

COMITATO NAZIONALE PER L'ENERGIA NUCLEARE
Laboratori Nazionali di Frascati

LNF-71/100
22 Dicembre 1971

M. Grilli: HADRONIC PRODUCTION BY e^+e^- COLLISIONS IN
THE GeV REGION ($2E$, TOTAL ENERGY, ≈ 1 GeV).

M. Grilli: HADRONIC PRODUCTION BY e^+e^- COLLISIONS IN THE GeV REGION ($2E$, TOTAL ENERGY, $\gtrsim 1$ GeV). -

(Lectures delivered at the "International School of Yerevan Physical Institute", November 23 - December 4, 1971)

In these lectures I shall cover a subject of e^+e^- physics not discussed by V. Bayer in his preceding talk. In fact, I will discuss the hadronic production in the GeV region, starting from $2E \sim 1$ GeV. Note that at these energies ($2E > 1$ GeV) we are, at least, at two ρ^0 widths and at several ω widths (~ 20) from the peak of these resonances. Moreover, as the ϕ resonance is narrow (~ 4 MeV) we will be very soon, increasing $2E$, well outside the ρ, ω, ϕ region.

The total range covered by the present lectures will be $2E = 1$ to 2.4 GeV (in the next months we hope that Adone can reach its full energy 3.0 GeV). As we will see the first 400 MeV of this energy range (from 1 to 1.4 GeV) are, unfortunately, very poorly explored. This lack of information is relevant, as we will see, in order to clarify the mechanisms of the multi-hadronic production.

Because, the present lectures will be devoted mainly to results and to their limits and possible physical interpretations. Only schematic information on experimental apparatus will be reported (References to papers, in which these have been described will be reported).

The results I will report come from ADONE, ACO and VEPP-2. The source for these lectures has been the more recent works published by these groups, as well as private informations from Adone's groups concerning their present analysis of data. I thank these groups for their collaboration.

2.

Unfortunately, at present, there are not yet enough (data) to draw a clear and complete picture of the hadronic production in the GeV region, as clear as that presented by Bayer for lower energy. Experiments and analysis are still in progress. I will report and summarize the present situation and I will try some first conclusions.

The topics of present lectures will be

- 1) Generalities on experimental techniques
- 2) Two body final state: $e^+e^- = h^+ + h^-$ ($h = \text{hadron}$). In this part I will report results on π 's form factor and preliminary information on process $e^+e^- = p\bar{p}$
- 3) Multiple hadronic production.

1. - GENERALITIES ON EXPERIMENTAL TECHNIQUES. -

In a colliding beam machine the origin of "good" events (i. e. events due to beam-beam collision) is localized in space (interacting region of e^+e^- bunches) and in time (for example, in Adone the time interval between two successive bunch-bunch collision is of about 117 ns). In all experiments both conditions have been used in order to select good events. In fact an event to be considered as a candidate event produced by an e^+e^- collision:

- 1) must come from the e^+e^- interaction region ("source")
- 2) must be in time with the bunch-bunch collision (as determined by the radiofrequency phase).

Examples of source and time distribution, measured by Adone's groups are shown in Fig. 1a, b.

Moreover, a further requirement which can be used in the case of a two body final state process is the collinearity between the two tracks (see Fig. 2). Remember that in a colliding beam machine c. m. and lab. system coincide.

In these experiments we have two types of background:

- 1) Cosmic rays
- 2) machine's background.

"Source" and "time" criteria reported above clearly reject cosmic rays. (see Fig. 1). In order to further cut down this background veto counter and special time of flights techniques⁽³⁾ has been used by different groups. Also this last procedure uses a peculiarity of a colliding beam machine. In fact, in a two-body process $e^+e^- = a\bar{a}$ both produced particles have the same velocity and opposite directions. So a and \bar{a} reach at the same time counters placed at the same distance from

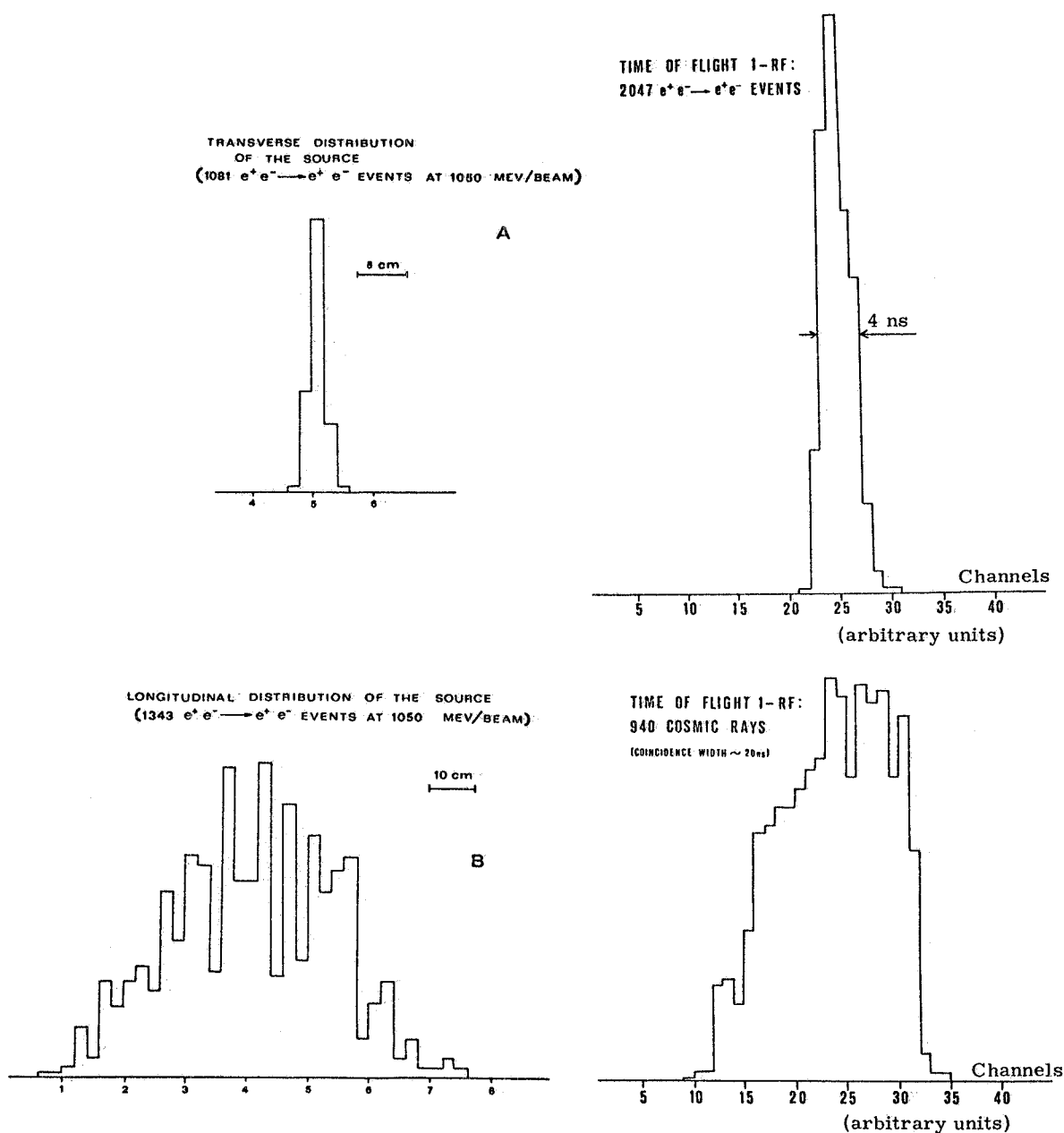


FIG. 1 - a) Transverse (A) and longitudinal (B) distributions of e^+e^- collisions points, from process $e^+e^- = e^+e^-$ (1a) at $E = 1.05$ GeV ("sources dimensions" in Adone). The longitudinal dimension of source results to be σ_z (standard deviation) $\approx \pm 20$ cm at 1.05 GeV. The σ_z measured energy dependence in Adone is $\sigma_z(\text{cm}) \sim 20 E^{3/2}$ (GeV). (Do you remember that in Adone, as well as in ACO and VEPP-2, one has a head-on bunch-bunch collision).

b) Time of flight distributions between the instant of crossing between e^+e^- bunches ("RF signal") and signal from counters of an Adone's apparatus (counters 1 in Fig. 11), in the case of true e^+e^- events or cosmic rays.

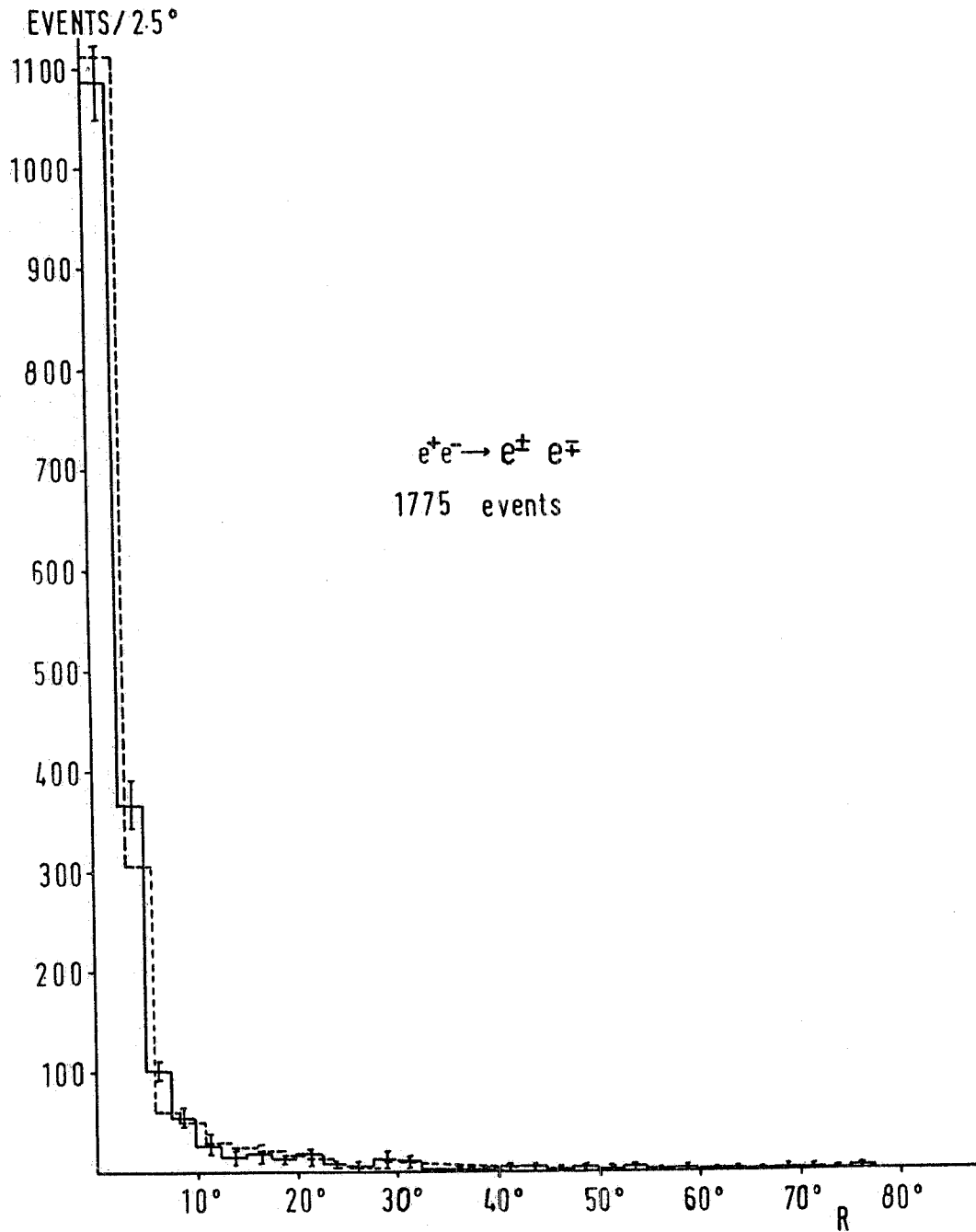


FIG. 2 - Non collinearity angle (R) distribution from process $e^+e^- = e^+e^-$. The dashed histogram is the theoretical prediction based on the first-order radiative corrections with peaking approximation⁽²⁾.

"source" and in the opposite side with respect to the interaction region (see Fig. 3). These techniques have been especially studied by groups^(16, 4) involved in the measurement of two body "rare" process (like $e^+e^- = \mu^+ \mu^-$), as in these cases the cosmic rays background is a serious problem.

2) machine's background comes from beam-gas interaction (residual gas in the donut) or from beam losses against donut's walls. This last contribution is easily recognized by looking at the picture of events (looking to the "source" of the event), whereas beam-gas background can be subtracted by means of runs with only one beam circulating in the storage ring.

The discrimination between different particles, i. e. between different e^+e^- processes, has been carried out by experimental groups by means of standard techniques and criteria (pulse height; e. m. shower in the case of an electron or photon; nuclear interaction in the case of an hadron etc.).

2. - TWO BODY FINAL STATE PROCESSES. -

In this part I shall report data from Adone, VEPP-2 and ACO about process :

$$(2.1) \quad e^+e^- = h\bar{h} \quad (h = \text{hadron}).$$

Moreover, because only very few events $e^+e^- = K^+K^-$ (5 events) has been detected. I shall discuss only the cases $h = \pi$ (§ 2.1) and $h = p$ (§ 2.2).

2.1. - The measurement of process :

$$(2.2) \quad e^+e^- = \pi^+\pi^-$$

in the GeV region ($2E > 1$ GeV) turns out to be more difficult than at ρ^0 peak because of the unfavourable ratio π/e at this energy. For example in the Adone's case (BCF⁽⁴⁾ and $\mu\pi$ ⁽⁵⁾ groups) the observed ratio (before corrections for nuclear absorption of π 's) is around or less than 1%. This fact requires a high rejection factor against the electrons. It has been obtained by requiring (in the BCF and $\mu\pi$ groups measurements) no e. m. showers along the path of both particles and, on the contrary, a given frequency of nuclear interactions produced by these⁽⁶⁾.

