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Frascati - Roma - Padova Collaboration:

RELAZIONI PRESENTATE AL "15th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS"

Kiev (USSR), Agosto-Settembre 1970.

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The following three articles were prepared for presentation at the International Conference on High Energy Physics to be held at Kiev in August 1970. They are based on the analysis of events as of June 30, 1970 and the results are subject to possible changes as further refinements are introduced.

The presentation of these results after only a few months from the start of normal operation of Adone was made possible by the dedicated and efficient work of the machine group. The active collaboration of this group, and in particular Dr. M. Placidi, in all phase of the preparation and running of this experiment is greatfully acknowledged.

We would like also to acknowledge the many contributions made during the preparation of this experiment by Drs. R. D'Ettore-Piazzoli, B. Sechi-Zorn, E. Schiavuta and V. Valente.

This experiment would not have been possible without the active partecipation of our tehnicians: M. Bertino, R. Giantin, M. Moroni, G. Nicoletti and A. Pecchi.

For the construction of much of the experimental apparatus we would like to thank the high-energy-physics shop headed by G. Di Stefano.

Finally we would like to express our thanks to S. Stipcich and the documentation service for their cooperation in expediting the publication of this report.

BHABHA SCATTERING BY e^+, e^- COLLIDING BEAMS IN THE GeV REGION(*)

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1. - Introduction

In an experiment carried out at the Frascati storage ring, Adone, we have investigated (together with other reactions discussed in the following reports) the Bhabha scattering process

$$e^+e^- \rightarrow e^+e^- \qquad (1)$$

at total energies of the colliding beams, 2E, ranging from about 1.5 to 2.4 GeV. We report here the results of a preliminary analysis(*) of data collected in the period from January to March 1970[1]. A more complete analysis of these data and of data collected in subsequent runs will be reported elsewhere.

The events were produced by head-on collisions of the e^+,e^- Adone bunches[2]. This entails the disadvantage of a rather long "source", for the bunches have an effective length

(*) The results reported in this paper (June 30, 1970) are subject to possible changes as the analysis of the data goes further ahead.

approximately proportional to $E^{3/2}$, which gives the source an effective length of about 40 cm at E = 1 GeV. The transverse linear dimensions of the bunches are a few mm. The machine operated in the energy range .75 to 1.2 GeV per beam. The luminosity, L, increased steeply with energy. Typical values of L at E = 1 GeV (with e^+, e^- currents of 30 ÷ 40 mA) were around $5 \times 10^{32} hr^{-1} cm^{-2}$ soon after injection. The luminosity lifetime was of a few hours (typically 5 hours at E = .8 GeV and about 2.5 hours at E = 1 GeV).

In recent years the colliding beam technique has been applied already to test quantumelectrodynamics (QED) at short distances(3,4). Both, Møller(3) and Bhabha(4) scattering processes, have been investigated at total energies in the center-of-mass system slightly above 1 GeV. The results of these experiments agree with the predictions of QED. The present investigation can be regarded as an extension of those tests, up to a total energy in the center-of-mass system more than twice as large.

The two lowest order diagrams of process (1), represented in Fig. 1, involve the exchange of a space-like virtual pho

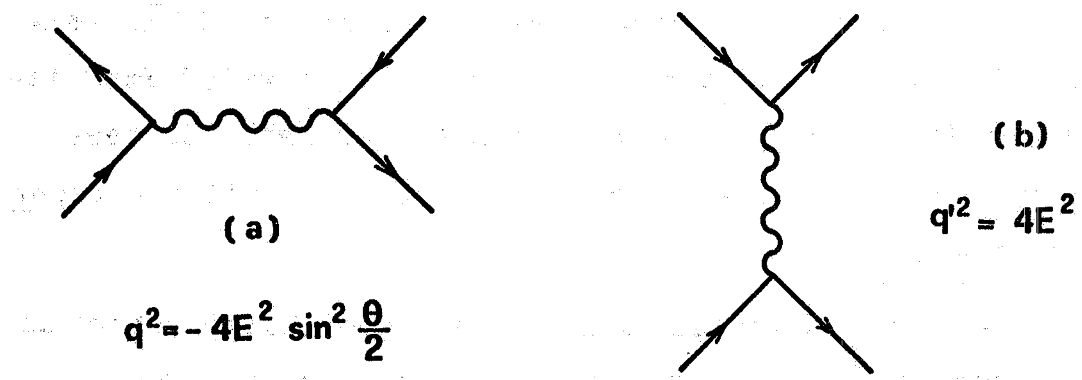

FIG. 1 - Feynman diagrams of lowest order for e^+e^- elastic scattering. Space like (a) and time-like (b) virtual photons are involved, of squared four-momentum transfers given respectively by $-4E^2 \sin^2(\theta/2)$ and $4E^2$ ($2E = E_+ + E_-$ being the total energy of the two colliding beams; θ the scattering angle).

