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HADRON PAIR PRODUCTION BY ELECTRON-POSITRON COLLIDING BEAMS

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Hadron Pair Production by Electron-Positron Colliding Beams (*).

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Measurements of the total cross-section for the reaction

$$e^+e^- \to h^+h^- ,$$

where h is either a pion or a kaon, are reported here for center-of-mass energies ($E_+ + E_- = 2E$) ranging from 1.2 to 2.4 GeV. The experiment was conducted at Adone, the Frascati e^+e^- colliding-beam machine. These (1) and other results recently obtained by another group (2) at Adone, extend those from Orsay (3) and Novosibirsk (4) to

(*) Work partly supported by the U.S.A.E.C.

(1) Preliminary results on these measurements were given in: C. BERNARDINI: *Proceedings of the 1971 International Symposium on Electron and Photon Interactions at High Energies* (Ithaca, N. Y., 1971), p. 37; M. CONVERSI: *Proceedings of the Daresbury Study Week-End*, No. 2 (Oct. 1971), p. 85; M. GRILLI: *Lectures Delivered at the International School of Yerevian Physical Institute* (Yerevian, 1971); Frascati report LNF-71/100.

(2) V. ALLES BORELLI, M. BERNARDINI, D. BOLLINI, P. L. BRUNINI, E. FIORENTINO, T. MASSAM, L. MONARI, F. PALMONARI, F. RIMONDI and A. ZICHICHI: *Phys. Lett.*, **40** B, 433 (1972); and work presented at the *XVI International Conference on High-Energy Physics, Batavia, Chicago, Sept. 1972.*

(3) D. BENAKSAS, G. COSME, B. JEAN-MARIE, S. JULLIAN, F. LAPLANCHE, J. LEFRANCOIS, A. D. LIBERMAN, G. PARROUR, J. P. REPELLIN and G. SAUVAGE: *Phys. Lett.*, **39** B, 289 (1972).

(4) V. E. BALAKIN, G. I. BUDKER, L. M. KURDADZE, A. P. ONUCHIN, E. V. PAKHTUSOVA, S. I. SEREDNYAKOV, V. A. SIDOROV and A. N. SKRINSKY: *Phys. Lett.*, **41** B, 205 (1972).

higher energies, giving further information on the meson form factor and probing this new energy region for $J^P = 1^-$ resonant states decaying into two pions. Although a ρ' state ($m_{\rho'} \approx 1.6$ GeV, $\Gamma_{\rho'} \approx 0.35$ GeV) decaying into four charged pions has been observed [5-7], the effect of this resonance on the pion form factor barely is seen. The energy dependence of the cross-section inferred from our results is s^{-m}, where $s = (2E)^2$ and $m = 2.7 \pm 0.6$.

The apparatus used in this experiment was composed of two spark chamber-counter telescopes placed on opposite sides of a colliding-beam straight section of Adone. A view, in projection, of this apparatus is shown in Fig. 1. Considering the $\sin^2\theta$

