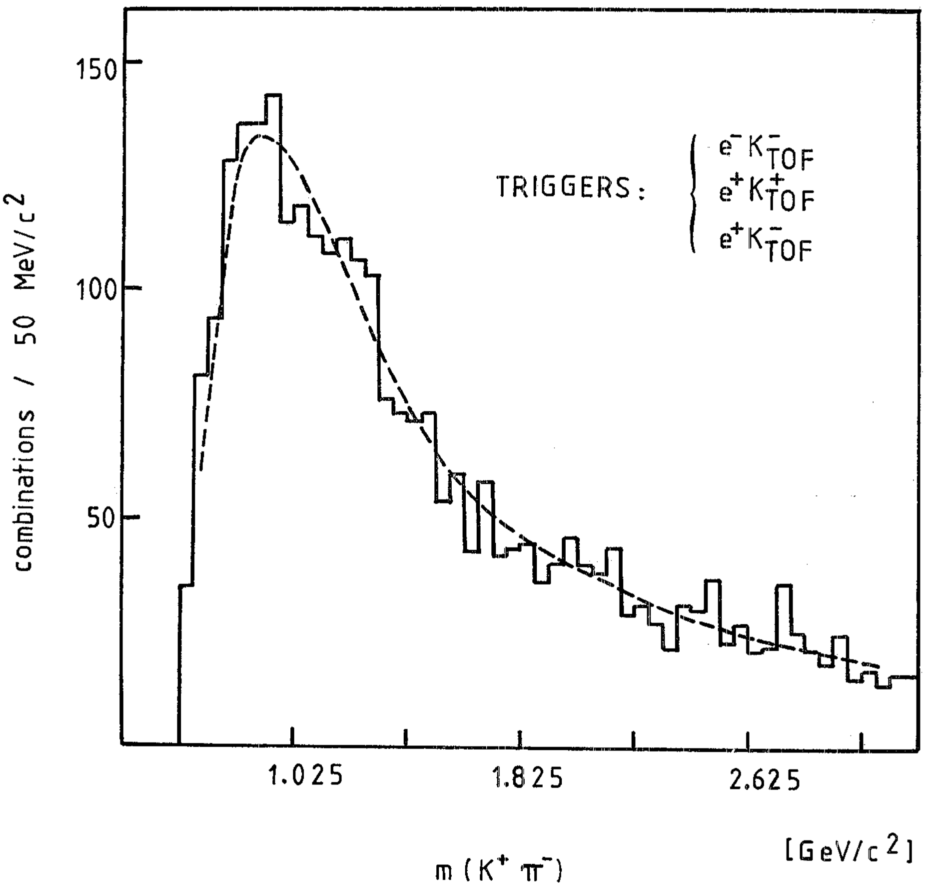


Fig. 4*d*. – Same as fig. 4*a*, but for the sum of the triggers ($e^-K^-_{TOF}$), ($e^+K^+_{TOF}$) and ($e^+K^-_{TOF}$).

taken [11,12]

$$\text{i)}\ \frac{\bar{D} \to e^- + \text{anything}}{\bar{D} \to \text{all}} = (8.5 \pm 1.5)\,\%\,,$$

$$\text{ii)}\ \frac{\bar{D} \to Ke^-\bar{\nu}}{\bar{D} \to e^- + \text{anything}} = (60 \pm 15)\% \qquad (\text{where } K = \tfrac{1}{2}K^0 + \tfrac{1}{2}K^+),$$

([11]) J. M. FELLER, A. M. LITKE, R. J. MADARAS, M. T. RONAN, A. BARBARO-GALTIERI, J. M. DORFAN, R. ELY, G. J. FELDMAN, A. FONG, B. GOBBI, G. HANSON, J. A. JAROS, B. P. KWAN, P. LECOMTE, D. LÜKE, J. F. MARTIN, D. H. MILLER, S. I. PARKER, M. L. PERL, I. PERUZZI, M. PICCOLO, T. P. PUN, P. A. RAPIDIS, R. R. ROSS, D. L. SCHARRE, T. G. TRIPPE, V. VUILLEMIN and D. E. YOUNT: *Phys. Rev. Lett.*, **40**, 1677 (1978).