The results of measurements carried out at ACO⁽⁷⁾, at Novosibirsk⁽⁸⁾ and Frascati^(4, 5) are shown in Fig. 4, in terms of $|F_\pi|^2$ (from equation

$$(2.3) \quad \sigma_{\pi\pi}(E) = \frac{\pi}{12} \frac{3}{E^2} |F_\pi(E)|^2$$

where: $\sigma_{\pi\pi}(E)$ is the cross section of process (2.2); E = energy of each

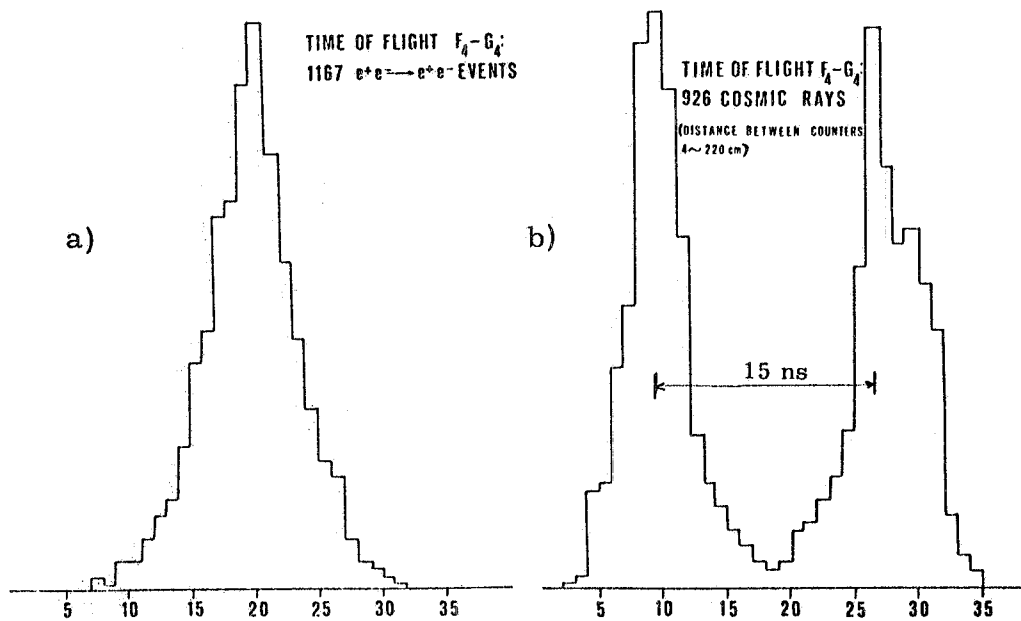


FIG. 3 - Time of flight distributions of pulses from two counters (counters 4 in Fig. 11), placed at the same distance (~ 1.1 m) from the Adone's interaction region in the opposite side with respect to this source^(1b). The two peaks in Fig. 3b are due to cosmic rays crossing the apparatus, the single peak of Fig. 3a to e^+e^- Bhabha scattering events.

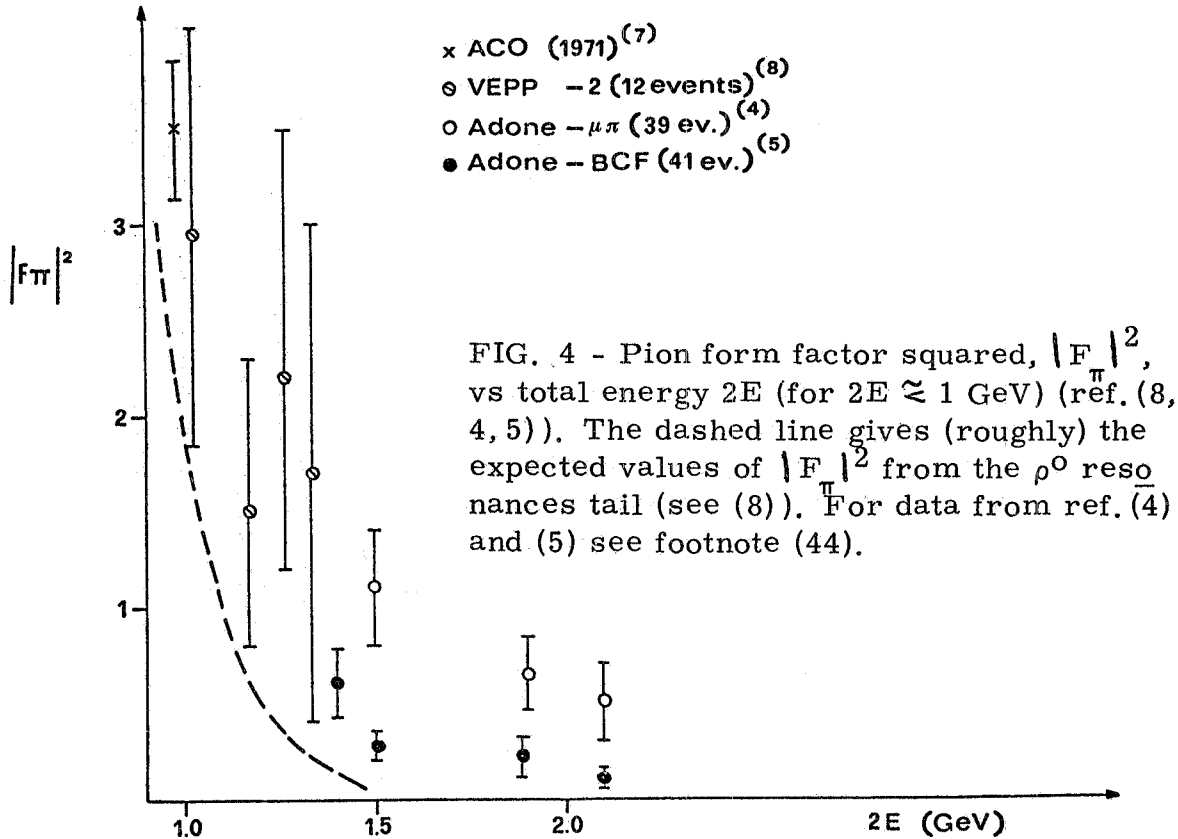


FIG. 4 - Pion form factor squared, $|F_\pi|^2$, vs total energy $2E$ (for $2E \approx 1$ GeV) (ref. (8, 4, 5)). The dashed line gives (roughly) the expected values of $|F_\pi|^2$ from the ρ^0 resonances tail (see (8)). For data from ref. (4) and (5) see footnote (44).

e^+ , or e^- beam; $\beta = c.m.$ velocity of produced pion).

The dotted line, in Fig. 4, gives (roughly) the expected values from the ρ^0 resonance (ρ^0 -tail)(8). It seems that systematically the experimental values are larger than the predicted values.(44) However the validity of such a calculation (contributions from a resonance well outside of its peak) is very questionable.

The same comparison has been made in Fig. 5 in terms of $\sigma_{\pi\pi}$. An explicit evaluation of this quantity, in the frame work of the vector meson dominance model, has been carried out by Kramer et al. (KUW)(9). They estimate a $\sigma_{\pi\pi} \sim 0.15$ nb (nb = 10^{-33} cm²) for $2E \sim 2$ GeV to be compared with a measured value of $0.5 \div 1$ nb (A little higher value, always lower than the experimental one, has been calculated by Vaughn(10) by means of the hard pion current algebra).

Moreover, the energy dependence of $\sigma_{\pi\pi}$ (particularly from the BCF data(4)) seems to be steeper than $1/s$ (point-like pion). This result can be inferred, also, from the fact that the measured ratio(5), between the pion pairs and the associated e^+e^- wide angle scattering events, is not constant with the energy (as should be if both processes $e^+e^- = \pi^+\pi^-$ and $e^+e^- = e^+e^-$ would follow the same $1/s$ energy dependence). Note that roughly (for $|F_\pi|^2 \sim \text{const}$) the energy dependence expected for $\sigma_{\pi\pi}$ on the ρ^0 tail region ($s \gg m_\rho^2$) is $1/s^3$. (Where, $1/s$ and $1/s^2$ contributions come from the photon and ρ^0 propagator, respectively(11)).

Before closing this subject let me add two "experimental" remarks:

1) in the data from VEPP-2 the separation between channels K^+K^- and $\pi^+\pi^-$ has been carried out (exploiting the information of water Cerenkov counters)(8). In the case of Frascati measurements only during apart of 1.5 GeV runs $\mu\pi$ group(5) has separately measured K^+K^- pairs from $\pi^+\pi^-$ pairs. Only 1 K^+K^- event was founded out to observed 16 hadron pairs. No separation has been carried out at other energies. So, a priori, the above results refer to the $(KK + \pi\pi)$ channel rather than to the $\pi\pi$ channel alone in the case of Frascati's experiments(12).

2) No effects of an eventual e^+e^- beams polarization (due to synchrotron radiation) have been considered(13). These, however, are expected to be much lower than the present errors of available measurements of $\pi^+\pi^-$ process.

2.2. - $e^+e^- = p\bar{p}$.-

This process has been recently measured, just above the threshold ($E = 1.05$ GeV), by the $p\bar{p}$ -Adone group(14). A sketch of their apparatus has been reported in Fig. 6. They have used all the general criteria

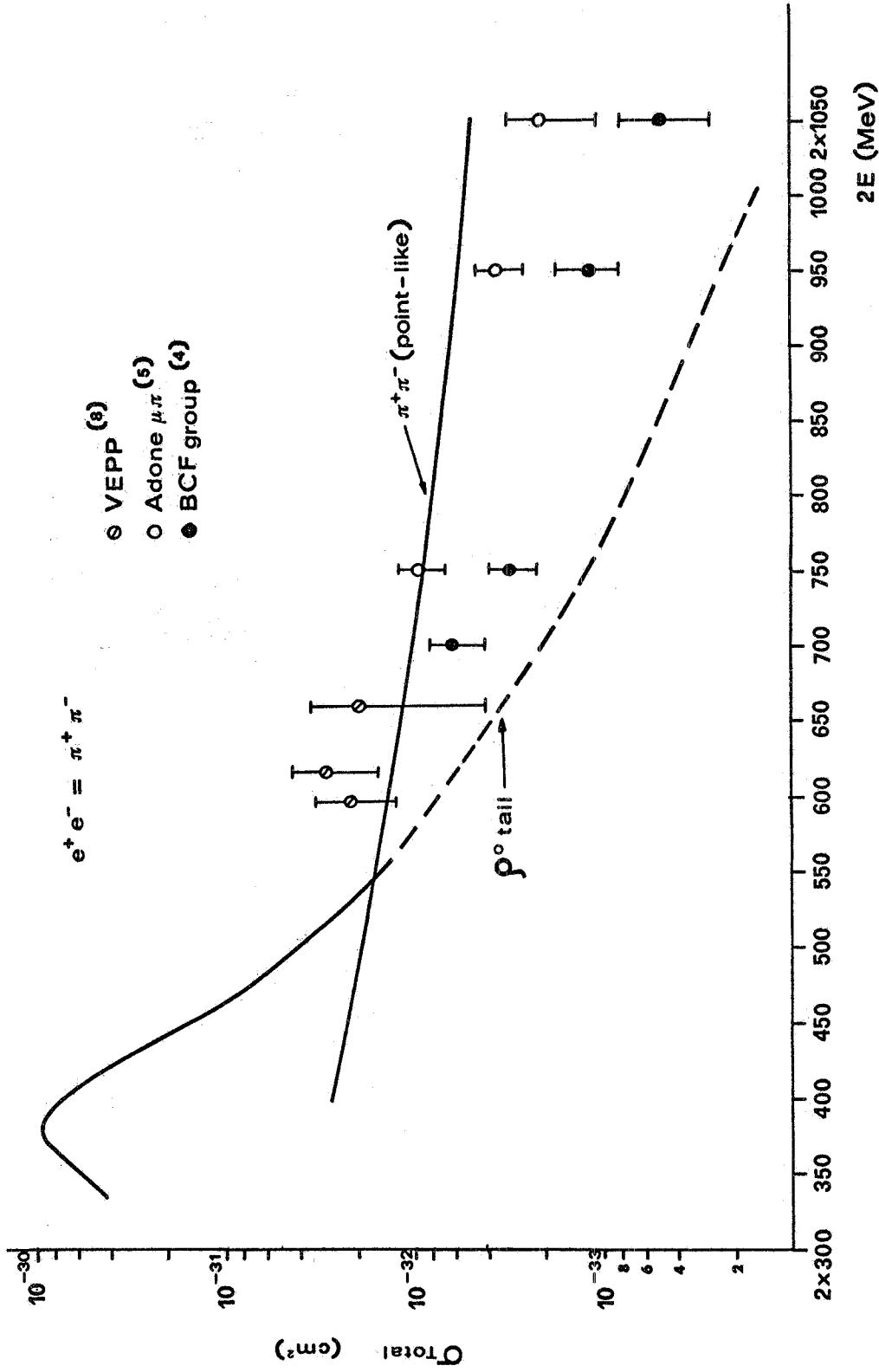


FIG. 5 - Measured total cross section, $\sigma_{\pi\pi^0}$, of process $e^+e^- = \pi^+\pi^-$ vs $2E$, for $2E < 1$ GeV. For comparison cross sections expected for a point-like pion and from ρ^0 resonance's tail are shown. This last curve was obtained by fitting with a Breit-Wigner curve the 1971-data from ACO (Fig. 17 in (7)). For data from ref. (4) and (5) see footnote (44).

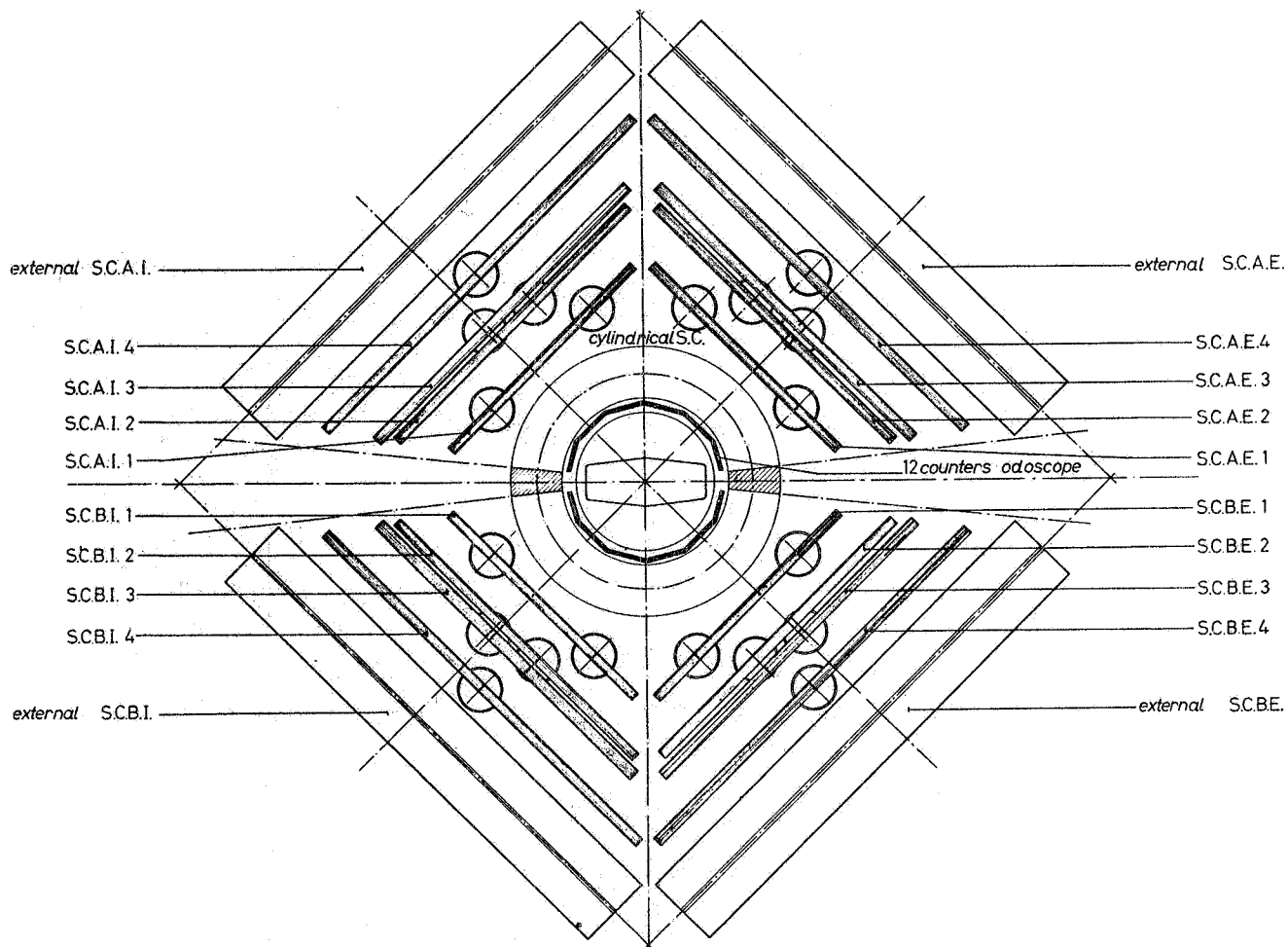


FIG. 6 - Front view of the apparatus for process $e^+e^- = p\bar{p}$.