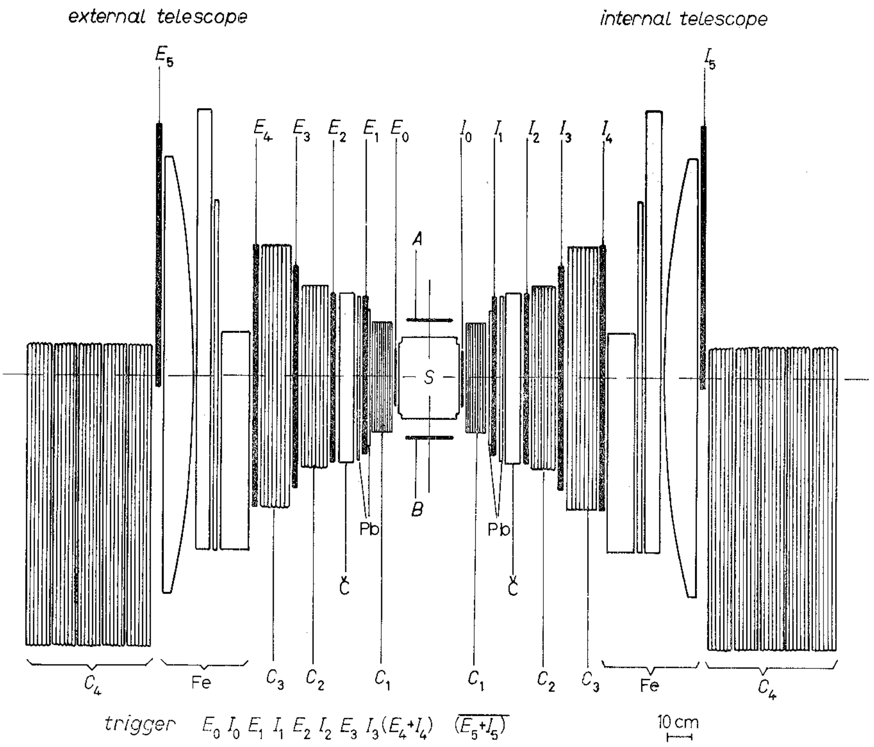

Fig. 1. – Schematic view of the apparatus along the beam direction. C_1 are thin-foil spark chambers used for space reconstruction of the events produced at the source S where the e^+, e^- bunches collide. C_2, C_3, C_4 are thick-plate spark chambers used to observe the development of electromagnetic showers and/or the nuclear interactions and the stopping of charged particles. Č are water Čerenkov counters. Counters $E_0, E_1, \ldots, E_5$ and $I_0, I_1, \ldots, I_5$ are scintillators. A and B are scintillators placed above and below the vacuum chamber to increase the solid angle for the multibody events [11] not considered in this paper.

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(5) G. Barbarino, F. Ceradini, M. Conversi, M. Grilli, E. Iarocci, M. Nigro, L. Paoluzi, R. Santonico, P. Spillantini, L. Trasatti, V. Valente, R. Visentin and G. T. Zorn: *Lett. Nuovo Cimento*, **3**, 689 (1972); F. Ceradini, M. Conversi, S. d'Angelo, K. Ekstrand, M. Grilli, E. Iarocci, M. Nigro, L. Paoluzi, P. Spillantini, R. Santonico, V. Valente and R. Visentin: *Phys. Lett.*, **43** B, 341 (1973).

(6) F. F. Liu, M. Davier, I. Derado, D. C. Fries, R. F. Mozley, A. C. Odian, J. Park, W. P. Swanson, F. Villa and D. Yount: *Nucl. Phys.*, **47** B, 1 (1972).

(7) H. H. Bingham, V. B. Fretter, W. J. Podolsky, M. S. Rabin, A. H. Rosenfeld, G. Smadja, G. P. Yost, J. Ballam, G. B. Chadwick, Y. Eisenberg, E. Kogan, K. C. Moffeit, P. Seyboth, I. O. Skillicorn, H. Spitzer and G. Wolf: *Phys. Lett.*, **41** B, 635 (1972).

dependence in the cross-section for the production of boson pair final states ([8]), the fraction of events with collinear particles incident on the solid angle of the apparatus is $\sim 20\%$ at $E = 1$ GeV. This percentage depends upon the energy, since the length of the interaction region of the bunches varies with beam energy as $E^{\frac{3}{2}}$. The master coincidence used in triggering the spark chambers of the apparatus is indicated in Fig. 1. Due to nuclear absorption the fraction of collinear h^+h^- events producing a trigger pulse is $\sim 35\%$.

