COMITATO NAZIONALE PER L'ENERGIA NUCLEARE
Laboratori Nazionali di Frascati

LNF-72/84
Ottobre 1972

C. Mencuccini : MULTIHADRON PRODUCTION IN e^+e^- COLLISIONS (2E > 1.2 GeV).

Estratto da : Proceedings of the Informal Meeting on Electromagnetic Interactions, Frascati, May, 1972.

Servizio Documentazione
dei Laboratori Nazionali di Frascati del CNEN
Casella Postale 70 - Frascati (Rome)

RESULTS ON MULTIHADRONIC PRODUCTION IN e^+e^- COLLISIONS AT TOTAL C. M. ENERGIES 2E > 1.2 GeV

C. Mencuccini

Laboratori Nazionali del CNEN, Frascati.

In this paper recent results on the reaction

$$e^+e^- \longrightarrow \text{many hadrons}$$

at total c. m. energies larger than 1.2 GeV will be reported. The last review talk of this subject has been given by C. Bernardini at the 1971 International Symposium on Electron and Photon Interactions at High Energies - Cornell(1) and since then a certain number of new results have been obtained. These results come essentially from the groups working around ADONE (the Frascati 1.5 GeV electron and positron storage ring) and refer to the total c. m. energy region $1.2 \lesssim 2E \lesssim 2.4$ GeV. The groups and people involved in these researches are indicated in Table I.

TABLE I

List of groups and authors working in ADONE at the reaction $e^+e^- \longrightarrow$ many hadrons. In the last column recent references are given where experimental details about the apparata can be found.

Group	Authors	Recent References
BCF	V. Alles-Borelli, M. Bernardini, D. Bollini, L. Brunini, E. Fiorentino, T. Massam, L. Monari, F. Palmonari, A. Zichichi	- EPS Conf., Bologna 1971 + analysis in progress
Boson	B. Bartoli, F. Felicetti, H. Ogren, V. Silvestrini, G. Marini, A. Nigro, N. Spinelli, F. Vanoli	- Phys. Letters 36B, 598 (1971) - Frascati Rep. LNF-71/91 (sent to Phys. Rev.)
$\gamma\gamma$	C. Bacci, R. Baldini-Celio, G. Capon, C. Mencuccini, G. P. Murtas, G. Penso, A. Reale, G. Salvini, M. Spinetti, B. Stella	- Phys. Letters 38B, 551 (1972) + analysis in progress
$\mu\pi$	G. Barbarino, B. Borgia, F. Ceradini, M. Conversi, M. Grilli, E. Iarocci, M. Nigro, L. Paoluzi, R. Santonico, P. Spillantini, L. Trasatti, V. Valente, R. Visentin, G. T. Zorn	- Frascati Rep. LNF-71/62 - Frascati Rep. LNF-71/96 (sent to Lett. Nuovo Cimento) + analysis in progress

All the experimental apparata essentially consist of counters and spark-chambers surrounding the colliding beams in several ways. The details of the set-ups have been given elsewhere so that here only a sketch is presented in Figg. 1, 2, 3 and 4. The main features of the apparata are given in Table II, where the symbols for the angles are explained in Fig. 5

As far as the total solid angle is concerned, it is worth noticing that ADONE operates with an head-on collision mode for the beams so that the interaction region has a longitudinal lenght which is not negligible with respect to the linear dimensions of the sensitive volume of the apparata. This reduces the effective solid angle of the apparata to values of the order of 20% of the total.

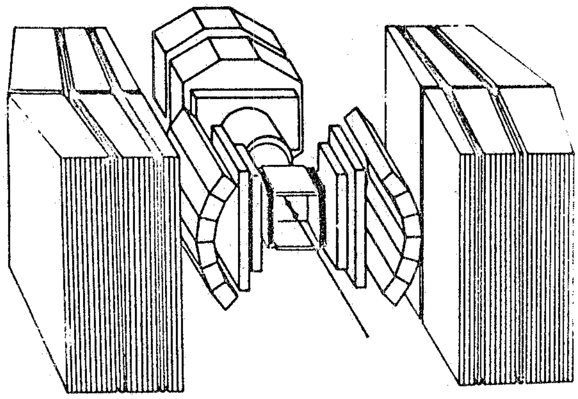

FIG. 1 - Schematic drawing of the apparatus of the BCF group. There are two telescopes of scintillation counters and spark chambers.

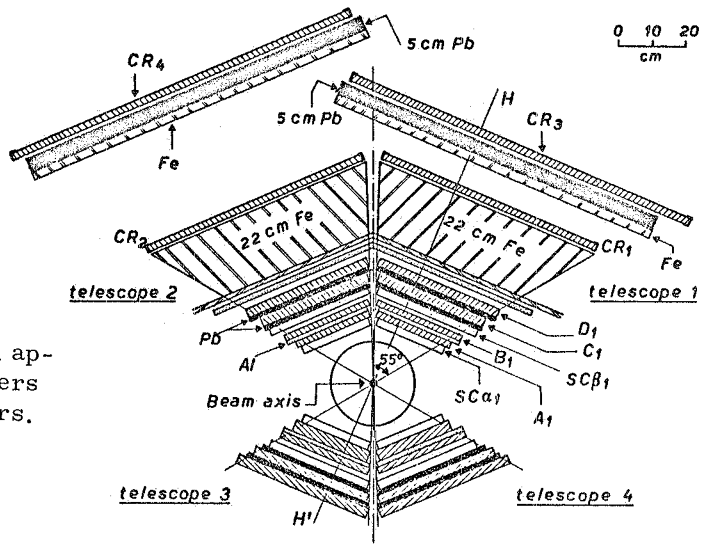

FIG. 2 - Schematic drawing of the Boson apparatus, consisting of scintillation counters and wire magnetostrictive spark chambers.