C.A.I. 1-4 (or E. 1-4) } Plastic scintillators
 C.B.I. 1-4 (or E. 1-4) }

External S.C. A.I., B.I., A.E., B.E. : wide bigap spark chambers.

A counters odoscope (12 counters) and the cylindrical spark chambers (cylindrical S.C.) were used to select collinear events.

outlined in section 1 to select two-body events produced by an e^+e^- collision (collinearity, source, time with the e^+e^- collision time). Moreover they have added specific requirements to be sure of the "proton nature" of both particles (energy loss in plastic counter, range, annihilation of \bar{p}). They require a stopping proton in one counter telescope ("proton telescope") and a larger energy release on the opposite telescope (" \bar{p} telescope"). This last larger energy release on the \bar{p} arm is due to charged secondaries from annihilation star.

Correlation between the energy loss in the two quoted telescopes is shown in Fig. 7. Two different experimental conditions are shown:

- a) - standard running condition ($E = 1050$ MeV);
- b) - background runs (e^+e^- runs at 950 MeV, below $p\bar{p}$ detection threshold; $E = 1050$ MeV with only one beam circulating in Adone). The last situation (one beam at 1050 MeV) was used to evaluate background due to electron (or positron)-nucleus interactions in the residual gas in the Adone. As we see (Fig. 7) "collinear and in time events" with the correct loss in the p arm (~ 80 MeV) and larger loss (> 150 MeV) in the \bar{p} arm occur in the standard runs but not in the background runs (these are equivalent to ~ 0.6 of standard runs).

From the analysis of about half of data collected, they have given the following results⁽¹⁴⁾:

- a) - an upper limit (90% confidence level)

$$\sigma(e^+e^- = p\bar{p}) < 9 \times 10^{-34} \text{ cm}^2 \quad E = 1.05 \text{ GeV}$$

(8+4 candidate events-before a complete background subtraction has been operated);

- b) - reducing the events to only 5 very clear events which seems to be, without any doubt, $p\bar{p}$ events (events with a loss in the \bar{p} arm larger than 150 MeV):

$$\sigma \sim 4 \times 10^{-34} \text{ cm}^2$$

How these results compare with Brookhaven and CERN measurements⁽¹⁵⁾ on the inverse process ($p\bar{p} = e^+e^-$), and with the dipole model prediction it is shown in Fig. 8⁽¹⁶⁾. Many other predictions for this very interesting process has been carried out by different theorists (see, for example⁽¹⁷⁾).

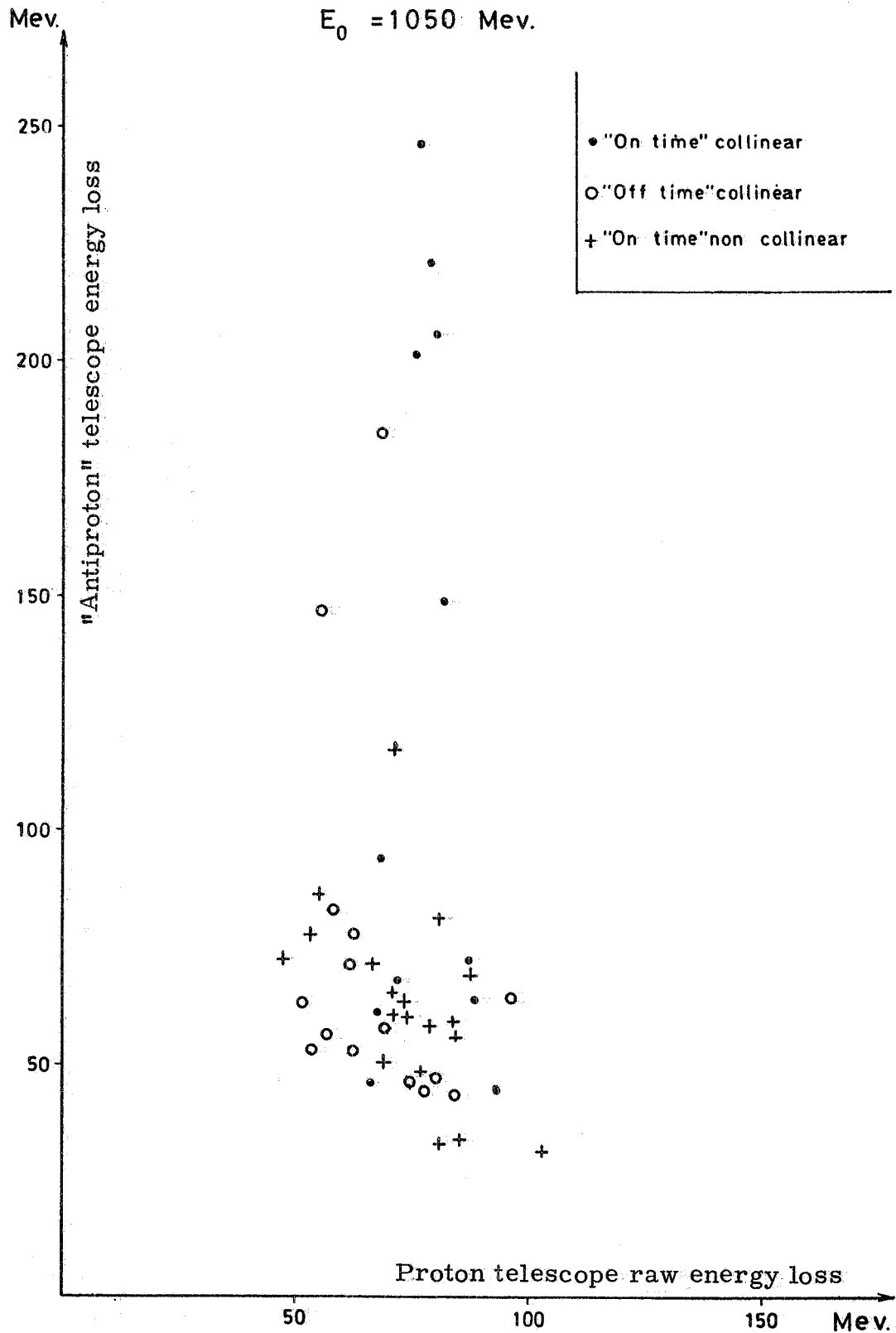


FIG. 7 - Energy release in the proton telescope vs energy release in the opposite \bar{p} telescope (abscissa) for standard running condition (a) and for background runs (b), see text. The expected total proton energy loss is $\sim 80 \text{ MeV}$, that in the \bar{p} arm is larger because of the secondaries from annihilation star.

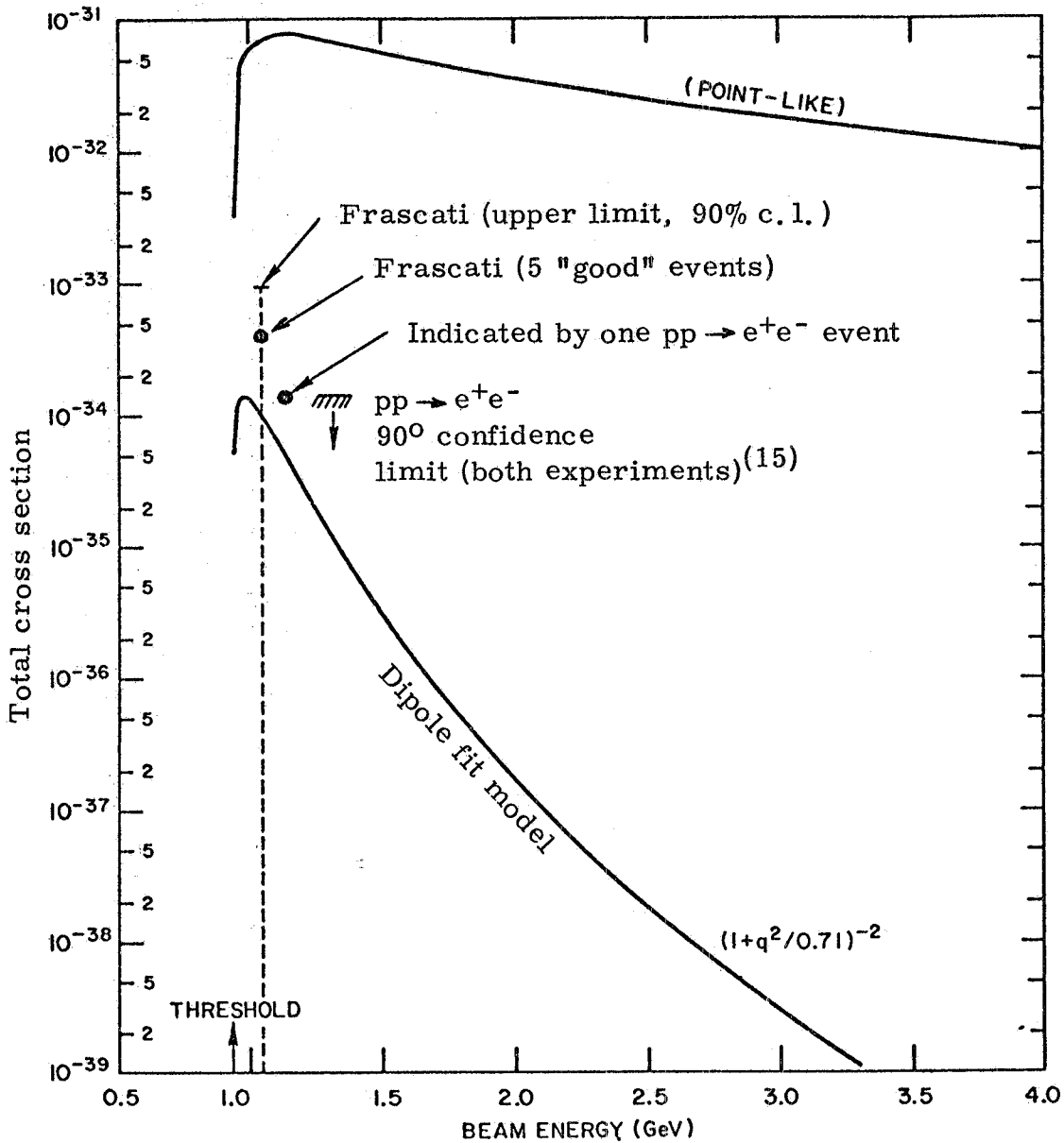


FIG. 8 - Total cross section of process $e^+e^- = p\bar{p}$ at $2E = 1.05 \text{ GeV}$ ⁽¹⁴⁾. An upper limit (90% c.l.) and a preliminary value based on 5 "good" events, measured by the Adone $p\bar{p}$ group are shown. For comparison upper limit for this cross section extrapolated by the Cern⁽¹⁵⁾ and Brookhaven⁽¹⁵⁾ measurements on the inverse process ($p\bar{p} = e^+e^-$) are also shown. Predictions from the dipole fit model of proton form factor have been reported, from⁽¹⁶⁾.

3. - MULTIPLE HADRONIC PRODUCTION. -

We discuss here processes in which more than two hadrons are produced.

Such events, which satisfy all the criteria previously discussed for an event to be due to e^+e^- collision, have been observed (in ACO, VEPP and ADONE) over the entire energy range we are discussing. In a large fraction of these events three or more charged particles are detected. In the case of only two visible tracks, events are made by two non collinear tracks which are also non-coplanar with the beam direction. (This means that there is an angle $\Delta\phi \neq 0$ between the two planes defined by the beam direction and the first or second track of these events, respectively. Usually a cut off for $\Delta\phi > 10 \div 15^\circ$ has been used by the experimental groups). In fact, almost all coplanar but non-collinear events are due to radiative corrections to a true two body process.

As we known, first evidence for such events has been reported by Frascati and Novosibirsk groups⁽¹⁸⁾ at the Kiev Conference (1970). A much larger and cleaner evidence for this process is now available, and is based on a sufficiently large number of events (about 1300 events). Details on these events are reported on Table I. In this table events are divided according the number of charged and neutral particles detected by the apparata ("Neutral" means a γ or a π^0).

Track (T) in Table I means a charged hadron. Evidence of hadronic nature of particles produced in these events has been exhaustively discussed by all groups^(18, 5, 22). As I said, it is essentially based on their behaviour in traversing nuclear matter (nuclear interactions along the tracks, attenuation in traversing absorbers, pulse height, etc.).

In the same table also the corresponding number of associated e^+e^- wide angle scattering (WAS) events (monitor reaction⁽²⁰⁾) or the time integrated luminosity, L, during the experiment has been reported⁽²¹⁾. These quantities enter in the calculation of the absolute value of the cross section (see, for instance, eq. (3.5)).

The distribution of events in different categories found by different groups cannot be directly compared, because each apparatus detect with a different efficiency various types of events. These differences came from different angular acceptance of the set-ups and from different requirements (number of particles, kinetic energy of these, etc.) in the master trigger.

As said before, I will not describe in details these apparata. I will only sketch them in Fig. 9÷13 and summarize their main characteristics.