In order to identify $\pi\pi$ and KK final states, which are found to be quite rare, it was essential to reject with high efficiency the rather large background due to other two-body final states. This was particularly important for e^+e^- wide-angle scattering (WAS) events, as they were about two orders of magnitude more frequent than the h^+h^- events (*). In addition, the large rate of cosmic-ray muons through the apparatus (~ 1/s) made efficient rejection of it essential. With this in mind the following detailed information on each event was recorded along with the photograph of the two orthogonal views of the spark chambers:

i) pulse heights in the two counter pairs I_2I_3 and E_2E_3 (H_I and H_E),

ii) relative time between the bunch-bunch collision and the event ($T_{1\text{-}RF}$),

iii) time intervals between I_3 and E_3 (T_{33}) and between I_4 and E_4 (T_{44}),

iv) all those counters which had a coincident pulse, including the two threshold Čerenkov counters Č, used to distinguish pions from kaons at total particle energies below 800 MeV.

The search for $e^+e^- \to h^+h^-$ events began with the analysis of the spark chamber pictures. Candidates for hadron-pair events were required to produce two single tracks aligned within 8° in chambers C_1 and appearing to come from a point of the e^+e^- interaction region S. Single scatterings and nuclear interactions producing hadronlike secondaries, along either or both tracks, can occur in chambers C_2 and C_3. Showers, defined as a grouping of nonaligned sparks, occurring along either track direction, were rejected as due to WAS events. The probability that a WAS event showed a pair of collinear tracks, without any shower, was measured to be $\sim 5\cdot 10^{-3}$ using collinear WAS events.

The events that remained as hadron pair candidates then were required to pass the following set of filter criteria:

i) Events should have secondaries near the minimum ionization in counters 2 and 3 in both telescopes. These counters were calibrated with cosmic-ray muons and with electrons from WAS events. The results for one telescope are shown in Fig. 2. Requiring pulse heights less than two times the minimum in both telescopes further reduced the WAS events contamination to less than 10^{-4}.

ii) Events should be in time with the bunch-bunch collision. Distributions of $T_{1\text{-}RF}$ for WAS events and cosmic rays are shown in Fig. 3. The time interval of ± 2.5 ns includes about 95% of all possible h^+h^- events and rejects $\sim 60\%$ of those cosmic-ray events which gave a trigger pulse.

([8]) N. Cabibbo and R. Gatto: *Nuovo Cimento*, **20**, 184 (1961); *Phys. Rev.*, **124**, 1577 (1961).
(*) The rate of WAS events was used as a measure of the luminosity of Adone ([9]).
([9]) B. Borgia, F. Ceradini, M. Conversi, L. Paoluzi, W. Scandale, G. Barbiellini, M. Grilli, P. Spillantini, R. Visentin and A. Mulachié: *Phys. Lett.*, **35** B, 340 (1971).

iii) Events should have a correct value for the time of flight T_{33} as explained below. This was also required for T_{44} if both particles penetrated to counters 4. As an example, the distribution of T_{33} for WAS events is shown in Fig. 4 along with the limits for h^+h^- events. From these distributions it was deduced that $\sim 90\%$ of hadron pairs should be included in the fiducial time interval applied to T_{33} and T_{44}. The fraction of cosmic-ray muons rejected by the restrictions both in T_{33} and in T_{44} was $\sim 95\%$.