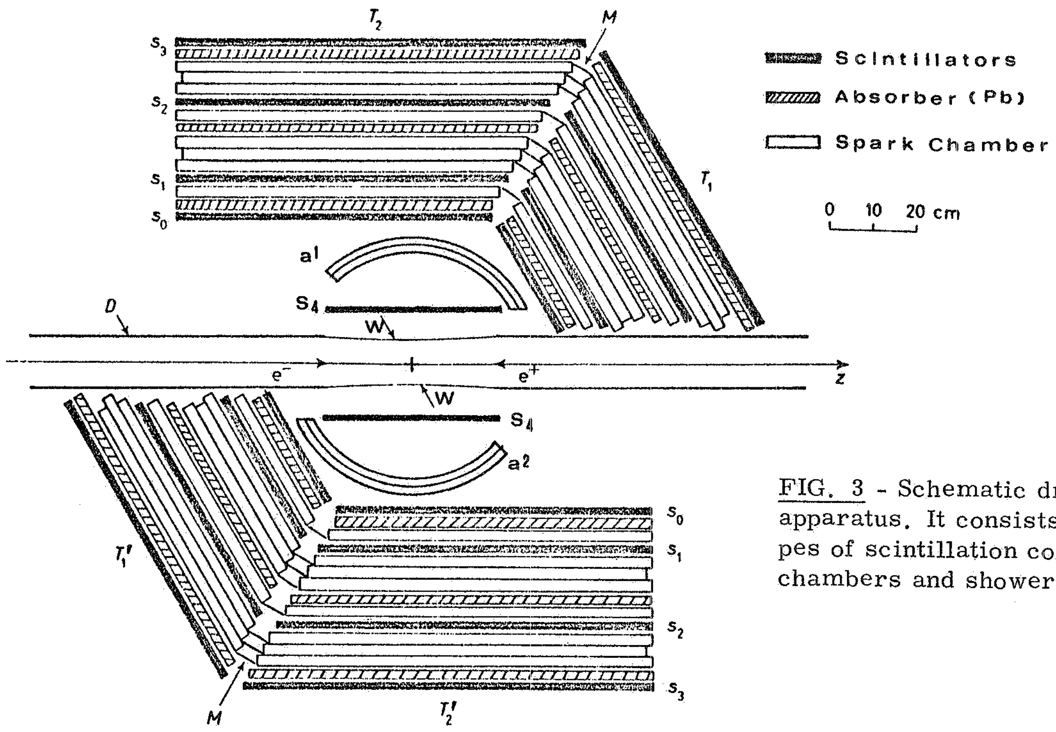

FIG. 3 - Schematic drawing of the γ-γ apparatus. It consists of four telescopes of scintillation counters, spark chambers and shower converters.

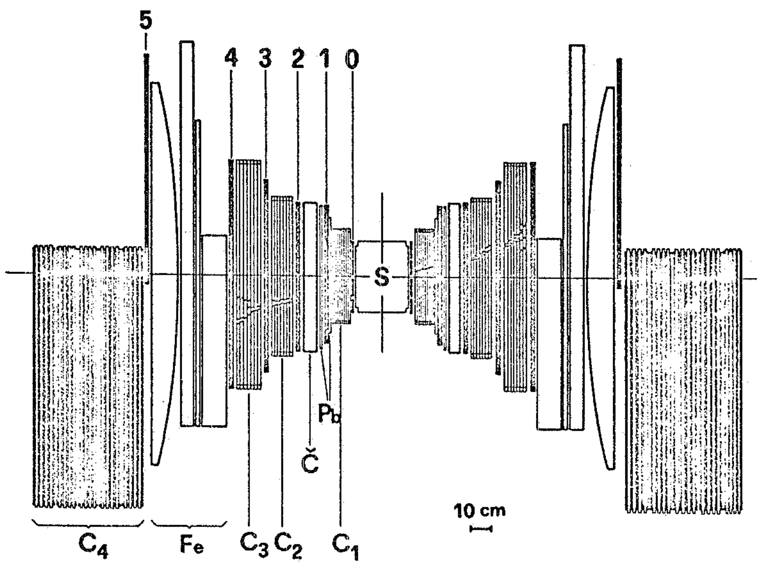

FIG. 4 - Schematic drawing of the μ-π experimental apparatus. The two telescopes are built-up with scintillation counters and spark-chambers. One of the π's from $e^+e^- \rightarrow \mu^+\mu^-$ is stopped in C_4.

TABLE II

Main features of the experimental set-ups. The angular regions $\Delta\theta$, $\Delta\phi$ are defined according to Fig. 5. In the last column, where the trigger requirements are summarized, $T_{MIN}(\pi)$ means the minimum kinetic energy necessary to trigger if the particle is a pion.

Group	$\Delta\Omega/4\pi$ ext. source	$\Delta\phi$	$\Delta\theta$	Trigger
BCF	$\sim$0.2	120^o	50^o - 130^o	$\geq$ 2 charg $T_{MIN}(\pi) \simeq$ 100 MeV
Boson	0.15	220^o	60^o - 120^o	$\geq$ 2 charg $T_{MIN}(\pi) \simeq$ 75 MeV
$\gamma\gamma$	0.2	120^o	20^o - 45^o 70^o - 110^o	$\geq$ 3 part (1 at least charged) $T_{MIN} \simeq$ 100 MeV
$\mu\pi$	0.2	140^o	53^o - 127^o	$\geq$ 2 charg $T_{MIN}(\pi)$ = 180 - 120 MeV

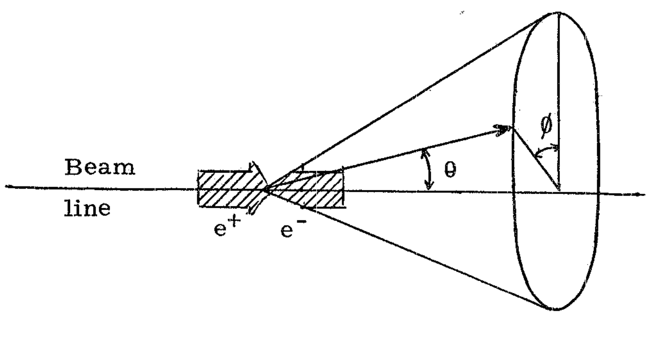

FIG. 5 - Geometry for an outcoming particle : θ is the angle with respect to the beam line and ϕ is the angle in the plane orthogonal to the beam line.

The monitoring system practically common to all the groups has been two-fold :

a) use of the Bhabha scattering in the small (3^o-6^o) angle region from devices installed in the $\mu\pi$ and BCF straight sections ;
b) use of wide angle e^+e^- scattering or $\gamma\gamma$ annihilation events as collected in each set-up.