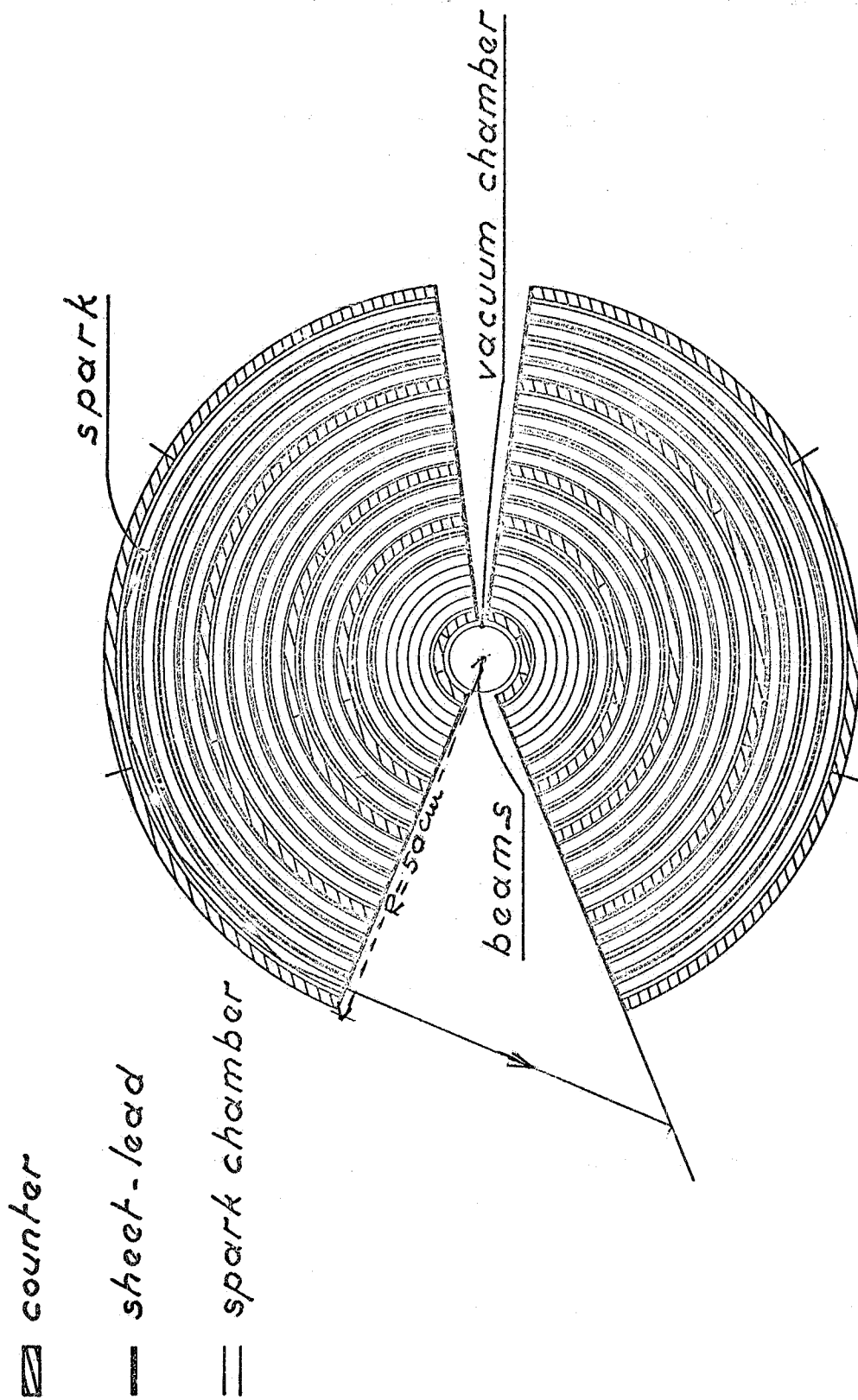


FIG. 9 - Schematic front-view of ACO apparatus (7). The first five thin foil spark chambers measure the spatial direction of each particle; Electron and photon showers observed in the lead-optical sp. ch. ($11 \times 0.5 = 5.5$ radiation length). Veto counter against cosmic rays (not shown). Longitudinal dimension of the apparatus: 80 cm. Source dimension: ± 1 mm (transverse dimension); 15 cm (longitudinal dimension). Angular acceptance:

$$\Delta\phi \sim 150^\circ \quad \frac{\Delta\Omega}{4\pi} \sim 0.6$$

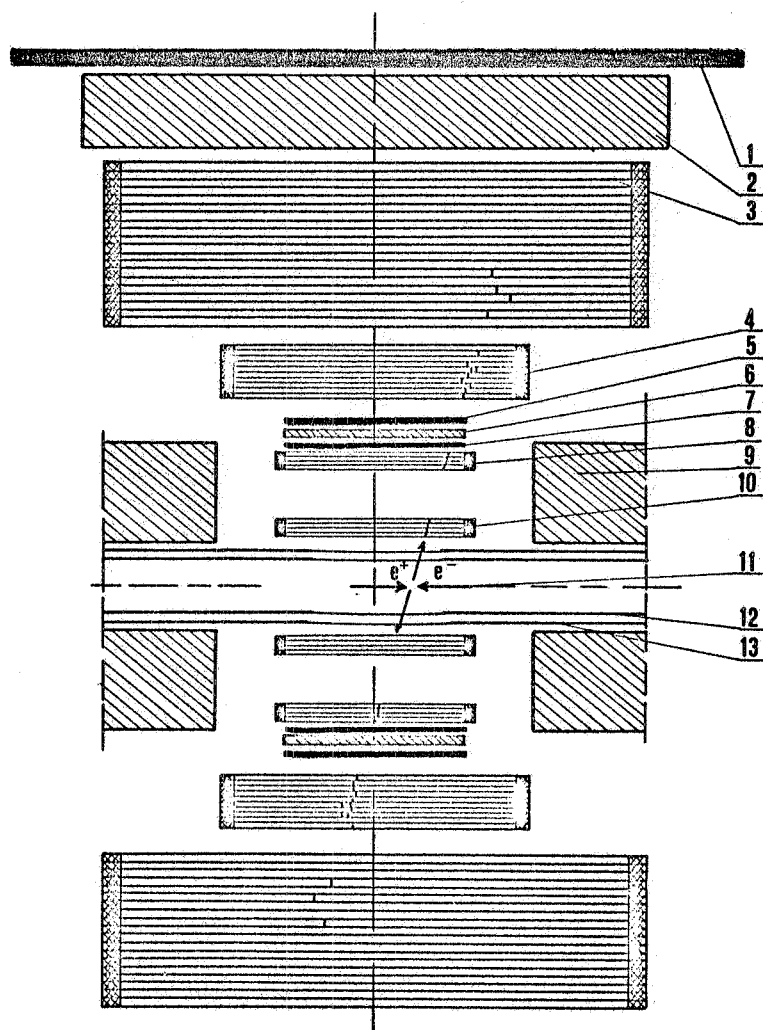


FIG. 10- General view of the Novosibirsk set-up.

- 1 - Veto counter (cosmic rays)
 - 2 - lead absorber
 - 3 - optical range sp. ch.
 - 4 - optical shower sp. ch. ($3+4 \approx 170 \text{ g/cm}^2$, F_e)
 - 5, 7 - scintillators
 - 6 - water Cerenkov counter (thickness = 7 cm)
 - 8 - Coordinate wire sp. ch. (to measure spatial direction of particles)
 - 9 - interaction region
 - 10, 11 - VEPP vacuum chambers
 - 12 - VEPP magnet
- Angular acceptance:

$$\Delta\theta = \pm 25^\circ \text{ (around vertical) } - \frac{\Delta\Omega}{4\pi} \sim 1/8$$

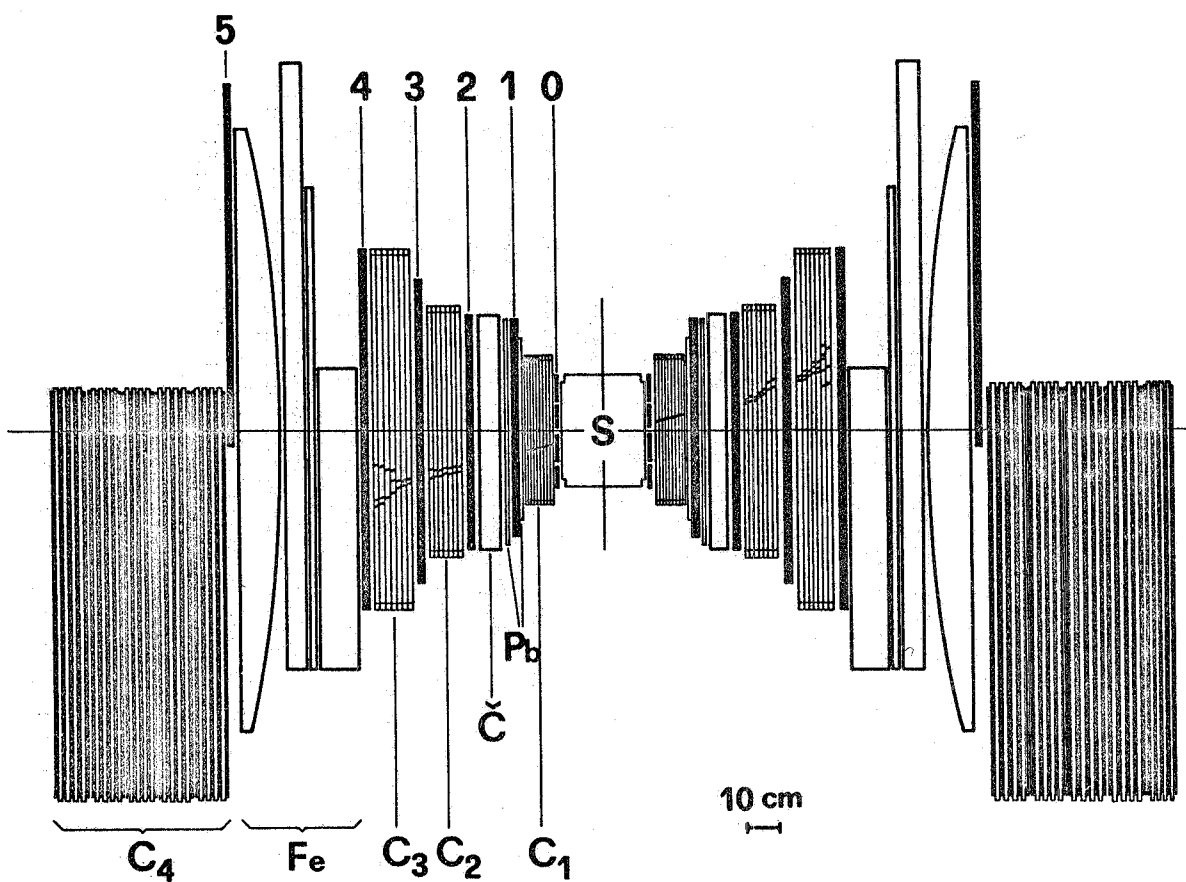


FIG. 11 - Front view of Adone $\mu\pi$ groups apparatus.

(Sparks from a real e^+e^- wide angle scattering event are shown)

C_1 : thin foil spark chambers (spatial reconstruction of events)

S: "Source" (for its dimensions see Fig. 1a)

C_2, C_3 : thick plate spark chambers, to observe e.m. showers
(~ 3.5 r.l., F_e) and/or the stop of charged particles.

\check{C} : water Cerenkov (10 cm)

C_4 : thick plate chambers, in which μ 's from $e^+e^- = \mu^+ \mu^-$
are stopped.

0-5: scintillators counters, (2+3): shower counter

Angular acceptance:

$$\theta = 53^\circ + 127^\circ \text{ (point source)}$$

$$\Delta\varphi = 150^\circ$$

$$\frac{\Delta\Omega}{4\pi} \sim \frac{1}{5} \text{ (extended source)}$$

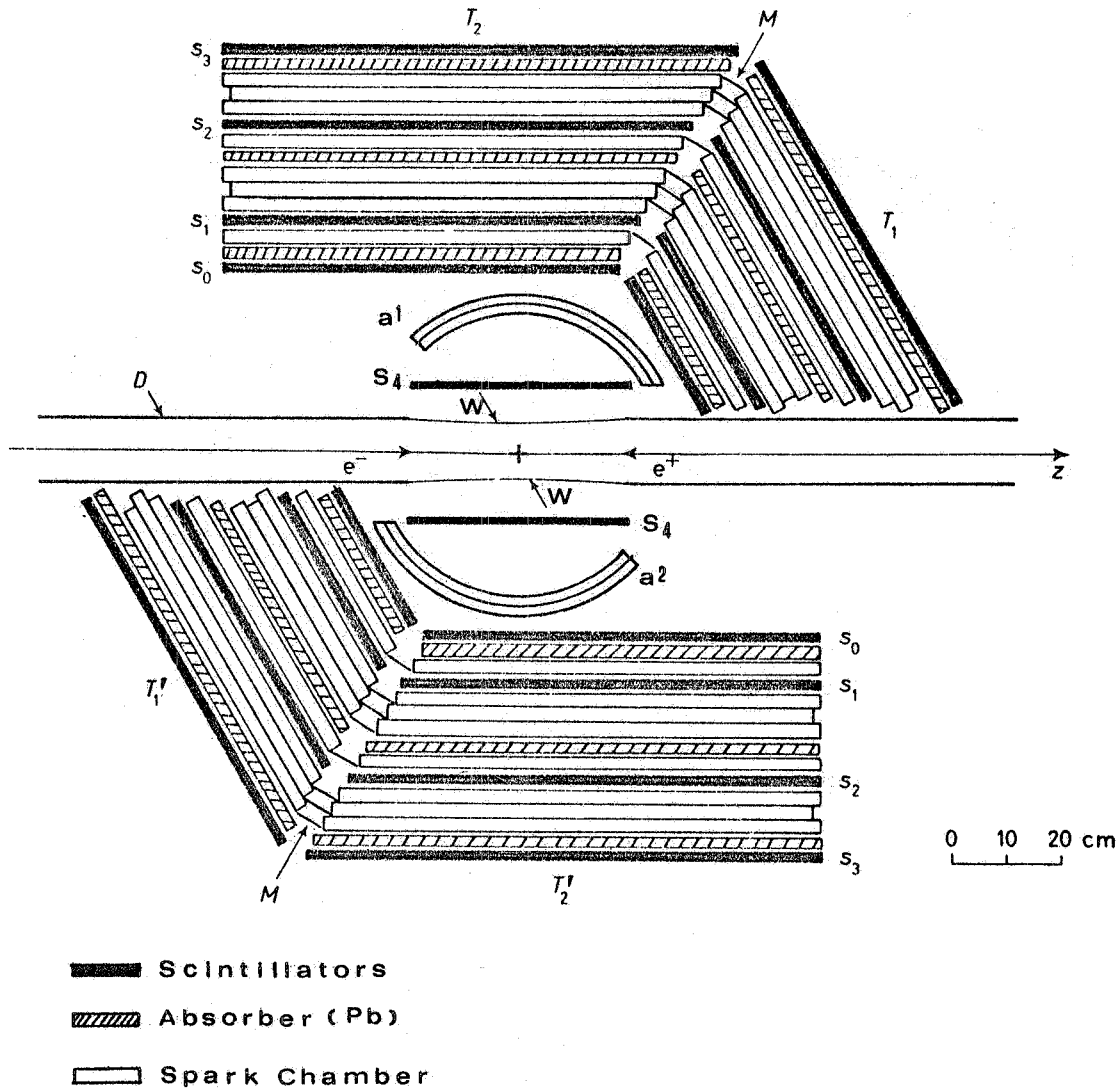


FIG. 12 - Lateral view of Adone $\gamma\gamma$ group apparatus.

a^1, a^2 : cylindrical thin foil (spatial reconstruction of events)

$S_0 - S_4$: plastic scintillators

Lead or iron absorber: 3.5 r.l. (total thickness)

Veto counter against cosmic rays (not shown)

Angular acceptance:

$$\left. \begin{aligned} \theta &= 20^\circ - 45^\circ \\ &= 70^\circ - 110^\circ \end{aligned} \right\} \text{(point source); } \frac{\Delta\Omega}{4\pi} = .23 \text{ (extended source)}$$

$$\Delta\varphi = \begin{matrix} \pm 30^\circ & \text{(around the vertical) for } T_2, T_2' \\ \pm 40^\circ & \text{" " " " } T_1, T_1' \end{matrix}$$