ton of four-momentum squared $q^2 = -4E^2 \sin^2(\theta/2)$ (Fig.1a) and of a time-like virtual photon of $q^2 = 4E^2$(Fig.1b). The probability amplitudes of these diagrams are usually modified by introducing a form factor of the type[5]

$$F(q^2) = 1/(1-q^2/\Lambda^2) \qquad (2)$$

in order to represent a possible break-down of QED. The parameter Λ, which has recently been given an interesting interpretation by T.D.Lee and G.C.Wick[6], gives then a measure of the deviations from standard QED, for which $\Lambda = \infty$.

The modified expression of the theoretical differential cross-section of Bhabha scattering[7] is then

$$\left(\frac{d\sigma}{d\omega}\right)_{th} = \frac{1}{8}\left[\frac{r_0}{\gamma}\right]^2 \left\{ \frac{1+\cos^4(\theta/2)}{\sin^4(\theta/2)}\left|F(q^2)\right|^2 - \frac{2\cos^4(\theta/2)}{\sin^2(\theta/2)} \cdot \right. \qquad (3)$$

$$\left. \mathrm{Re}\left|F(q^2)F^*(q'^2)\right| + \frac{1}{2}\left[1+\cos^2\theta\right] \cdot \left|F(q'^2)\right|^2 \right\}$$

where $\gamma = E/mc^2$ and $r_o = e^2/mc^2 = 2.82 \cdot 10^{-13}$cm. For a comparison with the experimental cross-section Eq.(3) has to be decreased by a factor $(1 + \delta)$ where $\delta(< 0)$ represents the contribution due to the radiative corrections. As the electric charge of the scattered particles is not determined in our experiment, no discrimination is made between forward and backward scattering. For each θ value we measure events scattered at θ or $\pi - \theta$. For the limit value $\theta = 90°$ the factor which multiplies $F(q^2)$ in Eq.(3) is 10 times larger than the factor which multiplies $F(q'^2)$. The experiment, therefore, allows a test of QED mainly for space-like momentum transfers.

Comparison of the experimental and theoretical differential cross-sections via Eq.(4) is made difficult, in pra ctice, by the above mentioned longitudinal extension of the source of the events. Due to the geometry of our apparatus (see Sec.2), a long source favours, in fact, the detection of collinear events with particles emitted perpendicularly to the beam direction. This hinders the observation of a possible depletion of the cross section for large momentum transfers (large values of θ).

Other approaches to test QED are possible, however, since we recorded simultaneously, for various energies E of the colliding beams, large angle $e^+e^- \to e^+e^-$ events ($53 < \theta < 127°$), by the main apparatus described in Sec.2, and small angle events ($3,5° < \theta < 6,1°$), by a monitoring system described in Sec.3 (and more in detail elsewhere[8]). The small angle scattering process involves only very small momentum transfers and it is not affected, therefore, by a possible break-down of QED at large momentum transfers. It can thus be used to determine the luminosity L of Adone [See Eq.(5), Sec.3]. Then the absolute cross-section integrated over the solid angle of the main apparatus can be obtained. Furthermore, the ratio between the rates of large angle and small angle scattering events (a ratio which is fairly insensitive to the length of the source) can be plotted as a function of the beam energy E, and compared too with the predictions of QED.

2. - Apparatus

The main apparatus, represented in Fig.2, was assembled using parts belonging to two distinct experiments designed to investigate[9][10] process (1), the reaction