As far as the experimental data on the reactions $e^+e^- \rightarrow$ many hadrons are concerned, it is well known that a peculiar feature of the e^+e^- interactions at total c. m. energies ranging from 1.4 to 2.4 GeV is the production of a large amount of final states with several ($\gtrsim$ 3) particles present.

In the various apparata this kind of events appear in several configurations in which charged and neutral (photons) particles are involved.

A rough idea of the material so far analysed by some of the ADONE groups and which is the basis of the results shown in the following, is given in Table III. This table essentially gives an indication on the gross amount of this data : something like 1400 events have been detected over several categories (6-10 depending on the apparata) and several (3-5) energies. The events on the table represent part of the statistics collected. All the data from BCF should be added and more data from $\mu\pi$ and $\gamma\gamma$ groups are still under analysis. A certain number of corrections (cosmic rays, machine background, etc.) have been applied before building up Table III. For details on this point see the references quoted in Table I.

TABLE III

List of analysed events (sum over all the energies).

Group	Events collected according to two main classes of detected configurations		Integrated luminosity cm^{-2}
	2 charged non coplanar	$\gtrsim$ 3 particles charged + neutrals	
Boson	534	164	24×10^{34}
$\gamma\gamma$	---	146	45×10^{34}
$\mu\pi$	$166^{(x)}$	~ 400	30×10^{34}
Total	700	~ 710	$\sim 10^{36}$

(x) - this category has a smaller integrated luminosity.

A statistical analysis of the behaviour of the charged particles detected while they go through the apparata has shown their hadronic nature. The elements supporting this conclusion are listed in Table IV. On this point a detailed analysis performed by the BCF group has been presented at the First European Physical Society Conference on "Meson and Related Electromagnetic Phenomena", Bologna (1971). The conclusion of this work is shown in Fig. 6.

TABLE IV

Nature of the observed particles

HADRONS : According to a statistical analysis on:
- $\frac{dE}{dx}$ in the counters
- interaction length
- distribution of the interactions along the path of the particles in the spark-chambers
- comparison with calibrations of the telescopes with appropriate π, μ and e beams (BCF)

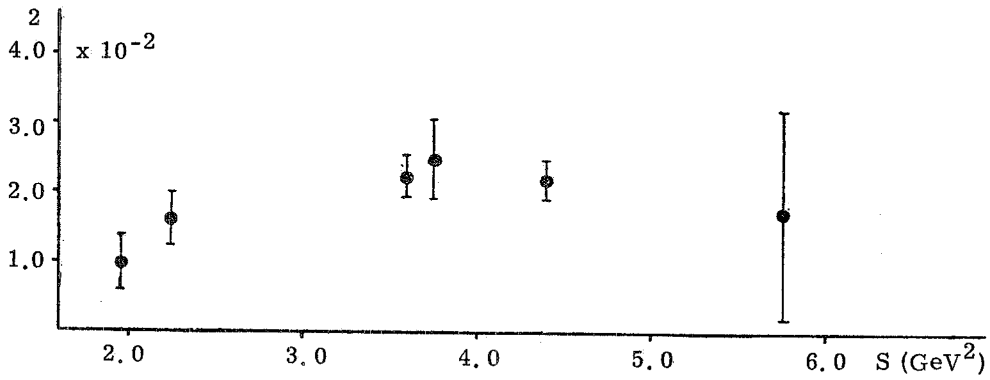

FIG. 6 - S-dependence of the ratio $\alpha_2 = \dfrac{e^+e^- \to h^{\pm}h^{\mp} \text{(with } R > 7.5^o \text{ and } |\varphi| > 5^o)}{e^+e^- \to e^{\pm}e^{\mp} \text{ (all R)}}$
where $h^{\pm}$ indicates positive or negative hadron and R is the angle supplement of the angle between the directions of the two hadrons. The selection criteria R > > 7.5^o and $|\varphi| > 5^o$ mean non collinear and non coplanar events.

Now the arguments leading to the assignement of an hadronic nature to the particles are essentially statistical and cannot give a signature of "π" or "K" to the single detected particle. However there are several elements supporting the hypothesis that practically all the particles are pions. The arguments in favour of the plausibility of this assumption are summarized in the following :

a) the cases of complete kinematical reconstruction are incompatible with particles being K's ;
b) all the consistency checks on the penetration of the particles in the spark chambers indicate the major part of them being π's ;
c) $p\bar{p}$ annihilation data show kaonic final states in less than 10% of the cases.

So all the analyses which will be referred to have been performed under the hypothesis that only pions are present. Obviously a contamination of a certain fraction of K's cannot be excluded.

The following step is then to calculate cross sections. To do this one has to solve the problem of determining the multiplicity and content of the various channels energetically allowed and consistent with the conservation laws.

But the identification of every reaction channel is far from simple : all the experimental set-ups cover a small solid angle so that only a limited fraction of the particles produced is detected. Furthermore the lack of knowledge of the momenta of the detected particles makes it impossible in the most of the cases to estimate what is missing of the reaction products.

So in order to try to interpret the data one has to make some hypothesis concerning the channels present and the angular and momentum distribution of the produced particles.

As a consequence the results which follow about cross sections are necessarily model dependent.

The assumptions made by all the three groups Boson, γγ and μπ are summarized in the following Table V. It is worth noticing that states with more than 6 π's are supposed negligible. The most of the analysis has been done making use of the invariant phase space momentum distribution for the correlations among the particles. There are indications that the calculated efficiencies of the apparata are quite insensitive to the production mechanism (Boson group). Work is in progress on this aspect of the analysis.

Once the assumptions on the possible channels are made, the connections among reactions and detected configurations of events have to be made. The situation is sketched in Table VI. The connections have features that will clearly influence the numerical structure of the equations connecting yields to cross sections through efficiencies.

Now, according to the assumptions on the allowed channels and the angular and momentum distributions, the efficiencies of the apparata can be calculated. Monte Carlo simulations

TABLE V

Type of analysis. $\sigma_{2^\pm}$ is the sum of the cross sections for reactions where 2 charged pions are produced : $\sigma_{2^\pm} = \sigma(\pi^+\pi^-\pi^o) + \sigma(\pi^+\pi^-2\pi^o) + \sigma(\pi^+\pi^-3\pi^o)$. $\sigma_{4^\pm}$ is the sum of the cross sections for reactions where at least 4 charged pions are produced : $\sigma_{4^\pm} = \sigma(2\pi^+2\pi^-) + \sigma(2\pi^+2\pi^-\pi^o) + \sigma(2\pi^+2\pi^-2\pi^o) + \sigma(3\pi^+3\pi^-)$.