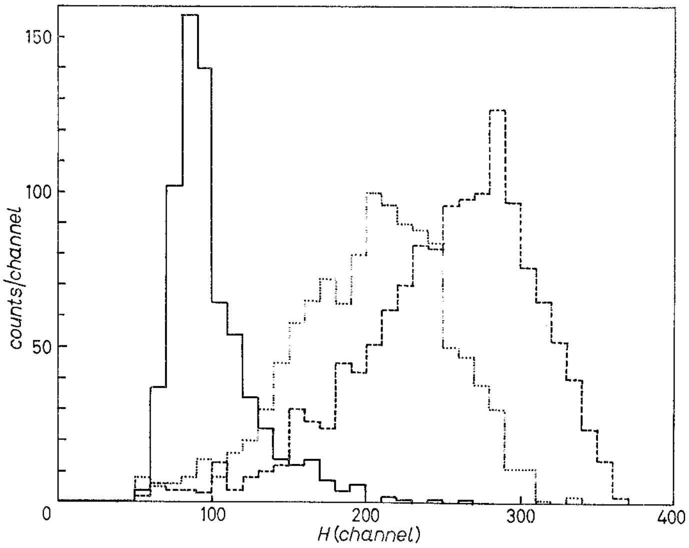

Fig. 2. – Distributions of pulse heights in counters 2 and 3, H, for cosmic rays (———) and for electrons of 750 MeV (···) and 1050 MeV (– – –).

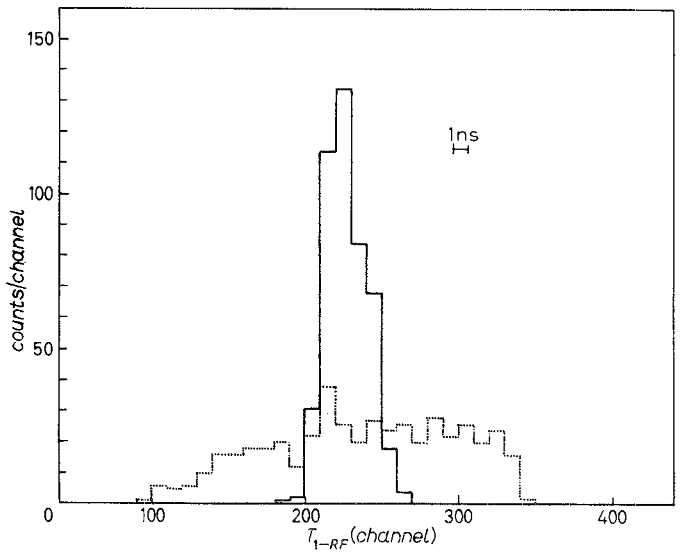

Fig. 3. – Distributions of the time of flights $T_{1\text{-}RF}$ between either one of counters 1 and the radio-frequency phase signal, for cosmic rays (···) and for electrons from e^+e^- wide-angle scattering (———).

iv) Finally, events should not have associated tracks in chambers C_4. This served to eliminate $e^+e^- \to \mu^+\mu^-$ events (10) and cosmic-ray muons from the sample. This, together with time-of-flight cuts and with the requirement of particle stopping before counters 5, brought the cosmic-ray contamination to $\sim 15\%$ of h^+h^- events.

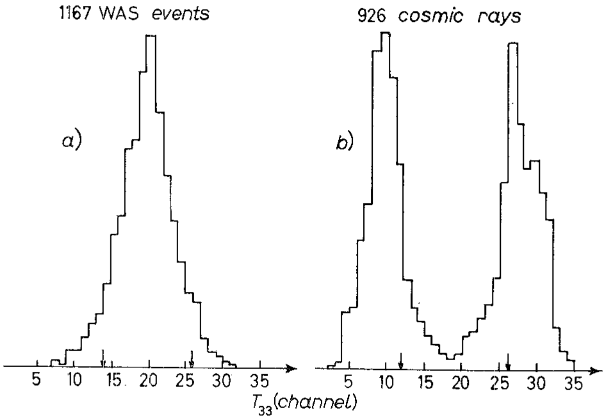

Fig. 4. – Distributions of the time of flights T_{33} between pulses from counters 3 of the two telescopes for electrons (a)) and for cosmic rays (b)). Limits for accepting $e^+e^- \to h^+h^-$ events are indicated by arrows.

The trigger condition and the absence of pulses in both counters 5 implied that the particles reached counters 3 or 4 and did not produce charged secondaries penetrating to counters 5 in order for the event to be recorded. The correction to the hadron pair cross-section due to nuclear absorption was evaluated using a Monte Carlo simulation of the experiment (11).