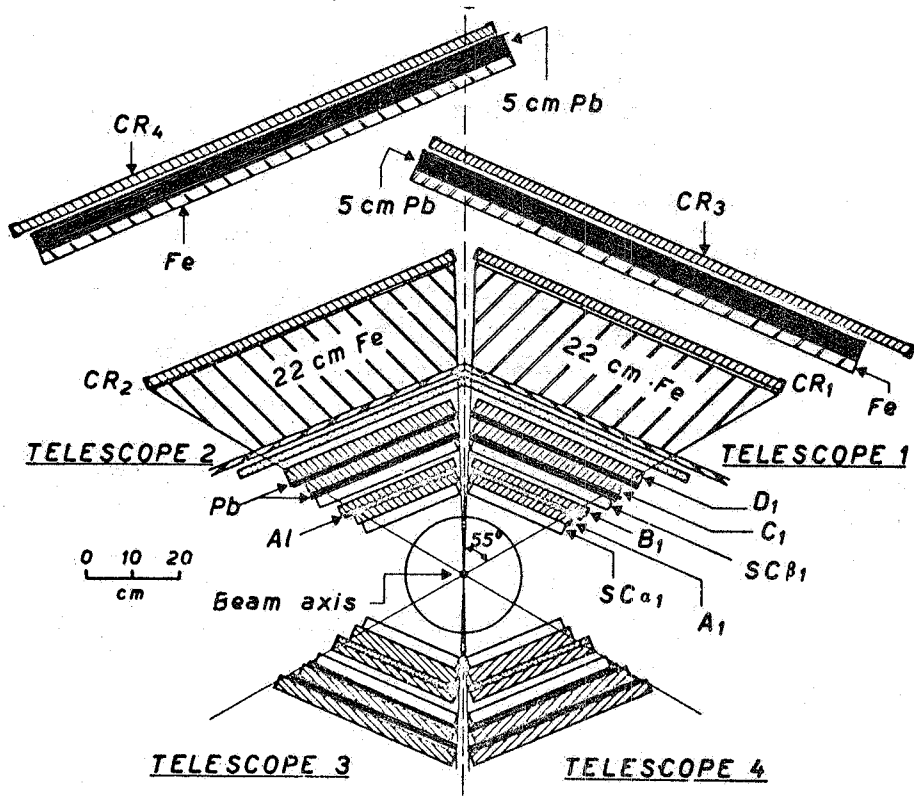


FIG. 13 - Front view of Adone Boson group

SC α , β : digitalized wire spark chamber (only the azimuthal angle ϕ is measured)

(A+B): shower counter

A, B, C, D: plastic scintillators

CR₃, CR₄: veto counter (cosmic rays)

Angular acceptance:

$$\Delta\theta = 58^\circ \div 1230 \text{ (point source)}$$

$$\Delta\phi = 4 \times 55^\circ = 220^\circ$$

$$\frac{\Delta\Omega}{4\pi} \sim .18 \text{ (extended source)}$$

We can say that:

1) all apparatus detect particles around $\theta = 90^\circ$. The $\gamma\gamma$ group also detects particles around $\theta = 30^\circ$ ($\theta =$ zenith angle of produced particle with respect to the beam direction);

2) $\mu\pi$ apparatus covers an angle around the horizontal plane (or machine plane) ($\phi = +40^\circ$), whereas all other apparatus see azimuthal angle around the vertical;

3) all, but ACO apparatus, have small solid angles ($\Delta\Omega/4\pi \sim 1/4 \div 1/8$), which are not adequate to see events with high multiplicity;

4) the main differences between the quoted experiments came from the different trigger used. For instance, ACO and ADONE $\gamma\gamma$ groups have a trigger with only neutral particles (π^0 or γ) or with neutrals + at least one charged particle, whereas all other groups require at least two charged particles. Moreover quite different triggering thresholds has been used by different groups⁽²³⁾.

In spite of all these remarks, the data of Table I show some interesting points:

1) the relevance of multiple hadronic events. For instance, in the case of the Adone- $\mu\pi$ group one has a ratio (multihadron events/WAS) of the same order of $\mu^+ \mu^-$ pairs/WAS, (WAS = e^+e^- wide angle scattering events);

2) the existence of several different types of detected events (2T, 2T+neutrals, 3T etc.) indicate that several different reactions are produced in a e^+e^- collision for $2E > 1$ GeV. It means the coexistence, at each energy, of reactions differing in the number of charged and neutral pions (see, for instance, eq. (3.1) ÷ (3.4)).

This fact, obviously, makes more difficult the problem of calculate the absolute value of cross section for multihadronic processes. In fact, the necessity of divide the collected sample of events in several different categories (belonging to different primary reactions) reduce the statistical significance of the results. Moreover, due to the small solid angle of the apparatus, their energy cuts on detected particles, and the loss due the nuclear absorption of produced pions, the detection efficiency for each channel turns out to be small (1 ÷ 10%) and strongly dependent on the total energy $2E$, the primary reaction and the category of detected events. We have, in conclusion, many contributing reactions, which we expect to change with the total energy and at a given $2E$ with detection efficiencies differing by a large factor. These crucial points of all the multihadron experiments have been pointed out by all groups and must be remembered when we look at the results.

Our following discussion will be centered on three points:

- (A) Evaluation of absolute cross sections (see 3.1)
- (B) Information about the mechanism of multihadron production (see 3.2)
- (C) Some comparison with the theory and conclusions (see 3.2).

3.1. - Evaluation of absolute C.S. -

In this section I will essentially discuss the procedures followed by the Adone's groups and their present results.

Similar procedures have been followed these groups. Both Boson⁽²²⁾ and $\gamma\gamma$ groups⁽²⁴⁾ have tried to extract, at each energy $2E$, the values of cross sections of processes⁽²⁵⁾:

$$(3.1) \quad e^+ e^- = \pi^+ \pi^- + \text{neutrals} (\sigma_{2,n}) \quad (\text{neutrals} \equiv (1 \div 4) \pi^0)$$

$$(3.2) \quad e^+ e^- = \pi^+ \pi^- \pi^+ \pi^- (\sigma_{4,0})$$

$$(3.3) \quad e^+ e^- = \pi^+ \pi^- \pi^+ \pi^- + \text{neutrals} (\sigma_{4,n}) \quad (\text{neutrals} \equiv (1 \div 2) \pi^0)$$

$$(3.4) \quad e^+ e^- = \pi^+ \pi^- \pi^+ \pi^- \pi^+ \pi^- (\sigma_{6,0})$$

from an overall fit of the observed distribution of events between the different categories (or configurations) reported in Table I.

These calculations (or fits) have been carried out starting from equations of the type:

$$(3.5) \quad N_D = L \sum_A \epsilon_D^A \sigma_A \quad \left\{ \begin{array}{l} N_D = \text{number of events in a given configuration, } D \\ L = \text{time integrated luminosity} \\ \epsilon_D^A = \text{efficiency to detect configuration } D \\ \text{from process } A \\ \sigma_A = \text{cross section to produce process } A \end{array} \right.$$

The number of equations is equal to that of different configurations detected (2T; 2T+ neutrals; 3T etc..). The number of unknown quantities is equal to the number of the assumed primary processes (4 in the case we are now discussing).

TABLE I - Multihadron events

Group	2E (GeV)	2 T (No collinear)	2 T+ neutrals	3 T	3 T+ neutrals	4 T	4 T+ neutrals	5 T	WAS	L (cm ⁻²)
ACO ⁽⁷⁾	0.99		34 ^(o)							3.1 x 10 ³³
VEPP-2 ⁽⁸⁾	1.18-1.34	38 ± 15								1.4 x 10 ³⁴
Adone-Boson	1.4 -2.4	577	109	67	7				3800	
Adone-μπ	1.4 -2.1	(x)	(x)	173	35	65	4	8	10335	
Adone-γγ	1.4 -2.4		59	26	13	5				4.4 x 10 ³⁵

(x) - The μπ group has 70 two tracks events (in correspondence of 3300 WAS).

(o) - Details of these events, according the number of detected γ, can be found in Table V in ref. (7).

In the first stage of the analysis all Adone groups have calculated the efficiencies ε_D^A assuming a statistical model for pion production (phase-space Montecarlo calculations). We will come back on the validity of this assumption in the next section (3.2). We can say, at present, that this assumption is adequate for a first evaluation of the cross sections.

Some of the results from Boson and $\gamma\gamma$ groups will be shown later (Figg. 14÷18).

The procedure followed by the $\mu\pi$ group differs, from that of these groups, because they have isolated some special configurations, which unambiguously are due to only one specific reaction.

Specifically:

1) from the observed 5 tracks events they have an unambiguous evidence for processes in which 6 or more charged pions are produced. Assuming that all the 8 observed 5-T events are due to process (3.4) (six charged pions) they obtain for $\sigma_{6,0}$ values of the order of few nb:

$$\sigma_{6,0} = 2.5 \pm 2.5 \text{ nb (2E = 1.65 GeV); } \quad \sigma_{6,0} = 2.5 \pm 0.9 \text{ nb (2E = 2.0 GeV)}$$

2) from events with 4 observed tracks they have isolated events (26 events) in which only 4 charged pions (and no more π^0 or charged pions) are produced. This has been done starting by the measured spatial angles of each track and by applying the E-p conservations equations⁽²⁶⁾.

The values obtained for $\sigma_{4,0}$ are shown in Fig. 16.

3) Finally, from 3 and 4T events (after subtraction of processes previously evaluated) they have obtained (from 258 events) the value $\sigma_{4,n}(4 \text{ ch. } \pi + (1 \div 2) \pi^0)$ also shown in Fig. 16.

The results of these analysis by Adone's groups, now discussed, are summarized and compared in Figg. 14÷18. In these figures also data from ACO and VEPP-2 are shown.

In Fig. 14 information concerning process (3.1): 2 charged pions + (1÷4) π^0 are summarized.

All measured points (very few) give a $\sigma_{2,n}$ around 10 nb in all the range explored.

In the case of the ACO measurement⁽⁷⁾ the separation between events with a different number of neutral pions has been clearly done⁽⁴²⁾.

The $\sigma_{2,n}$ value reported in Fig. 14, from the ACO experiment, is relative only to process $\pi^+ \pi^- \pi^0 \pi^0$ (10 events). The number of $\pi^+ \pi^- \pi^0$ detected events (3 events) agrees with that expected from

the ω^0 tail and the ρ^0 radiative tail⁽⁷⁾.

In the case of Adone $\gamma\gamma$ group the values reported for $\sigma_{2,n}$ are relative to the sum of processes in which two charged pions and $(1\div 4)$ π^0 are produced. In this case the assignment of events to specific channels ($\pi^+\pi^-\pi^0$, $\pi^+\pi^-\gamma$, $\pi^+\pi^-\pi^0\pi^0$ etc.) is in progress. This can be done by comparing the measured and expected distribution of the non-complanarity angle of the detected γ (with respect to the plane defined by the two charged particles), in events with two charged pions and one photon.

$$e^+e^- = \pi^+\pi^- + \text{Neutrals } (\sigma_{2,n})$$

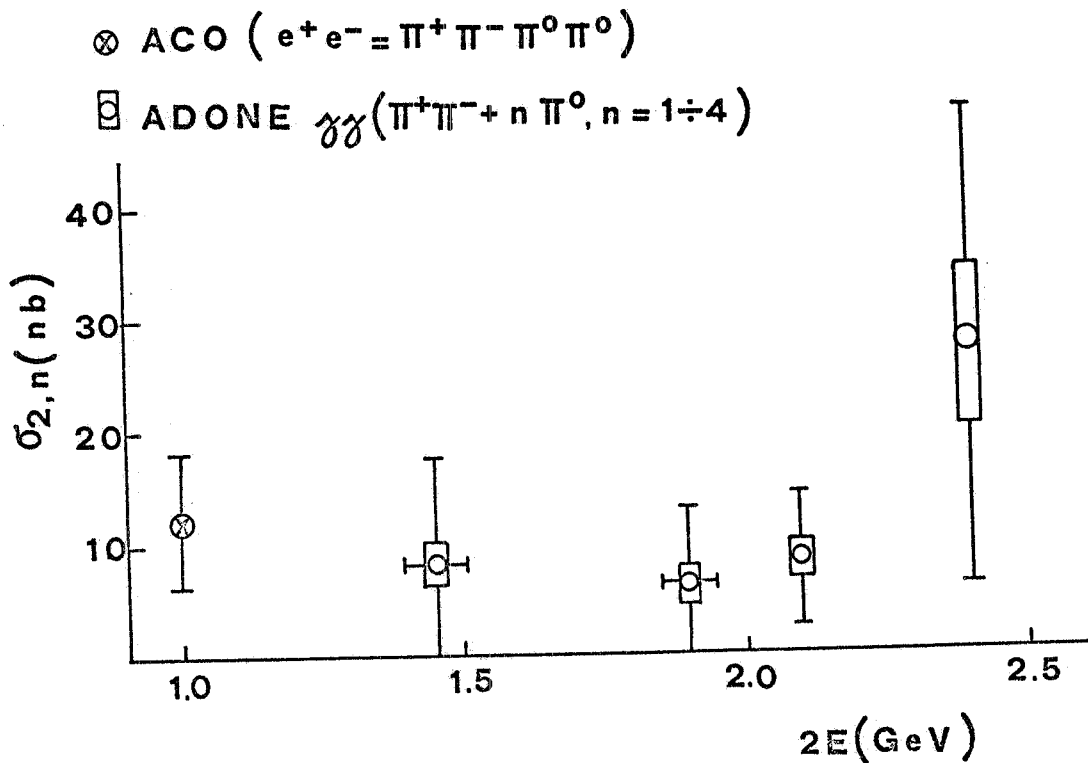


FIG. 14 - Cross sections for processes in which only two charged pions + neutral pions are produced ($\sigma_{2,n}$) at different total energy $2E$.

The value from ACO⁽⁷⁾ is relative to $\pi^+\pi^-\pi^0\pi^0$ process, that from Adone $\gamma\gamma$ group⁽²⁴⁾ to the sum of processes $\pi^+\pi^- + (1\div 4)\pi^0$; see text. In the case of $\gamma\gamma$ group the boxes represent a reasonable estimate of the systematic errors and the bars the statistical errors.

At present the experimental distribution (Fig. 15) seems to indicate that about 30% of events are compatible with the process $e^+e^- = \pi^+ \pi^- \pi^0$. In the hypothesis that all these events really came from the quoted process they obtain a $\sigma(\pi^+ \pi^- \pi^0) \approx 4 \pm 2$ nb, for $2E$ around 2 GeV⁽⁴³⁾. This is definitively larger than any VDM evaluation^(9, 27), through the contribution of the ρ^0 resonance tail [$\sigma(\pi^+ \pi^- \pi^0)_{\text{VDM}} < 1$ nb, $2E \sim 2$ GeV].