Reactions considered :		Cross sections
$e^+e^- \rightarrow \pi^+\pi^-\pi^o$		$\sigma(\pi^+\pi^-\pi^o)$
$\pi^+\pi^-\pi^o\pi^o$	$\sigma_{2^\pm}$	$\sigma(\pi^+\pi^-2\pi^o)$
$\pi^+\pi^-\pi^o\pi^o\pi^o$		$\sigma(\pi^+\pi^-3\pi^o)$
$\rightarrow 2\pi^+2\pi^-$		$\sigma(\pi^+\pi^-\pi^+\pi^-)$
$2\pi^+2\pi^-\pi^o$		$\sigma(2\pi^+2\pi^-\pi^o)$
$2\pi^+2\pi^-\pi^o\pi^o$	$\sigma_{4^\pm}$	$\sigma(2\pi^+2\pi^-2\pi^o)$
$2\pi^+2\pi^-\pi^+\pi^-$		$\sigma(3\pi^+3\pi^-)$

Correlation among particles in the final state :

1) Invariant phase space momentum distribution;
2) Quasi two-body reactions.

TABLE VI

Connections between reaction channels and detected configurations. A and D are the labels for the considered reactions and the configurations as detected in the apparata respectively.

Lab. A		Reactions $e^+e^- \rightarrow$	Detected configurations charged	Detected configurations neutrals	Lab. D
1		$\pi^+\pi^-\pi^o$	2	0	1
			2	1	2
2	$\sigma_{2^\pm}$	$\pi^+\pi^-\pi^o\pi^o$	1	2	3
			2	2	4
3		$\pi^+\pi^-\pi^o\pi^o\pi^o$	2	3	5
			1	3	.
4		$2\pi^+2\pi^-$	3	0	.
			3	1	.
5		$2\pi^+2\pi^-\pi^o$	3	2	.
	$\sigma_{4^\pm}$		4	0	.
6		$2\pi^+2\pi^-\pi^o\pi^o$	4	1	.
			4	2	
7		$2\pi^+2\pi^-\pi^+\pi^-$	5	0	

have been performed and the efficiencies calculated.

The main ingredients entering the calculations of the efficiencies are summarized in Table VII.

TABLE VII

Calculation of the detection efficiencies.

Ingredients :
- Invariant phase space momentum distribution - Geometry of the apparata - Energy cuts on the detected particles - Nuclear interactions - Spark chambers efficiency - Source shape - Photon detection efficiency - Trigger requirements (logic)

The results of these calculations give rather small values for the efficiencies ($\lesssim 1\%$ for configurations with at least 3 particles detected).

If now we put :

D : label for the detected configurations ;
$\mathcal{L}$: integrated luminosity at a certain energy ;
n_D : number of events in the configuration D collected in an integrated luminosity $\mathcal{L}$;
A : label for the 7 reactions considered ;
ε_D^A : efficiency for the detection of events from reaction A in the configuration D in the apparatus ;
σ_A : cross section for the reaction A ;

a system of relations of the following type is obtained :

$$n_D = \mathcal{L} \sum_A \varepsilon_D^A \sigma_A .$$

On this series of relations at each energy a sort of an overall fit of the observed distributions of events among the different configurations is made.

But the numerical structure of the system of relations $n_D = \mathcal{L} \Sigma \varepsilon_D^A \sigma_A$ and the rather poor statistics collected make very difficult a unique determination of the unknown cross section.

So statistical criteria have been used to select among the possible solutions of the system a certain class of solutions of similar "acceptable" χ^2.

In many cases this procedure brings to large uncertainties in the cross sections for the separate channels. However some particular combination of cross sections turns out to be reasonably determined (for instance : $\sigma_{2^\pm}$, $\sigma_{4^\pm}$, σ_{TOT}).

Some specific information on particular reaction channels is also found.

In the following recent results concerning the various cross sections will be presented.

Reactions with 2 charged pions in the final state.

Their total cross section is indicated by

$$\sigma_{2^\pm} = \sigma(\pi^+\pi^-\pi^0) + \sigma(\pi^+\pi^-2\pi^0) + \sigma(\pi^+\pi^-3\pi^0) .$$

The specific informations on these reactions are the following :

a) $\sigma(\pi^+\pi^-\pi^o)$ by means of a detailed kinematical analysis of the events in the configurations (2 charg + 2 neut) and (2 charg + 1 neut) it is possible to give a value for $\sigma(\pi^+\pi^-\pi^o)$ small around 1.8-2.1 GeV.

$$\sigma(\pi^+\pi^-\pi^o) \approx 2-3 \text{ nb} \qquad (\gamma\gamma \text{ group}).$$

b) $\sigma(\pi^+\pi^-3\pi^o)$ from the $\mu\pi$ group analysis it turns out that over the entire energy interval explored this channel is any way lower than 30% of $\sigma_{2^\pm}$ (from the frequency of showers accompanying 2 non coplanar charged particles).

$$\sigma(\pi^+\pi^-3\pi^o) < 0.3\ \sigma_{2^\pm} \qquad (\mu\pi \text{ group}).$$

c) $\sigma(\pi^+\pi^-\pi^o\pi^o)$ this channel seems to be the most relevant one for the $\sigma_{2^\pm}$, so the assumption is made that it is the only present. That is

$$\sigma(\pi^+\pi^-2\pi^o) \approx \sigma_{2^\pm}.$$

Under this hypothesis the values of the cross section versus the total c.m. energy 2E for the reaction $e^+e^- \to \pi^+\pi^-\pi^o\pi^o$ are given in Fig. 7. The experimental material around 1.5 GeV is statistically rather poor, but more data have been recently collected at energies ranging between 1.3 and 1.8 GeV so that other results will be available in a next future. Obviously a strong limitation to these data is the lack of knowledge of the number of π^o's present in the final state. We observe that the $\gamma\gamma$ points seem to be systematically lower than the $\mu\pi$ points. However within the above mentioned uncertainties and assumptions a value of $\sim$20 nb at 1.5 GeV and may be 10-15 nb around 2 GeV may be tentatively assumed for $\sigma(\pi^+\pi^-\pi^o\pi^o)$.