$$e^+e^- \to \mu^+\mu^- \qquad (4)$$

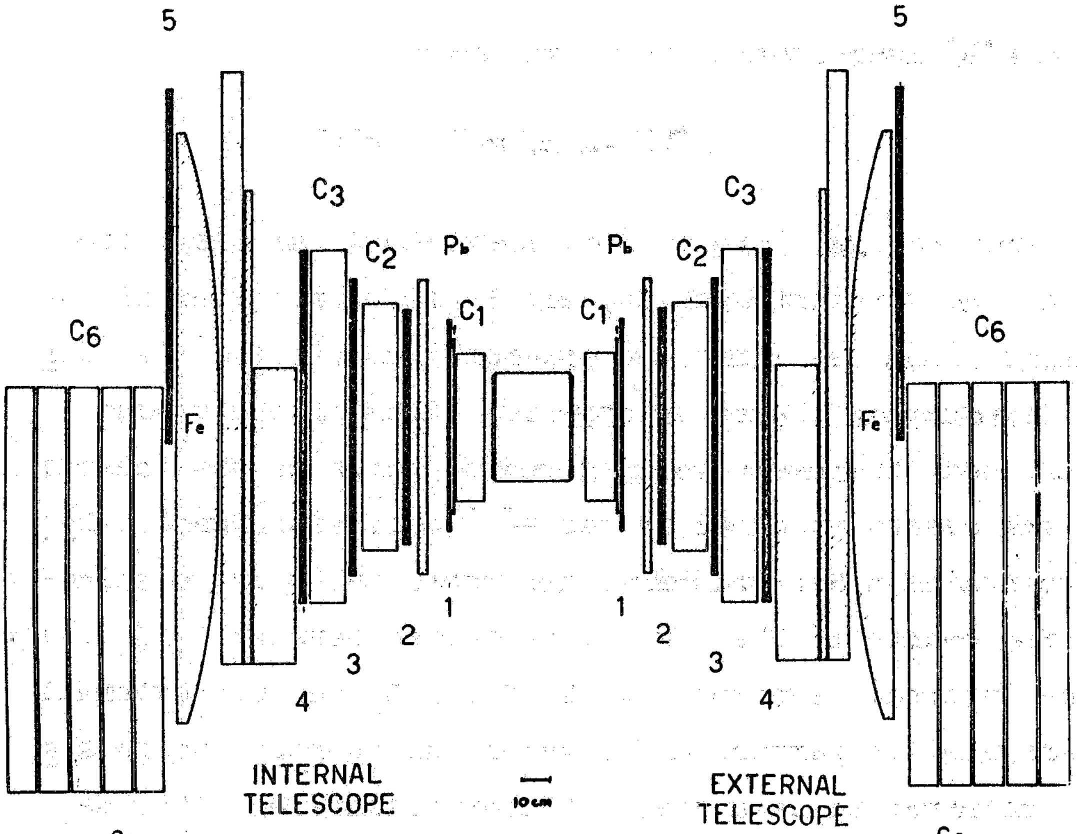

FIG. 2 a)