From application of the selection and filter criteria outlined above, the main background to hadron pair detection is substantially reduced, and we are left with 35 events. Less than 1 WAS event should now be present in this sample of candidates. This number, determined from 11 604 WAS events, is given as a conservative estimate. On the other hand, the contamination from cosmic-ray muons was evaluated on the basis of the $T_{1\text{-}RF}$ distribution of the candidates which passed all other selection criteria. It was then subtracted, thus reducing to 29.2 the number of h^+h^- events.

Other background events are those originated in the reactions $e^+e^- \to e^+e^- + a\bar{a}$, where $a\bar{a}$ is a particle-antiparticle pair, and $e^+e^- \to h^+h^- +$ anything. These reactions produce two-track events that generally are not collinear. The contribution from the first reaction was calculated and found to be negligible (*). The multihadron reaction $e^+e^- \to h^+h^- +$ anything was investigated simultaneously by the same apparatus (11)

(10) B. Borgia, F. Ceradini, M. Conversi, L. Paoluzi, R. Santonico, G. Barbiellini, M. Grilli, P. Spillantini, R. Visentin and F. Grianti: *Lett. Nuovo Cimento*, **3**, 115 (1972).

(11) M. Grilli, E. Iarocci, P. Spillantini, V. Valente, R. Visentin, B. Borgia, F. Ceradini, M. Conversi, L. Paoluzi, R. Santonico, M. Nigro, L. Trasatti and G. T. Zorn: *Nuovo Cimento*, **13** A, 593 (1973).

(*) During part of the runs ($\int L\,dt \sim 70\ \text{nb}^{-1}$ out of a total time-integrated luminosity of $\sim 250\ \text{nb}^{-1}$) the apparatus was operated in coincidence with a counter system (12) designed to detect processes $e^+e^- \to e^+e^- + a\bar{a}$. During these runs no collinear h^+h^- pair was observed among the $e^+e^- \to e^+e^- h^+h^-$ events.

(12) G. Barbiellini and S. Orito: Frascati report LNF-71/17 (Feb. 1971).

and found to contribute $\sim 10\%$ to the two-body process $e^+e^- \to h^+h^-$. This contamination (*) was estimated from the experimental distribution of the noncollinearity angle δ relative to the two-track events (Fig. 5*b*)).