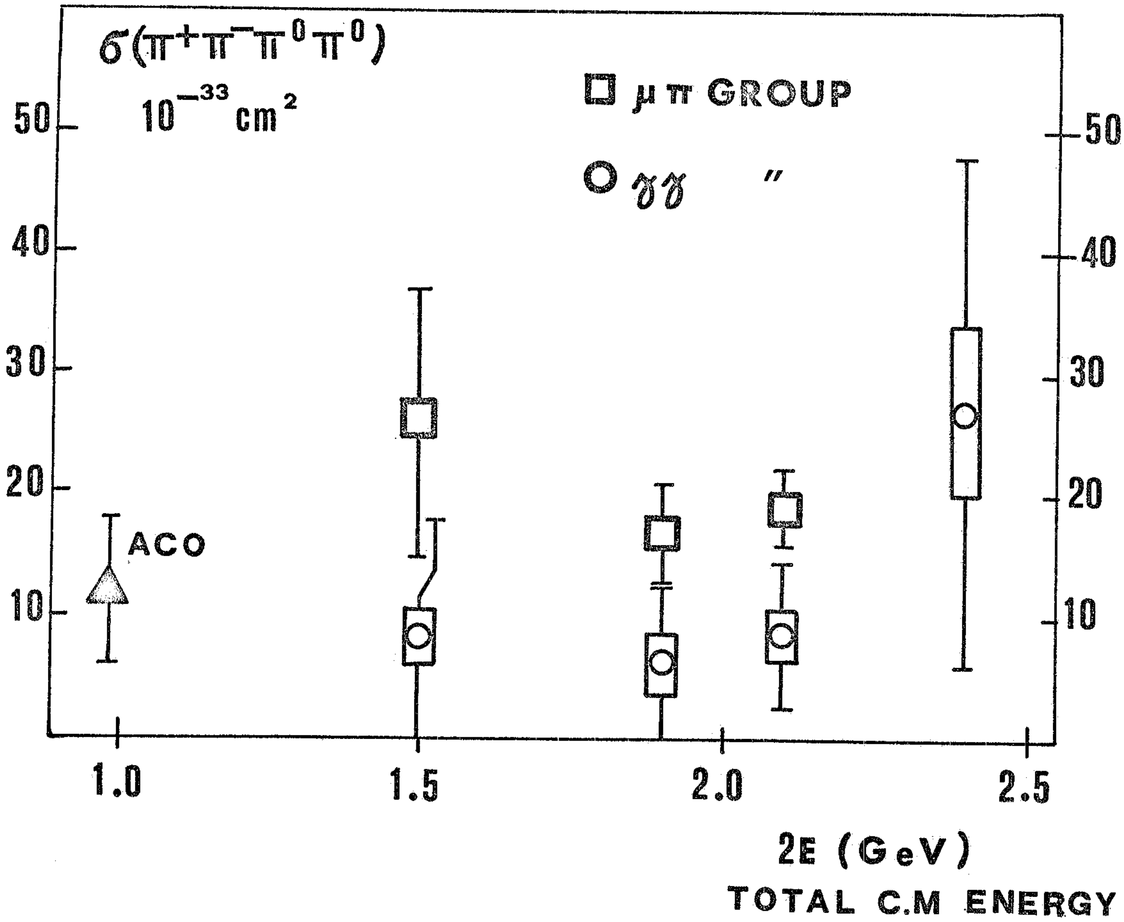

FIG. 7 - Values of the cross section for the reaction $e^+e^- \to \pi^+\pi^-\pi^o\pi^o$ as a function of the total c.m. energy.

Reactions with at least 4 charged pions in the final state.

The sum of the cross sections for reactions with at least 4 pions in the final state :

$$\sigma_{4^\pm} = \sigma(2\pi^+2\pi^-) + \sigma(2\pi^+2\pi^-\pi^0) + \sigma(2\pi^+2\pi^-2\pi^0) + \sigma(3\pi^+3\pi^-)$$

is a rather well determined combination of cross sections. Its values as a function of the total c.m. energy are shown in Fig. 8.