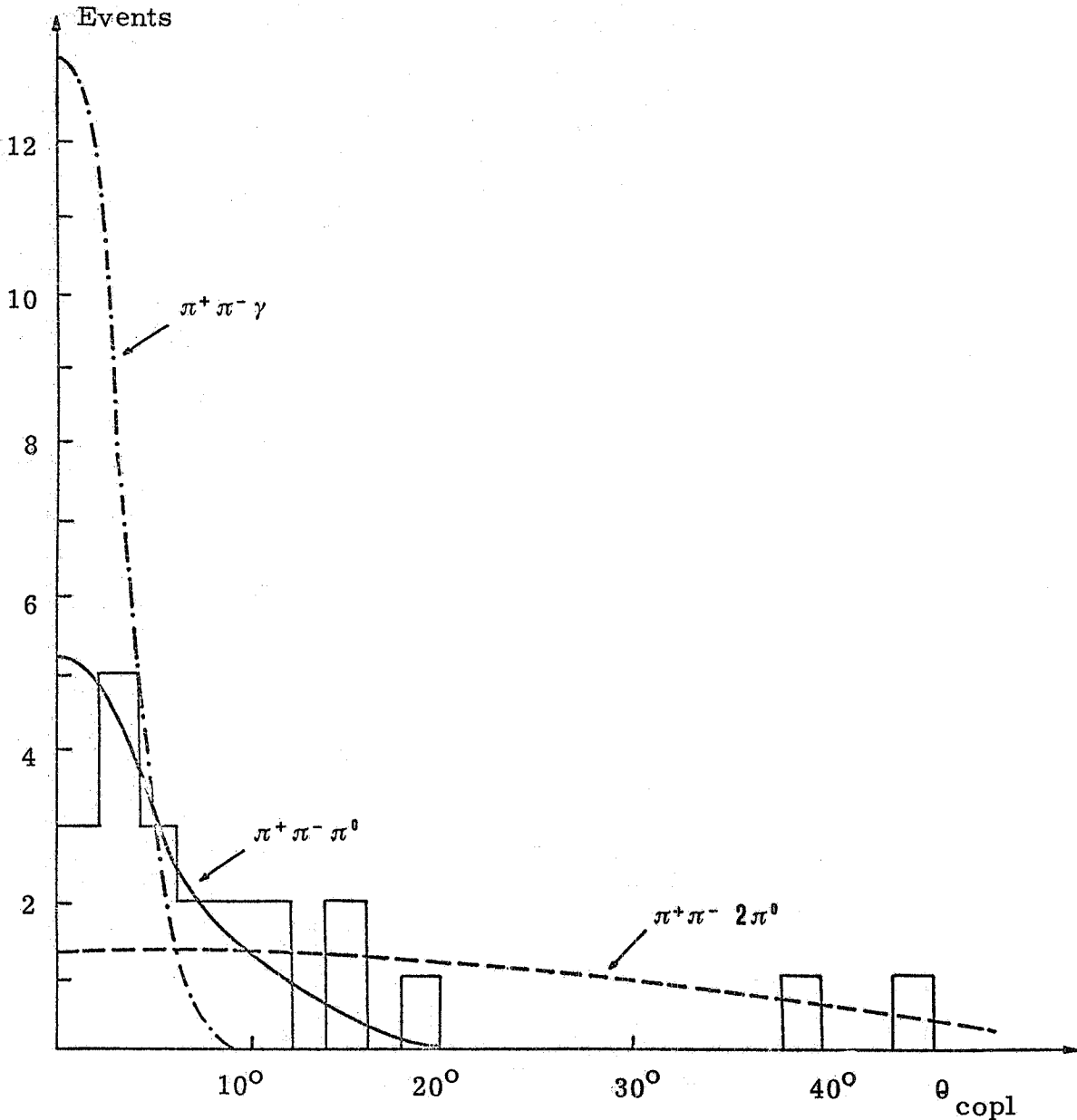


FIG. 15 - Distribution of non-coplanarity angle, θ , of detected γ with respect to the plane defined by the two charged particles, in events with 2 detected charged particles plus one photon. The expected distributions for different processes are also shown.

In Fig. 16 data concerning processes (3.2) and (3.3) are shown. About the energy dependence of these cross sections one can say that:

1) process $\pi^+ \pi^- \pi^+ \pi^-$ occurs with a "sizeable" cross section (in the nb region) for $2E$ larger than 1 GeV i.e. well above its kinematical threshold ($4m_\pi \sim 0.6$ GeV);

2) for $2E$ from 1.4 to 2.1 GeV the energy variation of $\sigma_{4,0}$ seems to be clearly steeper than that of $\sigma_{4,n}$. So, around 2 GeV $\sigma_{4,n}$ is clearly larger than $\sigma_{4,0}$. This result, from the Adone $\mu\pi$ group, qualitatively, agrees with a similar conclusion of $\gamma\gamma$ group⁽²⁴⁾. They have found, around 2 GeV, that $\sigma_{4n} \sim 2(\sigma_{40} + \sigma_{60})$.

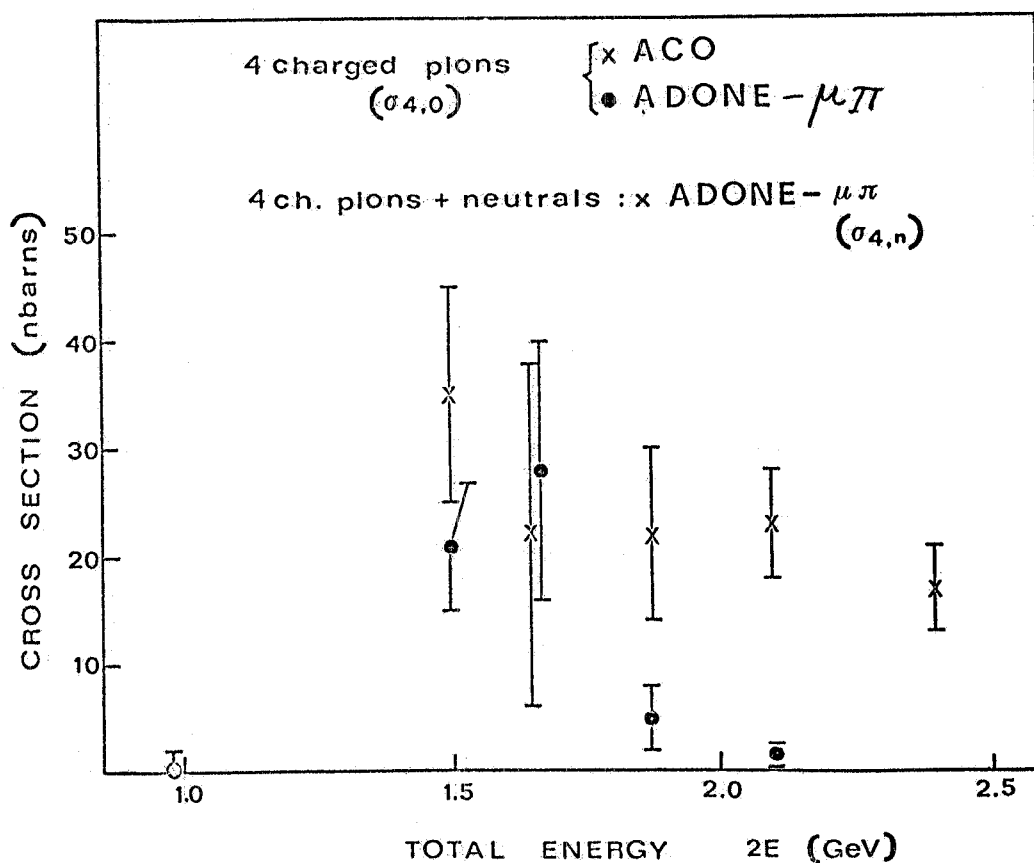


FIG. 16 - Cross sections for process $e^+e^- = \pi^+ \pi^- \pi^+ \pi^-$ ($\sigma_{4,0}$) or $e^+e^- = \pi^+ \pi^- \pi^+ \pi^- + (1-2) \pi^0$ ($\sigma_{4,n}$) vs $2E$. The value $\sigma_{4,0} = 80 \pm 35$ nb, $2E = 1.18 \div 1.34$ GeV, reported by the Novosibirsk group^(28, 18d) has been not reported for the reasons discussed in the text.

From the two track non coplanar events detected by the Novosibirsk group^(18d) (see Table I) they would have, for $2E = 1.18 \div 1.34$ GeV, a $\sigma_{40} = 80 \pm 35$ nb⁽²⁸⁾. In comparing this result with that from ACO and Adone, reported in Fig. 16, we must consider that:

1) events used by the Adone's $\mu\pi$ group to calculate $\sigma_{4,0}$ have a much clear signature than that detected by the Novosibirsk group (4-track events in Adone, 2 non coplanar tracks in VEPP-2);

2) since the Novosibirsk group has assumed that only the 4 charged pions process contributes, the measured value gives a lower limit for σ_{total} ⁽²⁹⁾, rather than the cross section for process (3.2) alone;

3) moreover, as stressed by Sidorov⁽²⁸⁾:

- a) - if one assumes some special mechanism (like $e^+e^- = \rho^0 \epsilon^0 = \pi^+ \pi^- \pi^+ \pi^-$) one has rather strong correlations between the two detected pions, which lead to cross-section "several time lower"⁽²⁸⁾ than the quoted value;
- b) - the number of events strongly depends on the triggering threshold (see Fig. 9 in⁽²⁸⁾). With thresholds in the Novosibirsk experiment comparable to that used in Adone⁽²³⁾, their number of detected events would decrease from 38 ± 15 to $5 \div 10$.

For all these reasons I have not reported in Fig. 16 the value estimated by the Novosibirsk group for $\sigma_{4,0}$.

In Fig. 17 the evaluation of $\gamma\gamma$ and $\mu\pi$ groups for the sum of processes (3.2), (3.3) and (3.4) (i. e. processes with, at least, 4 charged pions) are compared. These measurements are in reasonable agreement, except around 2 GeV where the $\gamma\gamma$ group estimates are somewhat lower than that of the $\mu\pi$ group.

In Fig. 18, finally, I have collected values measured for σ_{tot} , i. e. for processes in which more than 2 pions are produced. In the Adone's range the estimates from $\gamma\gamma$ group have been reported. These results should be compared with the lower limit given by the Boson group⁽²²⁾

$$\sigma_{\text{tot}} > 30 \text{ nb } (2E = 1.4 \div 2.4 \text{ GeV}).$$

This last value was obtained by assuming that all detected events are due to the process which, at each energy $2E$, has the highest efficiency. Moreover, from the analysis described before (overall fit of data) they, presently, estimate the following lower limits: 50 nb around 1.5 GeV and 30 nb around 2 GeV⁽³⁰⁾.

Summarizing can be said that the total multihadronic cross section, σ_{tot} , roughly averaged over $2E$ from 1.5 to 2.4 GeV, is $30 \div 50$ nb

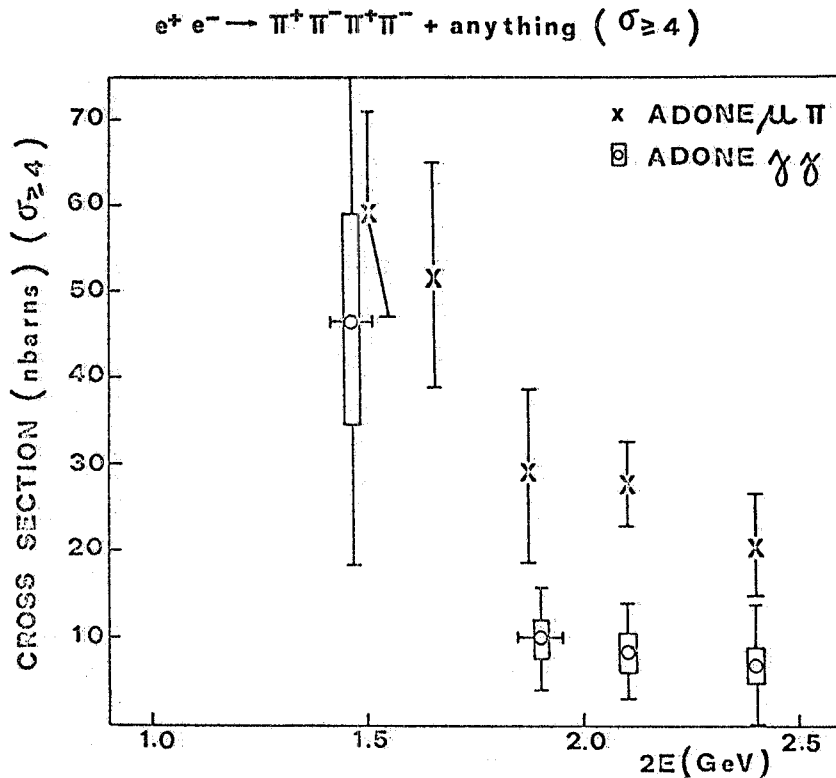


FIG. 17 - Cross sections for process in which at least four charged pions has been produced: $\sigma_{\geq 4} = \sigma_{40^+} + \sigma_{4n^+} + \sigma_{60}$. For the data from $\gamma\gamma$ group possible systematic error (box) and statistical error (bar) has been reported. The systematic error (not reported in the figure) in the case of $\mu\pi$ group is very probably of the same order.

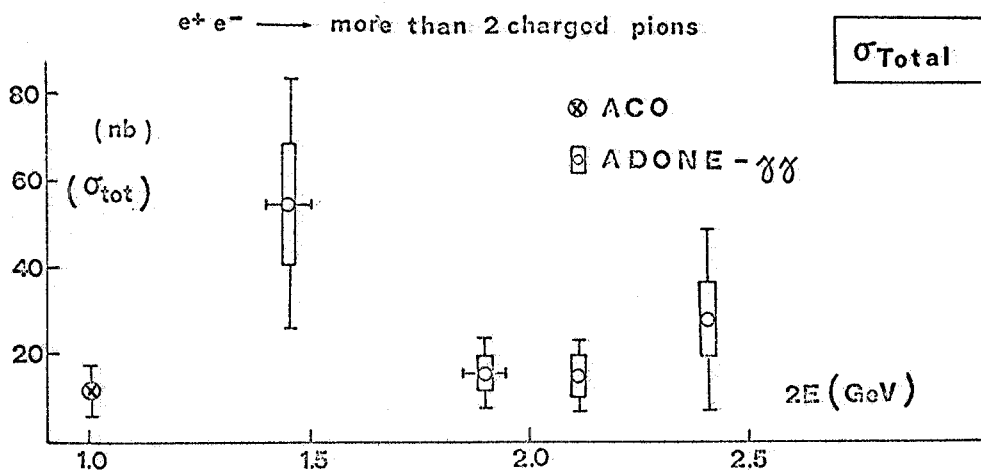


FIG. 18 - Total multi-hadronic cross sections vs $2E$. It means the cross section for production of processes in which more than two pions has been produced. In the Adone energy range data from the $\gamma\gamma$ group has been reported (boxes and bars indicate the possible systematic and statistical errors, respectively). Estimates for σ_{tot} by $\mu\pi$ and Boson groups are somewhat larger than the reported values by $\gamma\gamma$ group (see text).

(according different estimates). At least in part, these different estimates are connected with the difficulties, discussed before, to measure with the present Adone's apparatus the absolute values of multihadronic cross sections.

Only for reference, we recall that $\sigma(e^+e^- \rightarrow \mu^+ \mu^-)$ is of the same order (40 nb at 1.5 GeV, and 20 nb at 2.1 GeV).

Moreover, from previous discussion we can conclude that the data collected with Adone ($2E = 1.4 \div 2.4$ GeV) require in order to be explained at least three different channels. The more probable and contributing candidate seems to be (3.1), (3.2) and (3.3). Only a small contribution from processes with six or more charged pions seems to be necessary, at least for $2E < 2.1$ GeV.

Before closing this subject let me add some more comments:

1) unfortunately all processes have been measured only for few total energy $2E$. In particular, we need more data for 1.0 to 1.4 GeV. At present Adone's experiments are collecting data in the energy region $1.2 \div 1.4$ GeV.

We must wait for these data (and for more data at all the energies) before discussing, seriously, the energy dependence of different channels

2) a much larger statistics is necessary.

For these two reasons experimental groups of Adone are studying or constructing new apparatus, with much more larger solid angle of the present set-ups. One of these will be also furnished with a magnetic field ($B = 4.5$ KG)⁽³¹⁾.

3.2. - Mechanism for the multihadron production. -

The problem of the mechanism responsible for the multihadron production is relevant for two reasons:

i) detection efficiencies of the apparatus depends on it. For instance, in the case of the $\mu\pi$ Adone group the efficiency to detect 4 charged pions differs of about 40%, for $2E = 1.5 \div 2.1$ GeV, if they are produced through a statistical mechanism or process $e^+e^- \rightarrow A_1^+ \pi^+ = 2 \pi^+ + 2 \pi^-$ ($\epsilon_{stat} \sim 1.4 \epsilon_{A_1 \pi}$).

A similar effect in the case of Novosibirsk data has been previously reported, sec. 3.1;

ii) the solution of this problem essentially requires that one understand if at Adone's energies the hadronic production is dominated by the effects of resonances (as we know it occurs in the ρ^0, ω^0, ϕ^0 region) or presents already an asymptotic behaviour.