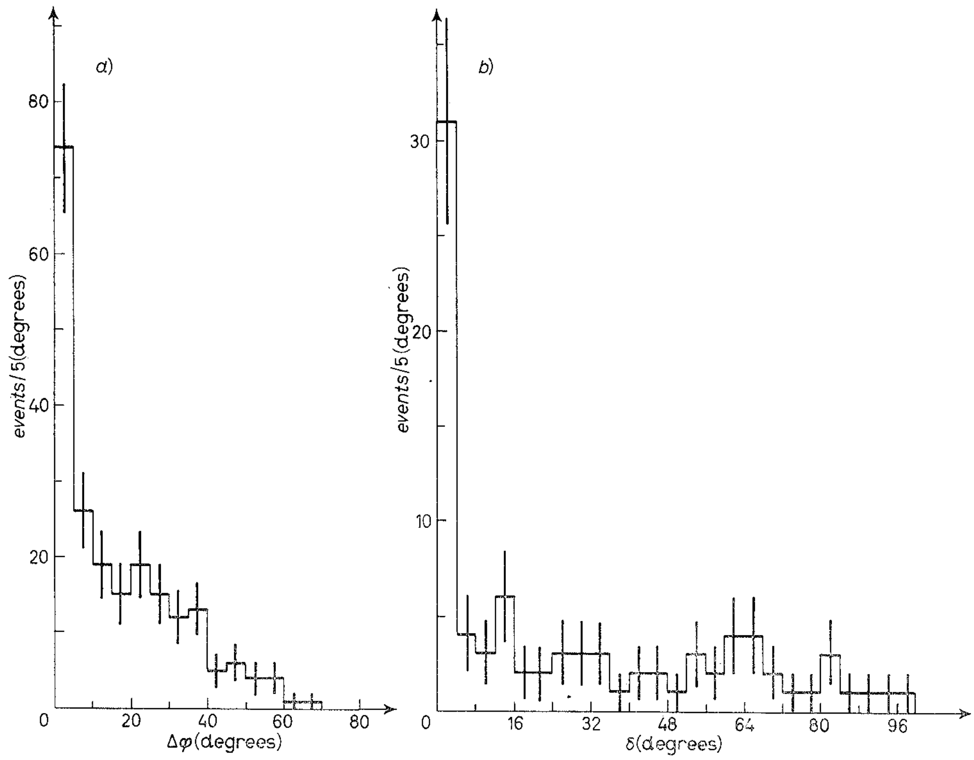

Fig. 5. – *a*) Distribution of the noncoplanarity angle $\Delta\varphi$ for all two-track events. For each track, φ is the azimuthal angle of the plane containing the track and the beam axis. *b*) Distribution of the noncollinearity angle δ for the two-track events with $\Delta\varphi \leqslant 10°$. h^+h^- events are required to have $\delta \leqslant 8°$.

After applying these corrections to the selected sample of h^+h^- candidates we were left with 26.8 events. As mentioned earlier, using a water Čerenkov counter a distinction between K- and π-mesons could be made below 800 MeV. At a beam energy of 750 MeV a special trigger to favour charged-kaon detection was introduced requiring penetration only to counters 3 in both telescopes, rather than to counters 4 of either telescope. With this arrangement only one K^+K^- pair was observed along with seven $\pi^+\pi^-$ pairs and 1982 WAS events. This tesult would indicate that the kaon form factor is comparable to the pion form factor (**). At the lowest energies explored, $E = 600$ and 650 MeV/beam, only pion pairs were accepted by the trigger which required a penetration unaccessible to K-mesons.

The results are summarized in Table I, where the number of WAS events, the time-integrated luminosity, the number of h^+h^- events, the efficiency and the total cross-section are reported for each energy.

(*) Present mostly at energies greater than 0.9 GeV/beam.
(**) This agrees with a similar result from Novosibirsk [4] at lower energies.

TABLE I. – *Summary of results on the reaction* $e^+e^- \to h^+h^-$.

Total energy (*) (GeV)	Number of WAS events	Time-integrated luminosity ($nbarn^{-1}$)	Number of corrected h^+h^- events	Efficiency for h^+h^- events	Cross section (nbarn)
1.20	361	2.26			
1.30	336	2.25			
1.25	697	4.8	5.0 ± 2.5	0.058	18 ± 9
1.40	427	5.10			
1.50	2158	22.71			
1.60	313	5.94			
1.65	202	3.38			
1.52	3100	37.2	10.7 ± 3.6	0.055	5.2 ± 1.8
1.80	188	4.71			
1.90	1702	35.35			
1.89	1890	40.1	3.0 ± 1.8	0.050	1.5 ± 0.9
2.10	5045	131.7	7.8 ± 3.5	0.046	1.3 ± 0.6
2.40	872	39.1	$0.3^{+1}_{-0.3}$	0.038	$0.2^{+0.7}_{-0.2}$

(*) When data collected at different energies are grouped together, the results refer to the mean value of the total energy, obtained from the partial time-integrated luminosities.