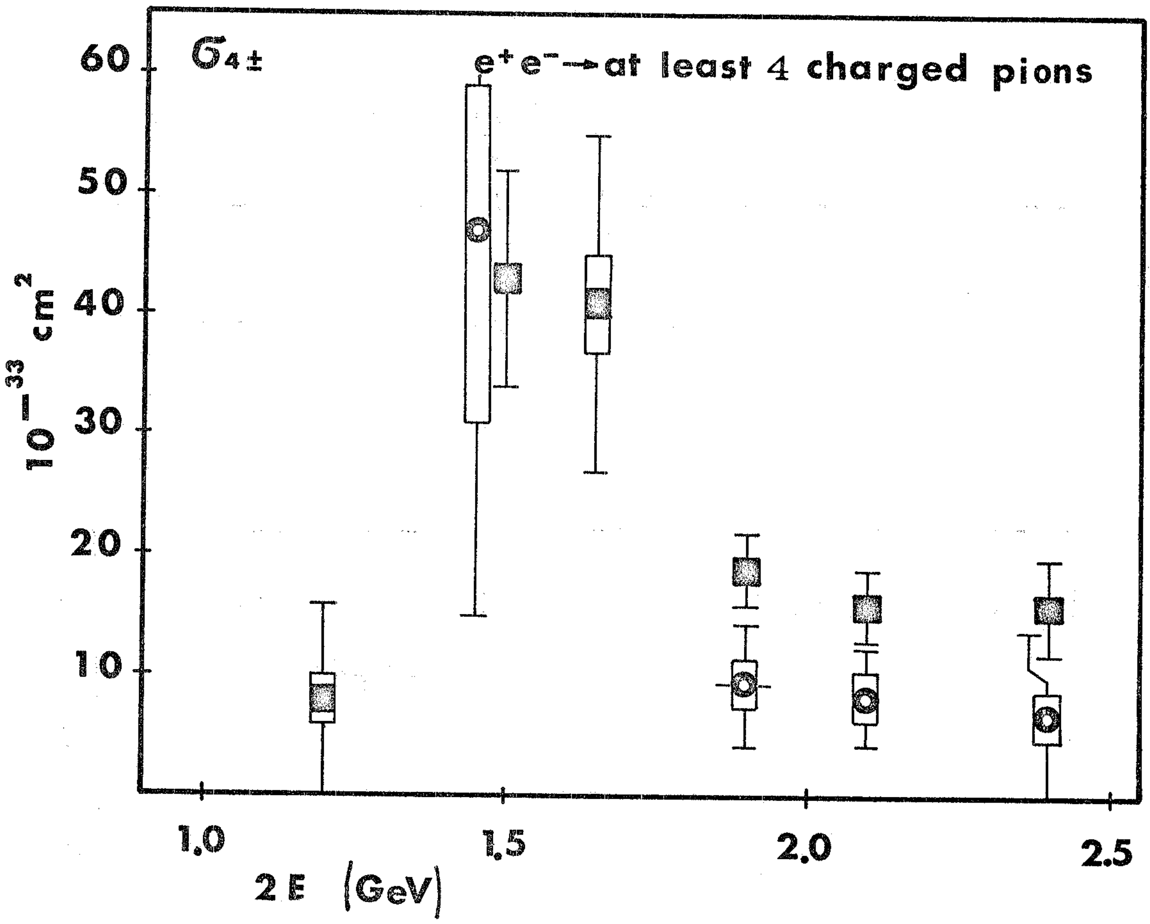

FIG. 8 - Values of the cross section for the reactions $e^+e^- \rightarrow$ at least 4 charged pions, that is $\sigma_{4^\pm} = \sigma(2\pi^+2\pi^-) + \sigma(2\pi^+2\pi^-\pi^0) + \sigma(2\pi^+2\pi^-2\pi^0) + \sigma(3\pi^+3\pi^-)$. (■ $\mu\pi$ group; ⊙ $\gamma\gamma$ group).

Here the energy dependence of the cross section shows a maximum around 1.5 GeV followed by a decrease towards a minimum which is reached around 1.8 - 2.0 GeV of total c.m. energy. The level at the maximum is ~ 40 nb whereas the valley has a level of ~ 10-20 nb. By a comparison with the results on $\sigma_{2^\pm}$ an evaluation of the ratio $\sigma_{2^\pm}/\sigma_{4^\pm}$ is made and values ranging from 0.5 to 1.0 are found, that is :

$$\frac{\sigma_{2^\pm}}{\sigma_{4^\pm}} \approx \begin{cases} 20/40 \approx 0.5 & \text{around 1.5 GeV} \\ 10\text{-}15/10\text{-}20 \approx 1 & \text{around 2 GeV.} \end{cases}$$

Beside this global indication about $\sigma_{4^\pm}$, some other piece of information is available on the single channels contributing to $\sigma_{4^\pm}$. Namely:

$\sigma(3\pi^+3\pi^-)$: small over all the energies with values in the range 0-4 nb (see Fig. 9);

$\sigma(2\pi^+2\pi^-+1,2\pi^0)$: the discrimination between the 2 channels is difficult so that the sum of the two cross section is given. The results are shown in Fig. 10.

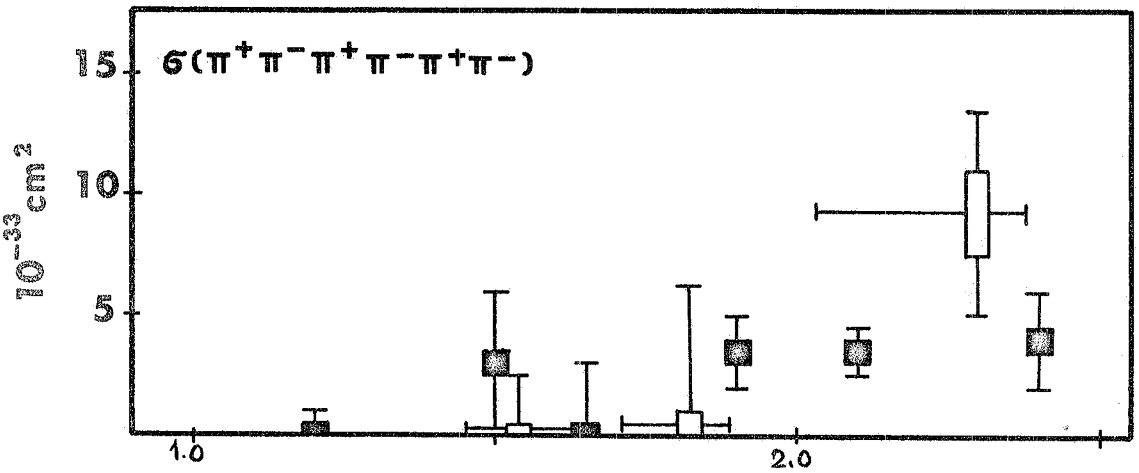

FIG. 9 - Values of the cross section for the process $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$ as a function of the total c. m. energy 2E (□ μπ group ; ■ boson group).