The first possibility has been postulated by many authors⁽³²⁾. It corresponds to processes like:

$$(3.6) \quad e^+ e^- \rightarrow \rho^0 \rightarrow \begin{matrix} \omega^0 \pi^0 \\ \downarrow \\ \pi^+ \pi^- \pi^0 \end{matrix}$$

$$(3.7) \quad e^+ e^- \rightarrow \rho^0 \rightarrow \begin{matrix} A_1^\pm \pi^\mp \\ \downarrow \\ \pi^+ \pi^- \pi^+ \pi^- \end{matrix}$$

$$(3.8) \quad e^+ e^- \rightarrow \rho^0 \rightarrow \begin{matrix} f^0 \rho^0 \\ \downarrow \quad \downarrow \\ \pi^+ \pi^- \quad \pi^+ \pi^- \end{matrix}$$

These processes are due to diagram of the type shown in Fig. 19 (for process (3.7)). In these cases the production is assumed to be due to contribution of the tail ρ^0 meson, which is coupled to the final state $A_1\pi$ (or $\omega^0\pi^0$ etc.). The numerical results of such calculations critically depend on the coupling of the ρ^0 (not a real ρ^0 , but a off-mass-shell ρ^0) to the photon and to the final state (vertex 1 and 2 in Fig. 19).

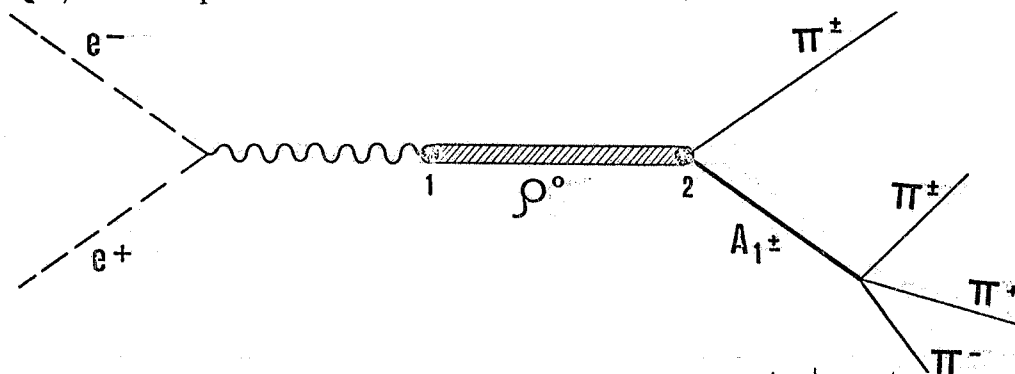


FIG. 19 - Diagram for process $e^+e^- \rightarrow \rho^0 \rightarrow A_1^\pm \pi^\mp = \pi^+ \pi^- \pi^+ \pi^-$. Similar diagram are involved also in the other quasi-two body processes (3.6) and (3.8) reported in the text.

On the contrary, an indication that we are already in an asymptotic region would be the dominance of a statistical mechanism for hadron production⁽³³⁾.

This alternative can be solved by measuring angular distribution or angular correlations, which are expected to be different in the two cases. (Moreover, the " ρ^0 meson tail mechanism" could be considered improbable, if the experimental cross sections would be absolutely larger than the predicted values).

The Adone's groups are now working in order to give an answer to this important question.

The present situation (in part, reported and discussed at the recent Cornell Conference)⁽³⁴⁾ can be shortly summarized as follows:

i) all observed angular distributions (by $\mu\pi$ group) in the case of 2 tracks events (Fig. 20: non-collinearity angle, $\Delta\theta$) and in the case of 3 tracks events (Fig. 21: angles between any two tracks of a 3T event) are consistent with an isotropic emission and, therefore, with the predictions of a statistical model.⁽⁵⁾

However, this conclusion must be taken with some care because:

- a) - we have severe angular cuts in the experimental set-up and, also, we are near to the threshold for a large part of quasi-two to body processes (like (3.7), (3.8) etc.). So "isotropy" does not necessarily involve a statistical model production. (The calculations of the expected angular distribution in the case of quasi two body processes are now in progress);
- b) - many channels contribute to the 2 T- and 3 T-events (especially to 2 T-events). We cannot, a priori, exclude that a statistical production dominates in some of these channels, or, in a given channel only for $2E$ larger than a given total energy. So, events must be subdivided, in order to get a much more clean answer, in more specific categories and not grouped in energy.

In fact, if one looks only at 4 track-event (to which we know that essentially contribute, only processes like $\pi^+ \pi^- \pi^+ \pi^- + (0 \div 2) \pi^0$) some first indications against a pure phase-space production were obtained and presented at Cornell Conference^(34, 5).

A more clear evidence, against a pure phase-space production has been recently obtained, by the $\mu\pi$ group⁽³⁵⁾, by analysing events due to channels $e^+e^- = \pi^+ \pi^- \pi^+ \pi^-$. Momentum distribution⁽³⁶⁾ (Fig. 22) from the 11 events produced at $2E = 1.5 \text{ GeV}$, seems to be different from the case of a pure phase-space production. At the same time invariant mass distribution of pions, two by two, $M(\pi\pi)$, and three by three, $M(\pi\pi\pi)$, also shown a departure from that expected by phase-space calculation (see Fig. 23). Enhancements in correspondence of ρ^0 and A_1 mass are observed.

Possible explanation of these effects are:

- 1) the 4-charged pions are produced in (about) 100% of cases in a $\rho\pi\pi$ state;
- 2) the quasi-two body process $A_1\pi$ occurs (eq. (3.7)).

These two hypothesis seems difficult to be distinguished, because, at a total energy around 1.5 GeV the A_1 mass region ($1.0 < M(3\pi) < 1.14 \text{ GeV}$) cover practically all the phase-space mass distribution of a $\rho\pi$. This means that the A_1 enhancement, in the $M(3\pi)$ distribution, can be a secondary effect (or reflection) of the ρ^0 production, in the $M(2\pi)$ spectrum.

The first explanation (i. e. $\rho\pi\pi$) could be:

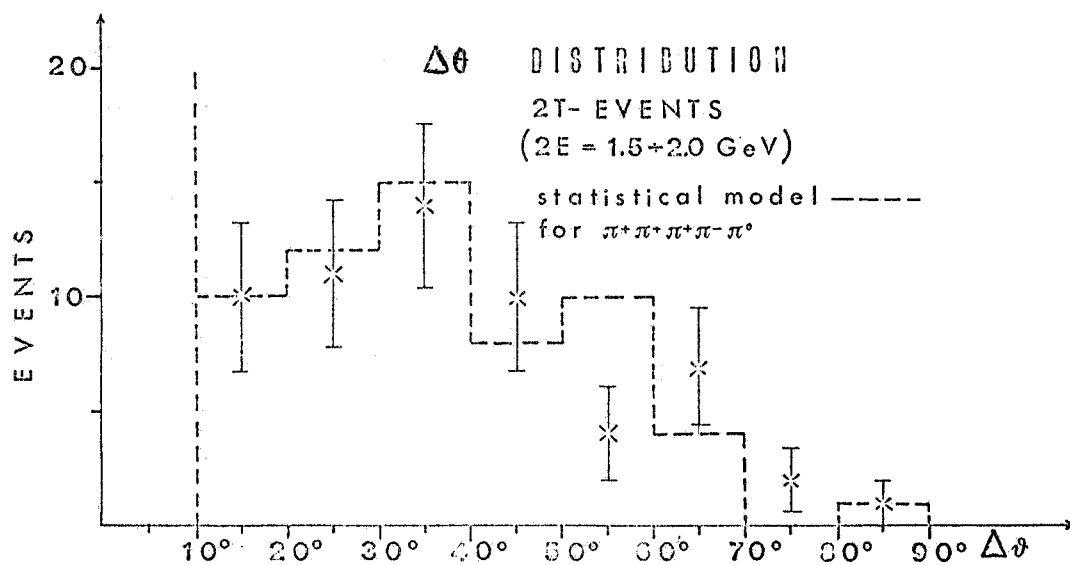


FIG. 20 - Non-collinearity angle distribution between the tracks in 2-track events⁽⁵⁾.

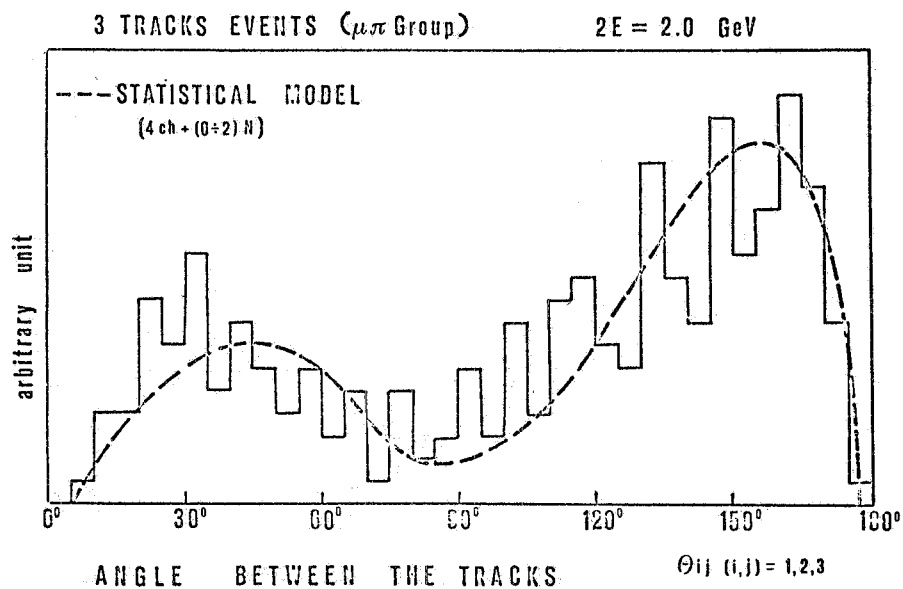


FIG. 21 - Distribution of relative angle between any two tracks of 3 tracks events⁽⁵⁾.

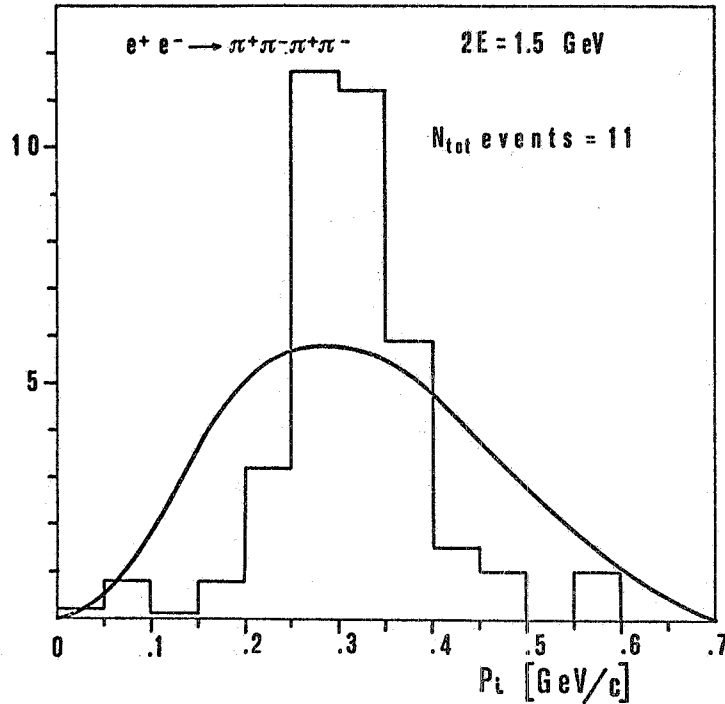


FIG. 22 - Momentum distribution of produced pions from process $e^+e^- = \pi^+\pi^-\pi^+\pi^-$ (ref. (35)). The experimental distribution is compared to that expected in the case of a phase-space production of four uncorrelated pions. This measurement corresponds to a total energy $2E = 1.5 \text{ GeV}$.

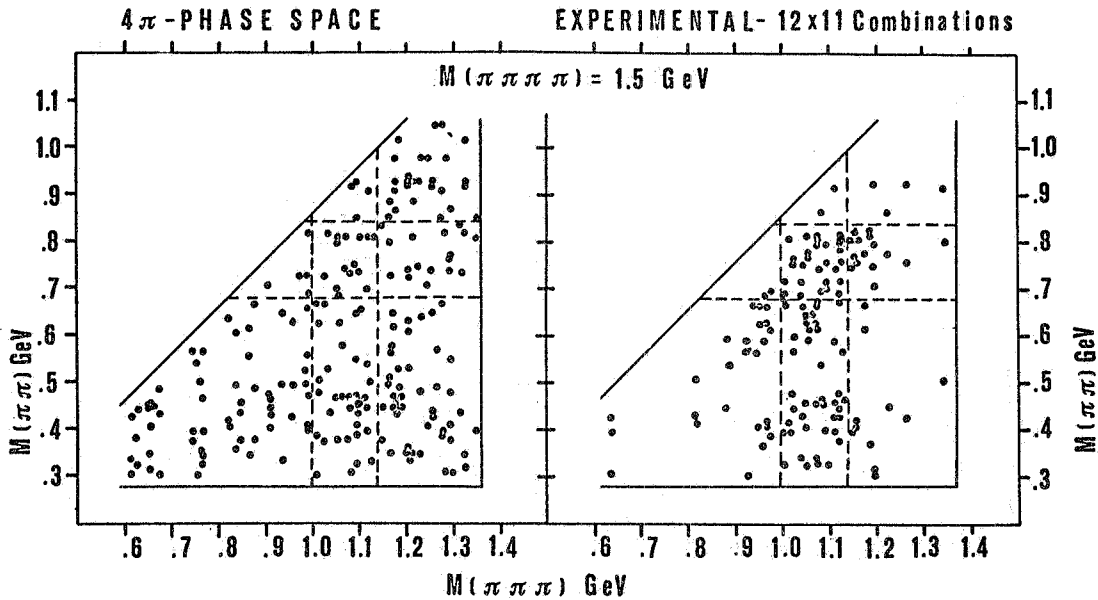


FIG. 23 - Invariant mass of pions two by two, $M(\pi\pi)$, vs invariant mass three by three, $M(\pi\pi\pi)$, in events $e^+e^- = \pi^+\pi^-\pi^+\pi^-$ at $2E = 1.5 \text{ GeV}$ (35). The experimental distribution is compared with that expected by four pions phase space calculations. Because charge of pions are not recognized each 4-tracks event give rise to 12 combinations ($M(\pi\pi)$ vs $M(\pi\pi\pi)$) in the graph.

a) - the analogue of what happens in the $p\bar{p}$ annihilation⁽³⁷⁾. One has in this process:

$$\frac{\bar{p}p = \rho^0 \pi^+ \pi^- = \pi^+ \pi^- \pi^+ \pi^-}{p\bar{p} = \pi^+ \pi^- \pi^+ \pi^-} = 1.00 \pm .17$$

b) - the analogue of the situation found by Davier et al.⁽³⁸⁾, by the analysis of process $\gamma p = p \pi^+ \pi^- \pi^+ \pi^-$. Their results could be explained by postulating the existence for a $\rho\pi\pi$ resonant state with $M = 1.6 \pm 0.1$ GeV, $\Gamma = 0.5 \pm .1$ GeV.

The analysis of the $\mu\pi$ group for $2E$ larger than 1.5 GeV is not yet complete (is in progress). At present it can be said that, in the limits of present statistics, no evidence for $A_1\pi$ process exists for $2E = 1.9 \div 2.1$ GeV⁽³⁹⁾ i.e. no evidence for an enhancement in the $M(3\pi)$ distribution around A_1 mass. At this energy the distributions (momentum, mass distributions) agree with the corresponding distribution found in the process $p\bar{p} = \pi^+ \pi^- \pi^+ \pi^-$ at $2E = 1.88$ GeV, which goes via a $\rho\pi\pi$ state.