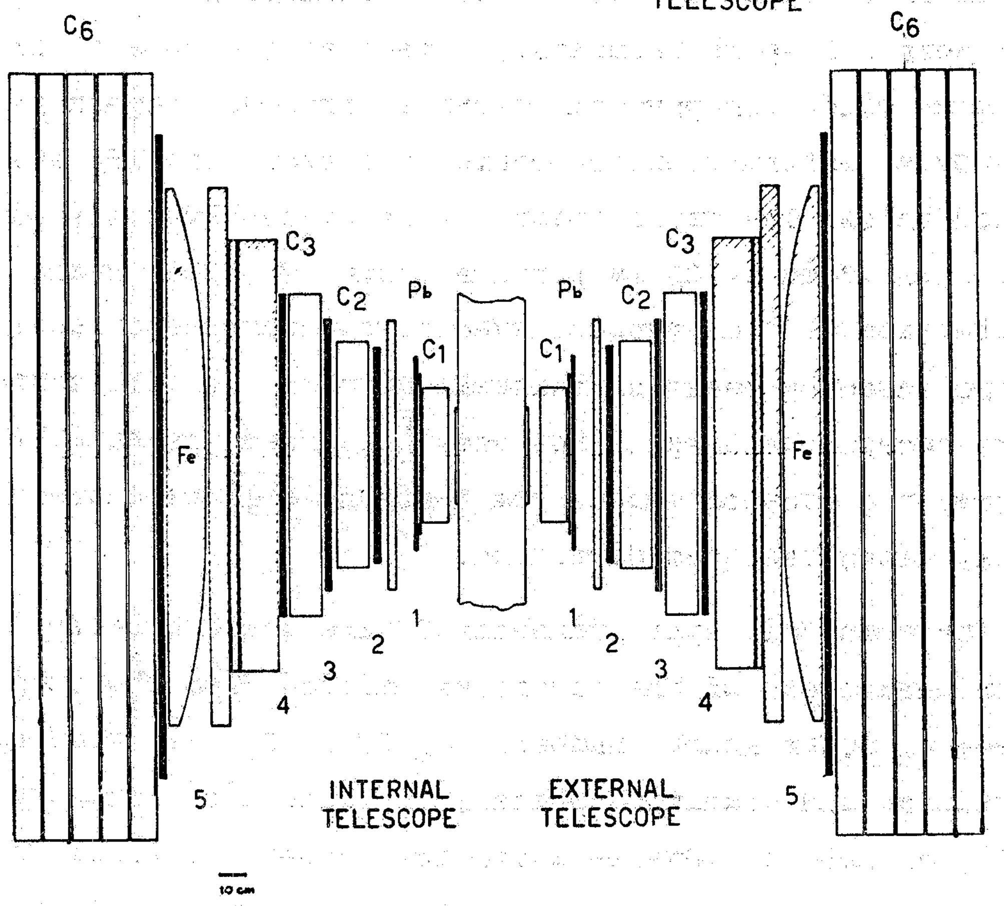

FIG. 2 b)

FIG. 2 - Main apparatus : a) Front view; b) Top view.

and the e^+e^- annihilation into two bosons

$$e^+e^- \rightarrow \pi^+\pi^-, \quad K^+K^-$$

From Fig.2a) (front view, seen along the beam directions at the straight section) and Fig.2b) (top view of the equipment), one sees that the apparatus consists of two identical telescopes, placed on opposite sides of the vacuum chamber, near the beam crossing region which is the source, S, of the events produced in the e^+e^- collision. Each telescope contains spark chambers, absorbers and plastic scintillation counters. The latter, indicated here by $I_1, I_2, \ldots I_5$ for the internal telescope and $E_1, E_2, \ldots E_5$ for the external one, are used in particular to select an appropriate coincidence, referred to as a "master" coincidence, Q_M. This master triggers all spark chambers, as well as the advance of the film on which the physical event is recorded together with relevant information concerning the event itself, as explained below. The whole apparatus is viewed by a single camera, in a 70 mm x 100 mm picture frame. To allow space reconstruction of the physical events, two perpendicular views are taken by means of suitable mirrors, for all spark chambers except the large final ones [C_6, used essentially to observe the stop of muons from process (4)] which are seen only along the beam direction.

The thin foil spark chambers C_1 are used to determine the directions of the particles emitted from the crossing region. Other spark chambers ($C_2, C_3, \ldots C_6$) are made up of thick iron and aluminium plates, in which e^+e^- from process (1) are able to develop a cascade shower and pions from e^+e^- annihilation may produce visible interactions. On the other hand, muons from process (4) loose their energy only by ionization, leaving single tracks in the chambers. If the muons are produced in e^+e^- collisions of total energy 2E within about 1700 to 1950 MeV, they stop in one of the large final spark chambers with a probability greater than 95%.

Each type of event has thus a different signature. Further information, useful to recognize unambigously the various events, is recorded on the same picture by means of lamps lighting on the occurrence of events selected with the help of coincidences among the pulses of the various counters.

Relevant information is also derived from pulse height measurements[11] on counters E_2, E_3, I_2, I_3, which are crossed each by a single particle in the case of events (4) and usually by more than one particle in the case of events (1) (the development of cascade showers being favoured by the Pb thickness placed before those counters: 2.5 and 3.8 radiation lengths before counters 2 and 3 respectively). The sum of the pulse heights of counters 2 and 3 is made separately for each telescope and recorded on the same picture.

Several types of master have been considered and tested before making a final choice. A good master must of course reject as much as possible unwanted events, due both to cosmic rays and machine background giving useless pictures, while selecting "good" events without appreciable loss.

The rate of cosmic rays crossing the solid angle of the apparatus $\left[\sim (1/4) \cdot 4\pi \right.$ from O, the center of the source$\left. \right]$ is relatively large, of order of 1 per second. Reduction of the master rate due to cosmic ray muons is achieved by two main methods (see also next paper):

(i) By requiring the master to be in coincidence with the machi ne R.F., so that the master pulse has to be in time with the presence of the e^+e^- bunches at the crossing region S;

(ii) by a time-of-flight technique[(12)], applied to the two counter pairs E_3, I_3 and E_4, I_4 (see next paper).