In Fig. 6 the electromagnetic form factor squared, $|F_\pi(s)|^2$, is plotted as a function of the 4-momentum squared, $s = (2E)^2$, under the hypothesis that the observed events

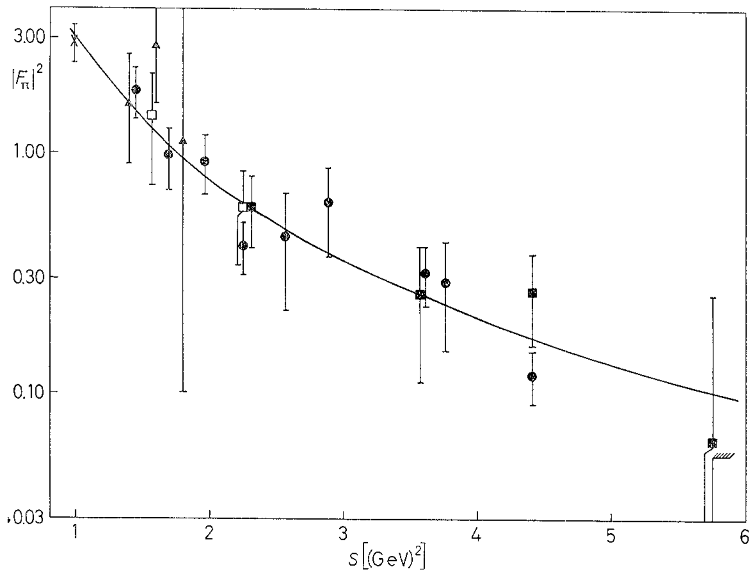

Fig. 6. – Pion form factor squared as a function of the 4-momentum squared s under the hypothesis that the observed events are pion pairs. White boxes refer to data with only pion pairs. Results from other esperiments are also shown (× Orsay, ▲ Novosibirsk, ● Adone BCF group, //// is an upper limit obtained by the BCF group). The full line is the best fit to the experimental points. □, ■ this experiment.

are $\pi^+\pi^-$ pairs. In the same Figure results from Orsay (3), Novosibirsk (4) and from the Adone BCF group (2) are also shown. The hypothesis that the observed events are all due to $\pi^+\pi^-$ pairs is true for the Orsay and Novosibirsk data, as well as for those of this experiment at $s \leqslant 2.25$ (GeV/c)^2. Hence the values at higher energies are upper limits for $|F_\pi|^2$. The best fit through all points gives for the slope of $|F_\pi|^2$, taken as s^{-n}, $n = 1.93 \pm 0.16$.

In order to obtain a more realistic value for $|F_\pi(s)|^2$ it is necessary to estimate the ratio $\sigma_{KK}/\sigma_{\pi\pi}$ for energies $2E > 1.5$ GeV. This estimate has been made in two different ways. First, on the basis of the vector-meson dominance model one obtains for the ratio $\sigma_{KK}/\sigma_{\pi\pi}$ a value close to 1 over the energy range explored. In this case the best fit gives $n = 2.70 \pm 0.16$ (fit 2) in Fig. 7). One sees that the estimated values of $|F_\pi|^2$ are still higher than expected from the Gounaris-Sakurai formula for the ρ^0 tail (13).