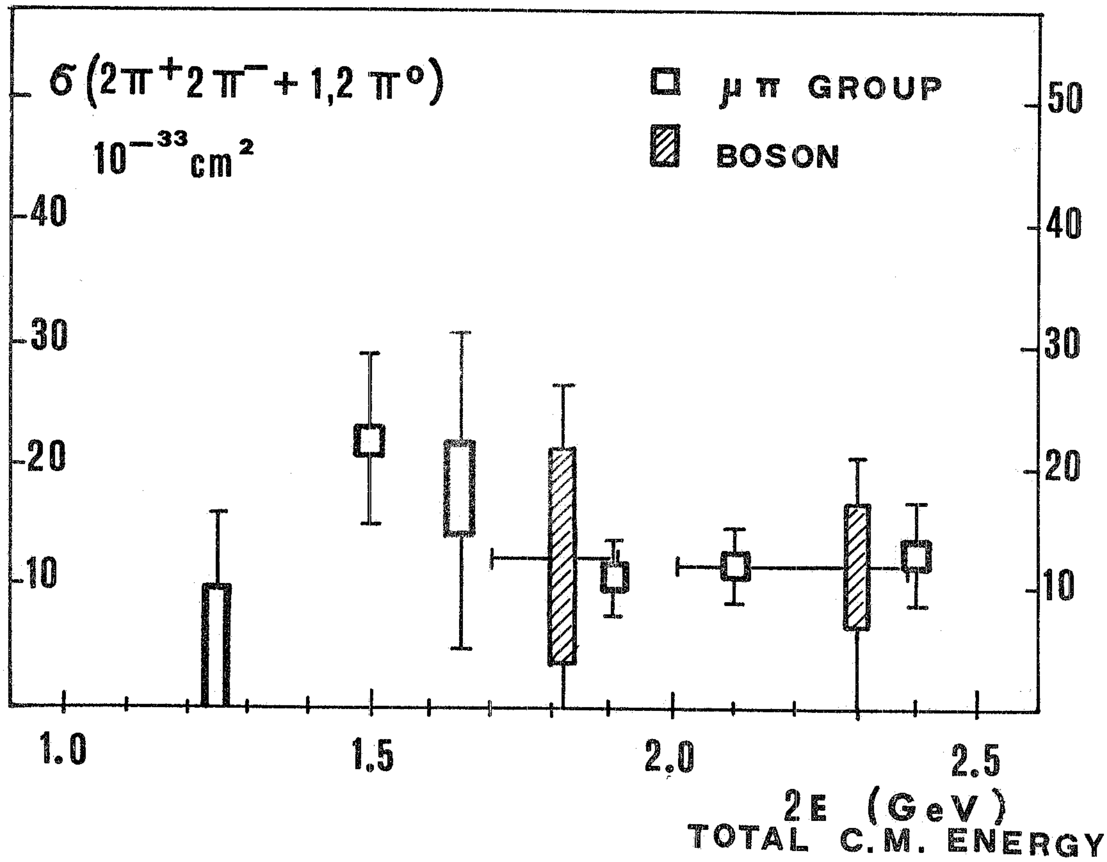

FIG. 10 - Values of the sum of the cross sections for the 2 reactions : $e^+e^- \rightarrow$ $\rightarrow \pi^+\pi^-\pi^+\pi^-\pi^0$ and $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$, as a function of the total c. m. energy 2E.

In the energy region around 2 GeV a value of the cross section of $\sim$ 10-15 nb is found; if compared with $\sigma_{4\pm}$ (taking into account also a small level from $\sigma(3\pi^+3\pi^-)$) it appears that a small room is left for the $\pi^+\pi^-\pi^+\pi^-$ reaction in this energy region.

This is in agreement with an indication from the $\gamma\gamma$ group according to which (neglecting the $3\pi^+3\pi^-$ channel) the conclusion is

$$\frac{\sigma(2\pi^+2\pi^- + \text{neutrals})}{\sigma(2\pi^+2\pi^-)} \approx 2 \qquad \text{around 2 GeV} \ .$$

The last reaction with 4 charged particles in the final state to be considered is now $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$. The values of the cross section for this reaction are shown in Fig. 11.

The energy dependence of $\sigma(2\pi^+2\pi^-)$ clearly shows a peak centered around 1.6 GeV with a total width of the order of 400 MeV and a value of the cross section $\approx$ 20-25 nb. Both the rise and the fall of the bump seem to have a rather sharp energy dependence. The hypothesis that this bump could be due to a ρ' meson ($J^P = 1^-$, $I^G = 1^+$) of mass 1600 MeV has been considered also in connection with the results from the reaction $\gamma p \rightarrow p+(\pi^+\pi^-\pi^+\pi^-)$ studied at SLAC ($\mu\pi$ group). In this respect it would be interesting to try to estimate the branching ratio $\sigma(\pi^+\pi^-\pi^o\pi^o)/\sigma(\pi^+\pi^-\pi^+\pi^-)$ around 1.6 GeV. This is far from being simple since the situation for the channel $\pi^+\pi^-\pi^o\pi^o$ is confused either for the lack of knowledge of the number of neutral pions accompanying the pair $\pi^+\pi^-$, or for the presence of a fairly large background outside the bump region (see also the point from ACO). So just a very rough indication can be given:

$$\frac{\sigma(\pi^+\pi^-\pi^o\pi^o)}{\sigma(\pi^+\pi^-\pi^+\pi^-)} \approx 0.5 - 1 \qquad \text{at 1.5 GeV.}$$

Anyway more data have been collected and are now under analysis.

Now putting together all the above informations a final result on the total cross section for producing hadronic states is reached. In Fig. 12 the values of the cross section

$$\sigma_{total}(e^+e^- \rightarrow \text{many hadrons})$$

are shown.

The cross section $\sigma_{tot}(e^+e^- \rightarrow$ many hadrons) turns out to be rather large if compared with the point-like cross section $e^+e^- \rightarrow \mu^+\mu^-$ which is also reported in Fig. 12. It ranges from 10 to 30 nb. The energy behaviour shows an increase which brings to its maximum around 1.5 GeV followed by a fall-off towards a minimum which is a reached around 1.9 GeV.

This is the situation as far as the multihadronic reactions are concerned in Adone. The limitations of certain assumptions and conclusions are self evident. However it is clear that we are facing a very interesting field of researches and that the instruments used for the first generation of experiments are not the best suited.

The next step clearly indicates the necessity to make esperiments able to give at each energy information useful to:

a) identifly every channel;
b) determine every relative rate between channels;
c) establish, by a complete kinematical analysis of a certain number of events, possible correlations among the pions.

So a second generation of experimental apparata for Adone has been decided and work is in progress. Namely two groups are building two new set-ups which should be ready to take data at the beginning of 1973.