([12]) W. BACINO, R. BURNS, P. CONDON, P. COWELL, A. DIAMANT-BERGER, G. DONALD-

iii) $\dfrac{\overline{D} \to K^* e^- \bar{\nu}}{\overline{D} \to e^- + \text{anything}} = (40 \pm 15)\%$

$$\left(\text{with } K^* = \tfrac{1}{2} K^{*0} + \tfrac{1}{2} K^{*+}, \quad \frac{K^{*0} \to K^+\pi^-}{K^{*0} \to \text{all}} = \frac{2}{3} \text{ and } \frac{K^{*+} \to K^+\pi^0}{K^{*+} \to \text{all}} = \frac{1}{3}\right).$$

The above values produce, for the branching ratio (5), the result

$$B(\overline{D} \to e^- K^+ + \text{anything}) = (4.3 \pm 1.2)\% .$$

For the D^0 decay, the branching ratio (6) is ([13])

$$B(D^0 \to K^- \pi^+) = (3.0 \pm 0.6)\% .$$

The inclusive charm production cross-section was assumed to follow the law

$$E \frac{d^3\sigma}{dp^3} = f(y/y_{\max}) \exp[-bp_T] ,$$

where $b^{-1} = 0.5$ GeV/c, and the function $f(y/y_{\max})$ gives the longitudinal-momentum dependence. For this, the following three cases were considered (*):

model I («central» production): $E \dfrac{d\sigma}{d|x_L|} \propto (1 - |x_L|)^3$;

model II («flat-y» production): $\dfrac{d\sigma}{d|y|} = \text{const}$;

model III («flat-x_L» production): $\dfrac{d\sigma}{d|x_L|} = \text{const}$.

A K_{e3}-like matrix was used to simulate the $\overline{D}$ decay (3).

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([13]) R. H. SCHINDLER, M. S. ALAM, A. M. BOYARSKI, M. BREIDENBACH, D. L. BURKE, J. DORENBOSCH, J. M. DORFAN, G. J. FELDMAN, M. E. B. FRANKLIN, G. HANSON, K. G. HAYES, T. HIMEL, D. G. HITLIN, R. J. HOLLEBEEK, W. R. INNES, J. A. JAROS, P. JENNI, R. R. LARSEN, V. LÜTH, M. L. PERL, B. RICHTER, A. ROUSSARIE, D. L. SCHARRE, R. F. SCHWITTERS, J. L. SIEGRIST, H. TAUREG, M. TONUTTI, R. A. VIDAL, J. M. WEISS, H. ZACCONE, G. ABRAMS, C. A. BLOCKER, A. BLONDEL, W. C. CARITHERS, W. CHINOWSKY, M. W. COLES, S. COOPER, W. E. DIETERLE, J. B. DILLON, M. W. EATON, G. GIDAL, G. GOLDHABER, A. D. JOHNSON, J. A. KADYK, A. J. LANKFORD, R. E. MILLIKAN, M. E. NELSON, C. Y. PANG, J. F. PATRICK, J. STRAIT, G. H. TRILLING, E. N. VELLA and I. VIDEAU: preprints LBL-10905 (1980) and SLAC-PUB-2507 (1980) (submitted to *Phys. Rev. D*), and references therein.

(*) $x_L = 2p_L/\sqrt{s}$ and $y = \frac{1}{2} \ln[(E + p_L)/(E - p_L)]$.

The cross-section for associated $D^0\bar{D}$ production was then computed for different combinations of D^0 and $\bar{D}$ models, with the further assumption that the two mesons were produced in an uncorrelated way. More precisely, the production cross-sections were estimated in the following five hypotheses:

1) both D^0 and $\bar{D}$ are produced in a « central » way;

2) both D^0 and $\bar{D}$ are produced « flat » in the rapidity variable y;

3) both D^0 and $\bar{D}$ are produced « flat » in the longitudinal fractional momentum variable x_L;

4) the D^0 is produced « flat » in x_L, whilst the $\bar{D}$ is produced in a « central » way;

5) the D^0 is produced « centrally », whilst the $\bar{D}$ is produced « flat » in x_L.