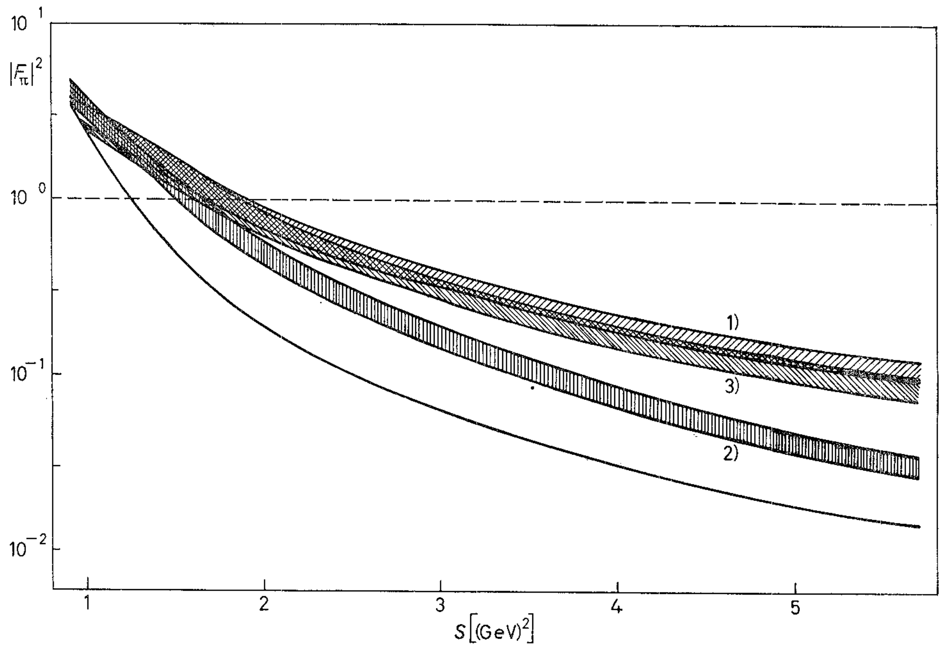

Fig. 7. – Different fits of the experimental data on the pion form factor squared assuming different values of the ratio $\sigma_{KK}/\sigma_{\pi\pi}$ for $s > 2.25$ (GeV/c)^2: 1) $\sigma_{KK}/\sigma_{\pi\pi} = 0$; 2) $\sigma_{KK}/\sigma_{\pi\pi}$ as predicted by the VMD model; 3) $\sigma_{KK}/\sigma_{\pi\pi} = \frac{1}{3}(\beta_K/\beta_\pi)^3$. The bands correspond to one standard deviation. The full line is the Gounaris-Sakurai formula for the ρ^0 tail (3).

As a second hypothesis we have assumed that for very large values of s $\sigma_{KK}/\sigma_{\pi\pi} \sim \frac{1}{3}$. This value has been evaluated on the basis of simple assumptions on SU_3 breaking in strange-particle production (14). The value obtained for the exponent is now $n = 2.08 \pm 0.16$ (fit 3) in Fig. 7).

If a simple power fit to $|F_\pi|^2$ is valid, then the value of the exponent n suggests a single-pole structure, with no clear evidence for new resonant contributions. A possible

(13) G. J. GOUNARIS and J. J. SAKURAI: *Phys. Rev. Lett.*, **21**, 244 (1968).
(14) D. M. RITSON: Invited talk at the *III International Conference on Experimental Meson Spectroscopy* (Philadelphia, Pa., 1972).

structure around the ρ′ mass (1.6 GeV), however, would be hidden by the experimental errors, since the $\rho'\pi\pi$ coupling is expected to be small (7,15):

$$\Gamma(\rho' \to \pi^+\pi^-)/\Gamma(\rho' \to \text{all}) < \sim 10\% .$$

At any rate, the estimated values of $|F_\pi|^2$ are higher than predicted by the ρ-dominance model. This may be interpreted in terms of inelastic effects due to multihadronic nonresonant intermediate states which might increase the $\pi^+\pi^-$ cross-section. Such an interpretation has been given by BAIER and FADIN (16) for Novosibirsk experimental results. An alternative interpretation has been put forward by GRECO and SRIVASTAVA (17), who suggest that the quoted enhancement of the $\pi^+\pi^-$ cross-section over the energy range explored can be understood in the framework of an extended vector-meson dominance model.

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We wish to thank Drs. A. BRAMON and M. GRECO for useful discussions and Dr. O. BARRA for his help during the analysis of the events.

(15) A. BRAMÓN and M. GRECO: *Journ. de Phys.*, C **3**, 93 (1971); *Lett. Nuovo Cimento*, **3**, 693 (1972).
(16) V. N. BAIER and V. S. FADIN: *JETP Lett.*, **15**, 151 (1972).
(17) M. GRECO and Y. N. SRIVASTAVA: Frascati Report 73/7 (1973).