The first set-up is a magnetic analyzer (B 4.5 KGauss) covering a solid angle $\Delta\Omega/4\pi \approx 40\%$. The group working at this project is the following:

W. Ash, B. Bartoli, D. Bisello, A. Cattoni, D. Cheng, C. Costa, B. Esposito, F. Felicetti,

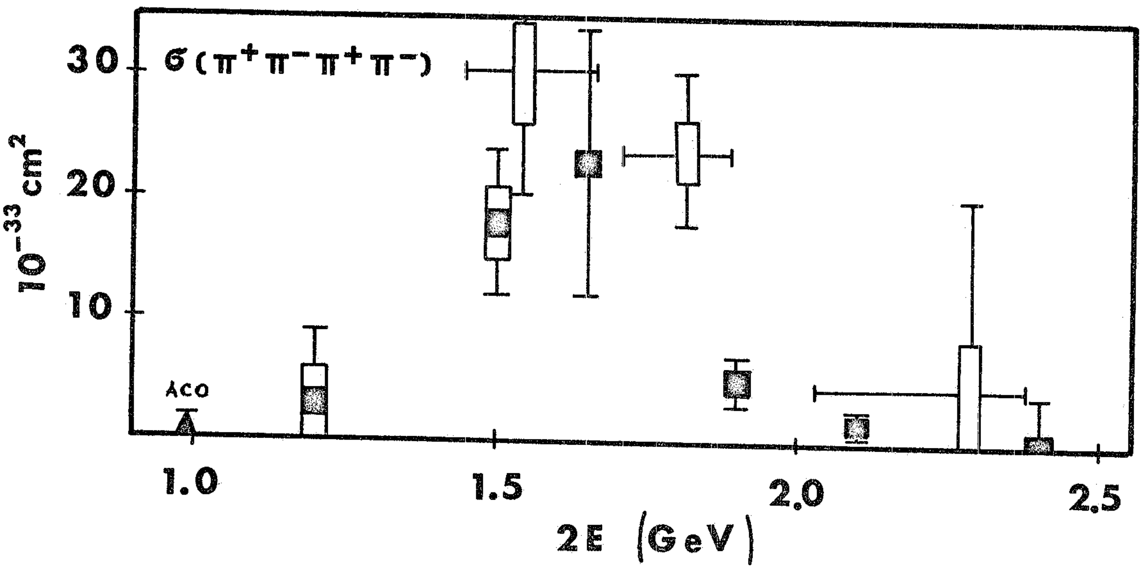

FIG. 11 - Values of the cross section for the reaction $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$ as a function of the total c. m. energy 2E (■ μπ group ; □ Boson group).

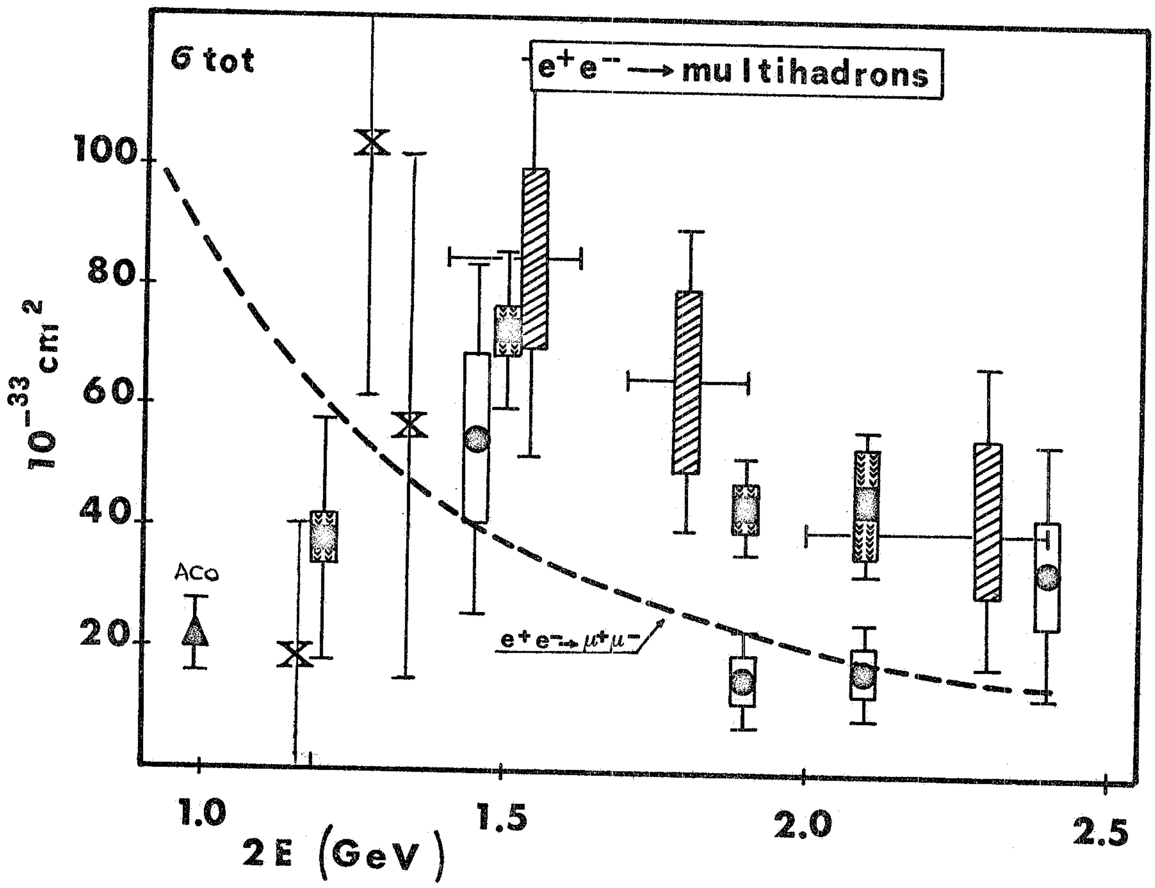

FIG. 12 - Cross section fro the reaction $e^+e^- \rightarrow$ many hadrons as a function of the total c. m. energy 2E (■ μπ group ; □ Boson group ; ● γγ group ; X Novosibirsk VEPP-2).

P. Monacelli, A. Mulachiè, M. Nigro, H. Ogren, I. Peruzzi, L. Pescara, A. Piazzoli, M. Piccolo, F. Ronga, R. Santangelo, D. Scannicchio, E. Schiavuta, F. Sebastiani, V. Silvestrini and F. Vanoli.

The second apparatus is a large solid angle shower detector ($\Delta\Omega / 4\pi \simeq 70\,\%$) which will complement the analysing magnet as far as solid angle and shower detection is concerned. The group involved in this second device consists of the following people :

C. Bacci, R. Baldini-Celio, M. Bernardini, G. Capon, M. Grilli, E. Iarocci. C. Mencuccini, G. P. Murtas, G. Penso, G. Salvini, M. Spinetti, B. Stella, V. Valente and A. Zallo.