Before closing the subject we are discussing, I will try to summarize some of the results and make a closer comparison with the theoretical predictions.

1) In the case of process $e^+e^- = \pi^+ \pi^- \pi^+ \pi^-$ evidence against a pure phase space production seems to be established. Evidence for the production of a $\rho\pi\pi$ state, instead of uncorrelated 4 charged pions, seems to be reached for all the energies explored. It is not clear, at present, if the $e^+e^- = A_1\pi$ process occurs, at $2E = 1.5$ GeV;

2) the cross section for this last process, (if it occurs), would be around 15 nb (at $2E = 1.5$ GeV). This is definitively larger than most of the theoretical prediction based on the ρ^0 tail contribution. In fact, both L-R^(32a) and KUW⁽⁹⁾ estimate a cross section ~ 3 nb at $2E = 1.5$ GeV (and ~ 1 nb at 2 GeV). These calculations are based on ρ^0 tail (VMD) plus "known" coupling constant between ρ^0 and final state. Really this coupling constant is extrapolated from the case of a real ρ^0 (for example, $g_{\rho A_1\pi}$ is taken from the $A_1 \rightarrow \rho\pi$ decay) to a virtual ρ^0 .

The values (~ 15 nb at 1.5 GeV, ~ 7 nb at 2.0 GeV) predicted by Vaughen et al.⁽¹⁰⁾ or Altukhov et al.⁽²⁷⁾ (ρ^0 tail + hard pion current algebra) would be in the range of measured cross section⁽⁴¹⁾.

Does the excess of the experimental value of $\sigma(e^+e^- = \pi^+ \pi^- \pi^+ \pi^-)$, with respect to that calculated by^(32a) and (9), mean that a new heavy vector meson, ρ' , exists⁽⁴⁰⁾? This fact is due to the existence of a $\rho\pi\pi$ resonant state, with $M \sim 1.6$ GeV, as postulated by Davier et al.⁽³²⁾?

3) the quasi-two body processes mechanism proposed by Laysac and Renard^(32a) and Kramer et al.⁽⁹⁾, is not able to reproduce the "large" values of measured cross section for processes with a "high" charged multiplicity (i. e. in which at least 4 charged pions are produced; Fig. 17).

In fact we have

$2E$ (GeV)	1.6	2.0	
$\sigma_{4,0} + \sigma_{4,n}$	~ 55	~ 20	(Experiment)
(in nb)	~ 4	~ 3	(Theory ^(32a))

(The experimental values was obtained as an average of data reported in Fig. 17).

4) This mechanism, on the contrary, better predicts the cross sections for processes ($\pi^+\pi^-$ + neutrals). In fact, it gives^(32a) a cross section from 10 to 5 nb in the range $2E = 1 + 2$ GeV, in qualitative agreement with the experimental data (Fig. 14).

However, a much more conclusive comparison between theory and experiment will be possible only when separate data on $\pi^+\pi^-\pi^0$ and $\pi^+\pi^-\pi^0\pi^0$ channels will be available. In fact, these calculations predict, that in the energy range we are discussing ($2E > 1$ GeV) the process $e^+e^- = \pi^+\pi^-\pi^0\pi^0$ (via a $\omega^0\pi^0$ intermediate state) is much more important than $e^+e^- = \omega^0 = \pi^+\pi^-\pi^0$.

Summarizing the subject of these lectures we can say:

1) now measurements from Novosibirsk and Frascati on process $e^+e^- = \pi^+\pi^-$ extend our knowledge of pion's form factor well outside the ρ^0 peak, (about 10 widths from it's peak) (sec. 2.1);

2) a first very interesting measurement of $\sigma(e^+e^- = p\bar{p})$ is now available (sec. 2.2);

3) first informations on different processes, responsible of the multihadronic production, and on their energy dependence now begin to be available from Adone's experiments;

4) analysis of these processes, as well as of elastic channel ($e^+e^- = \pi^+\pi^-$), seems to indicate that experimental cross sections are definitively larger than values predicted by the VDM;

5) the state $\rho^0\pi^+\pi^-$ seems to be dominant in the case of production of four charged pions, ($e^+e^- = \pi^+\pi^-\pi^+\pi^-$), as well as in the case of $p\bar{p}$ annihilation;

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- (11) - In fact $\sigma_{\pi\pi}$ for $s \gg m_\rho^2$ can be written as follows⁽⁹⁾:

$$\sigma_{\pi\pi} \longrightarrow \frac{1}{s} \times \frac{1}{s^2} \times \frac{m_\rho^4}{g_\rho^2} \times |F_\pi(s)|^2$$

↑ photon propagator
↑ ρ^0 propagator
↑ γ - ρ coupling constant

- (12) - The ACO data (2E=990 MeV) does not contain any contribution from K^+K^- process for kinematical reasons.
- (13) - This subject has been extensively discussed by V. N. Bayer in *Rendiconti Scuola Internazionale di Fisica "E. Fermi"* (Academic Press, 1971), p. 1; Only one direct check on the beam polarization has been carried out at ACO, with a positron beam alone circulating at $E = 536$ MeV. (J. LeDuff et al., Experimental evidence for the gradual building up of the polarization of a positron beam in the Orsay storage ring, Presented at the 1971 Intern. Symp. on Electron and Photon Interactions at High Energies, Cornell); A check made at VEPP-2 by V. E. Balakin et al. (Phys. Letters 34B, 328(1971)), by observing the rate of K^+K^- events (at ϕ^0 resonance) as a function of time after the beams were injected in the storage ring, give a correction to the measured cross section compatible with zero: $(2 \pm 3)\%$. Also experiments carried out at ACO with both e^+ and e^- colliding beam have failed to show evidence for a beam polarization. As pointed out by J. LeDuff et al. (loc. cit.) this may be due to long time constants, low counting rate or depolarization effects.
- (14) - M. Castellano, G. Di Giugno, J. Humphrey, I. Peruzzi, E. Sassi, U. Troya, G. Troise and S. Vitale, *Lett. Nuovo Cimento*, 2, 873 (1971).
- (15) - B. Barish et al., *Phys. Rev. Letters* 17, 720 (1966); M. Conversi et al., *Nuovo Cimento* 40A, 690 (1965).
- (16) - S. D. Drell, Rapporteur's report to the Amsterdam Intern. Conf. on Elementary Particles (1971); SLAC-PUB-948(TH) and (EXP) (1971).
- (17) - D. Schilknecht, H. J. Willutzki and G. Wolf, Desy report 71/28 (1971).
- (18) - a) R. Wilson, Rapporteur talk at the 15th Intern. Conf. on High Energy Physics, Kiev (1970);
 b) B. Bartoli, B. Coluzzi, F. Felicetti, G. Goggi, G. Marini, F. Massa, D. Scannicchio, V. Silvestrini and F. Vanoli, *Nuovo Cimento* 70A, 615 (1970);
 c) G. Barbiellini, M. Conversi, M. Grilli, A. Mulachì, M. Nigro, L. Paoluzi, P. Spillantini, R. Visentin and G. T. Zorn, Hadron production by e^+e^- colliding beams in the GeV region, Frascati report LNF-70/38 (1970);
 d) V. E. Balakin, G. I. Budker, I. B. Vasserman, O. S. Koifman, L. M. Kurdadge, S. I. Mishnev, A. P. Onnuchin, S. I. Seredryakov, V. A. Sidorov, A. N. Skrinsky, G. M. Tumaikin, V. F. Turkin, A. G. Khabkhashev and J. M. Shatunov, Experiments with colliding e^+e^- beams at energy of 2×590 , 2×630 and 2×670 MeV. Novosibirsk

report 62/70 (1970); A more recent analysis of the Novosibirsk data is in ref. (28).

- (19) - Details on these events according the number of detected γ can be found in Table V in ref. (7).
- (20) - n_{WAS} , number of WAS events, and L are connected by the following relation: $n_{\text{WAS}} = L \langle \sigma \rangle \varepsilon$, where $\langle \sigma \rangle$ is the QED cross section for Bhabha scattering integrated over the apparatus and ε is it's efficiency in detecting this process.
- (21) - Different methods (e^+e^- small angle scattering, double bremsstrahlung) have been used to measure the luminosity; see, for example, (1a), and also J.E. Augustin et al., Phys. Letters 31B, 673 (1970); P.I. Golubrichy et al., Atomnaya Energya 22, 168 (1967).
- (22) - B. Bartoli, F. Felicetti, H. Ogren, V. Silvestrini, G. Marini, A. Nigro, N. Spinetti and F. Vanoli, Phys. Letters 36B, 598 (1971).
- (23) - Minimum kinetic energy for a pair of pions to trigger the apparatus of following groups: $T_1 = 80$ MeV, $T_2 = 190$ MeV ($\mu\pi$); $T_1 = T_2 = 75$ MeV (Boson group); $T_1 = T_2 = 95$ MeV ($\gamma\gamma$ group); $T_1 = T_2 = 45$ MeV (VEPP-2 group).
- (24) - C. Bacci, R. Baldini-Celio, G. Capon, C. Mencuccini, G.P. Murtas, G. Penso, A. Reale, G. Salvini, M. Spinetti and B. Stella, Multiple production from e^+e^- annihilation and a first observation of $\gamma + \gamma$ interaction ($e^+e^- \rightarrow e^+e^- + \text{others}$), Presented at the 1971 Intern. Symp. on Electron and Photon Interactions at High Energies, Cornell (1971).
- (25) - In effect these analysis have been tried assuming a larger number of produced reactions, for instance⁽²⁴⁾ $\pi^+ \pi^- \gamma$, $\pi^+ \pi^- \pi^0$, $\pi^+ \pi^- \pi^0 \pi^0$ etc. In the present discussion I have grouped in (3.1) and (3.3), for statistical reasons, channels with γ or $(1 \div 4) \pi^0$. Note that there is a given degree of arbitrariness in the a priori choice of occurring reactions and to restrict, for example, to processes with a maximum multiplicity of six. Only, the reasonableness of the results justify the assumptions made.
- (26) - This procedure was previously tested on 4-track Montecarlo generated events. It results that all events coming from a $(\pi^+ \pi^- \pi^+ \pi^-)$ process were correctly reconstructed and only about 30% of events from processes $(\pi^+ \pi^- \pi^+ \pi^- + (1 \div 2) \pi^0)$ can simulate a $\pi^+ \pi^- \pi^+ \pi^-$ event.
- (27) - A.M. Altukov and I.B. Khriplovich, On the multiple π -meson production in the e^-e^+ colliding beams experiments, Novosibirsk report 36/71 (1971).
- (28) - V.A. Sidorov, Novosibirsk colliding beam experiments, Rapporteur's talk at 1971 Intern. Symp. on Electron and Photon Interactions at High Energies, Cornell (1971).
- (29) - In fact, the detection efficiency for other processes, like $\pi^+ \pi^- \pi^0 \pi^0$ or $\pi^+ \pi^- \pi^+ \pi^- \pi^0$, not considered in the Novosibirsk calculations, is lower than that for $\pi^+ \pi^- \pi^+ \pi^-$ process.

- (30) - Private communication by Boson group. The final results of their analysis can be found in a work by B. Bartoli et al., Nuovo Cimento to be published (Note added in proof).
- (31) - W. Ash, et al., A magnetic analyzer to be used for Adone colliding beam experiments, Frascati report LNF-69/2 (1969).
- (32) - Assuming a contribution from ρ^0 resonance tail:
- a) J. Layssac and F. M. Renard, Lett. Nuovo Cimento 1, 197 (1971); and also Hadronic production in e^+e^- collisions, Montpellier report PM/71/2 (1971);
 - b) see also the previously quoted papers (9, 10, 27).
- Assuming the existence of a new vector meson ρ' ($m \sim 1.5$ GeV, $\Gamma \sim 350$ MeV):
- c) A. Bramon and M. Greco, Lett. Nuovo Cimento 1, 739 (1971).
- (33) - Statistical model: J. D. Bjorken and S. J. Brodsky, Phys. Rev. 1D, 1416 (1970); An alternative mechanism for the asymptotic region is the "jet model", discussed by N. Cabibbo et al., Lett. Nuovo Cimento 4, 35 (1970) and by G. Calucci et al., Report RPP/C/1 (1970).
- (34) - Frascati's reports to Intern. Symp. on Electron and Photon Interactions at High Energies, Cornell (1971):
- a) C. Bernardini, Results on e^+e^- reactions at Adone (1.4 + 2.4 GeV) Rapporteur's talk and Frascati report LNF-71/63 (1971);
 - b) C. Bacci et al. (24);
 - c) B. Borgia et al. (5);
 - d) B. Bartoli et al. (22).
- (35) - Private communication from $\mu\pi$ group. Their analysis is in progress and final results will be published.
- (36) - Remember that the momenta were not directly measured. They have been obtained by the application of the E-p conservation equations, starting from the measured spatial angle of produced pions (in the 4 charged pions events).
- (37) - C. Baltay et al., Phys. Rev. 145, 1103 (1966).
- (38) - Davier et al., The reaction $\gamma p \rightarrow p \pi^+ \pi^- \pi^+ \pi^-$ at high energy and photon dissociation into 4 pions, SLAC Report (1971).
- (39) - Could this fact mean that for $2E = 2$ GeV any effects of resonances, and, therefore of process like (3.6) + (3.8) disappear? A similar conclusion seems to come also from the Adone $\gamma\gamma$ group (24), which has found no evidence of the quasi two body process (3.6) from the analysis of events mostly at 2 GeV.
- (40) - See on this subject recent papers by G. Barbarino et al. ($\mu\pi$ group); Observation of a broad peak in the production of four charged pions by e^+e^- collisions around 1.6 GeV, Frascati report LNF-71/96 (1971) and Lett. Nuovo Cimento, to be published; A. Bramon et al.: The reaction $e^+e^- \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ and the ρ' meson, Frascati report LNF-71/97 (1971) and Lett. Nuovo Cimento, to be published (note added in proof).

- (41) - The same models^(10, 27), however, should explain also, at the same time, the results of process $e^+e^- = \pi^+\pi^-$. On the contrary, as reported in sec. 2.1, these results seem to be somewhat larger than predicted by these models⁽¹⁰⁾.
- (42) - Remember that we are speaking about the 2nd version of the ACO apparatus, which has a "good" solid angle $0.6 \pm 0.7 (4\pi)$, a factor 3 larger than that of the $\gamma\gamma$ Adone apparatus.
- (43) - Details of this point and on more recent results from the " $\gamma\gamma$ -group" can be found in the following work: C. Bacci, R. Baldini-Celio, G. Capon, C. Mencuccini, G. P. Murtas, G. Penso, G. Salvini, M. Spinetti and B. Stella, Multihadronic cross sections from e^+e^- annihilation at C. M. energies between 1.4 and 2.4 GeV, to be published (Note added in proof).
- (44) - In the Adone energy range the values obtained for $|F_\pi|^2$ by the $\mu\pi$ group are systematically larger than that by BCF group. Probably this difference largely depends from different evaluation of the corrections due to nuclear absorption of pions. Both groups are now working in order to obtain final results of their measurements on $\pi^+\pi^-$ production, based on a statistics larger than that reported here (Note added in proof).

I like to thank very much all the colleagues of Adone's experimental groups. Their collaboration in discussing more recent and unpublished results of their analysis of data makes possible to prepare these lectures.