The efficiencies for e^- and K^+_{TOF} detection, $\sim 45\%$ and $\sim 70\%$, respectively, and the acceptances of the apparatus corresponding to the various production mechanisms listed above were calculated by Monte Carlo simulation.

The total integrated luminosity, relative to an initial sample of about $3 \cdot 10^6$ collected events, was $4.4 \cdot 10^{36}$ cm^{-2}.

Table I contains the cross-section estimates for $D^0\bar{D}$ pair production. The overall uncertainty is $\sim 50\%$.

TABLE I. – *Production cross-sections for* $D^0\bar{D}$ *in* pp *interactions at* $\sqrt{s} = 62$ GeV *vs. different models.*

	D^0 production distribution		$\bar{D}$ production distribution		σ_{tot} (μb)
1	$E(d\sigma/d\|x_L\|) \propto (1-\|x_L\|)^3$	(I)	$E(d\sigma/d\|x_L\|) \propto (1-\|x_L\|)^3$	(I)	575
2	$d\sigma/d\|y\| = \text{const}$	(II)	$d\sigma/d\|y\| = \text{const}$	(II)	1290
3	$d\sigma/d\|x_L\| = \text{const}$	(III)	$d\sigma/d\|x_L\| = \text{const}$	(III)	> 5000
4	$d\sigma/d\|x_L\| = \text{const}$	(III)	$E(d\sigma/d\|x_L\|) \propto (1-\|x_L\|)^3$	(I)	1000
5	$E(d\sigma/d\|x_L\|) \propto (1-\|x_L\|)^3$	(I)	$d\sigma/d\|x_L\| = \text{const}$	(III)	3610

5. – Conclusion.

We have observed the pair production of D^0 and $\bar{D}$ charmed mesons. The D^0 was detected via the hadronic decay mode $K^-\pi^+$; the associated anticharm meson, $\bar{D}^0$ or D^-, was identified via its semi-leptonic decay into an e^- and a K^+.

Even though the total cross-section estimates are affected by large errors, the case in which both the D^0 and the $\bar{D}$ are produced « centrally » provides the lowest cross-section value. This, even if higher, is the closest to present theoretical predictions (14). However, as previously observed for the $\Lambda_c^+\bar{D}$ associated production study (5), charm cross-sections, as measured at the ISR, tend to be larger then any theoretical expectation.

The hypothesis of a « central » charm-meson production is supported by the experimental x_L distribution of the D^0, measured in the same experiment. This will be reported elsewhere (15).

Our present results on $D^0\bar{D}$ pair production are further evidence for associated charm production at the ISR and provide a deeper knowledge of this phenomenon in high-energy proton-proton interactions.

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(14) See, for instance, B. L. COMBRIDGE: *Nucl. Phys. B*, **151**, 429 (1979); C. E. CARLSON and R. SUAYA: *Phys. Lett. B*, **81**, 329 (1979); H. FRITZSCH and K. H. STRENG: *Phys. Lett. B*, **78**, 447 (1978).

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● RIASSUNTO

È studiata la produzione associata di coppie di mesoni con « charm » ($D^0\bar{D}$) in interazioni pp a $\sqrt{s} = 62$ GeV. La sezione d'urto totale è valutata usando differenti ipotesi sui modelli di produzione. Il valore più basso per la sezione d'urto si valuta con un modello di produzione « centrale », sia per il mesone D^0 che per l'antimesone $\bar{D}$.

Измерения ассоциированного рождения $D^0\bar{D}$ в pp взаимодействиях при $\sqrt{s} = 62$ ГэВ.

Резюме (*). — В pp взаимодействиях при $\sqrt{s}=62$ ГэВ исследовано ассоциированное рождение пар очарованных мезонов ($D^0\bar{D}$). Приводятся оценки полного поперечного сечения, используя различные гипотезы для распределений рождения. Наименьшая величина для поперечного сечения соответствует модели « центрального » рождения для D^0 и для $\bar{D}$.

(*) *Переведено редакцией.*