The rate of triggers due to the machine background depends, of course, on the conditions of operation of Adone. Under typical conditions of operations (e^+ and e^- currents of some 10 mA and residual pressure of $\sim 10^{-9}$ torr) it has been found that the over-all background rate is tolerable (say less than 1 per minute) if one combines the machine R.F. coincidence and the correct time of flights, T_3 and T_4 between the counter pairs E_3, I_3 with the requirement of a sevenfold coincidence involving counters 1, 2, 3 of both telescopes and counter 4 of either telescope. The resultant master coincidence Q_1 $\left[Q_1 = E_1E_2E_3I_1I_2I_3\ (E_4 + I_4)\cdot T_3T_4\cdot(\text{R.F.})\right]$ has, on the other hand, a detection efficiency of nearly 100% for the muon pairs and more than 80% for the electron pairs. To reduce further the loss of electron pairs and of other possible events involving hadronic final states, another master coincidence, Q_2 $\left[Q_2 = E_1E_2E_3 I_1I_2I_3\ (E_4 + I_4)\cdot(E_5 + I_5)\cdot(\text{R.F.})\right]$ was added to Q_1, with no requirements for correct T_3 and T_4 timing but with counters 5 used as veto-counters. The rate of the master coincidences $Q_M = Q_1 + Q_2$ is about 1 per minute when no beams are circulating in Adone. The efficiency of Q_M in the detection of e^+e^- pairs is 93%.

3. - The monitoring system.

The determination of absolute cross-sections (integrated over the solid angle of the apparatus) implies a knowledge of the absolute luminosity, L, of Adone. This is obtained by the monitoring system sketched in Fig. 3, which detects e^+e^- elastic scattering events occuring with angles θ from 3.5° to 6.1°. The momentum transfers involved are so small that one can assume the validity of QED. Assuming a 100% detection efficiency for the system, the integrated cross section, σ , is related to the measured counting rate, $\dot{n}$, by the simple relationship

$$\dot{n} = L\sigma \tag{5}$$

which allows to determine the luminosity L.

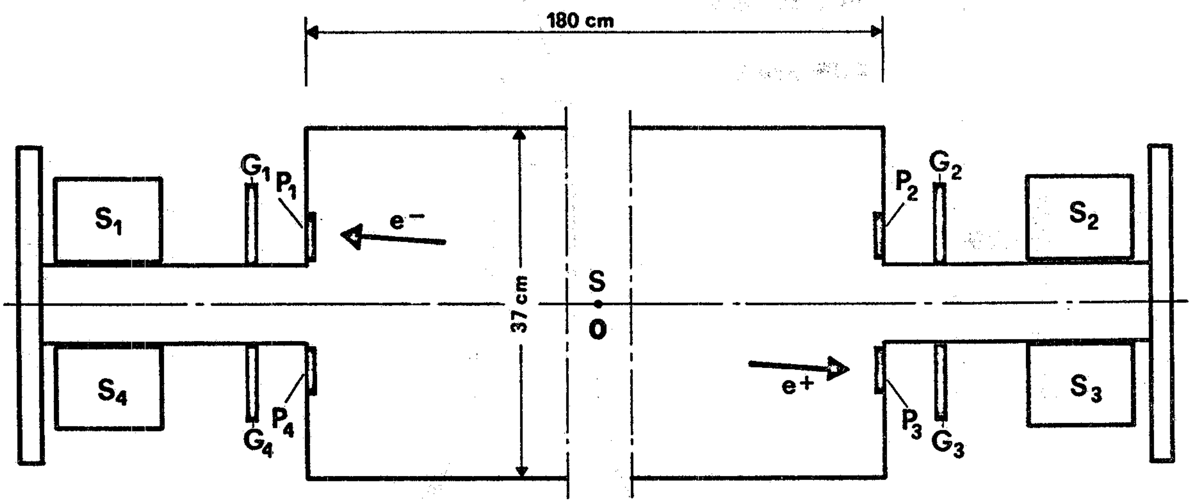

FIG. 3 - The luminosity monitoring system. Counters P_i, G_i are plastic scintillators. Counters S_i are "sandwiches" (0.5 cm thick Pb plates alternated with 0.3 cm thick plates of plastic scintillator) which discriminate the high energy electrons from e^+e^- elastic scattering, against low energy background electrons (see Fig. 5).

The monitoring system represented in Fig. 3 is slightly different from the one previously described[8], in that the Cerenkov counters of the previous instrument have been replaced by the plastic scintillators G_1, G_2, G_3, G_4, of Fig. 6. Rejection of background events, which was formerly based on the directionality of the Cerenkov light, is now achieved by a time of flight technique, measuring the time distance between pulses from counters G opposite to the center O of the beam crossing region (G_1,G_3 and G_2,G_4). Using time-to-height converters for each pair of counters G(G_1,G_3 and G_2,G_4) the time distribution of the monitoring events was recorded by means of a multichannel pulse-height--analyser. A typical distribution obtained during a run is reproduced in Fig.4.

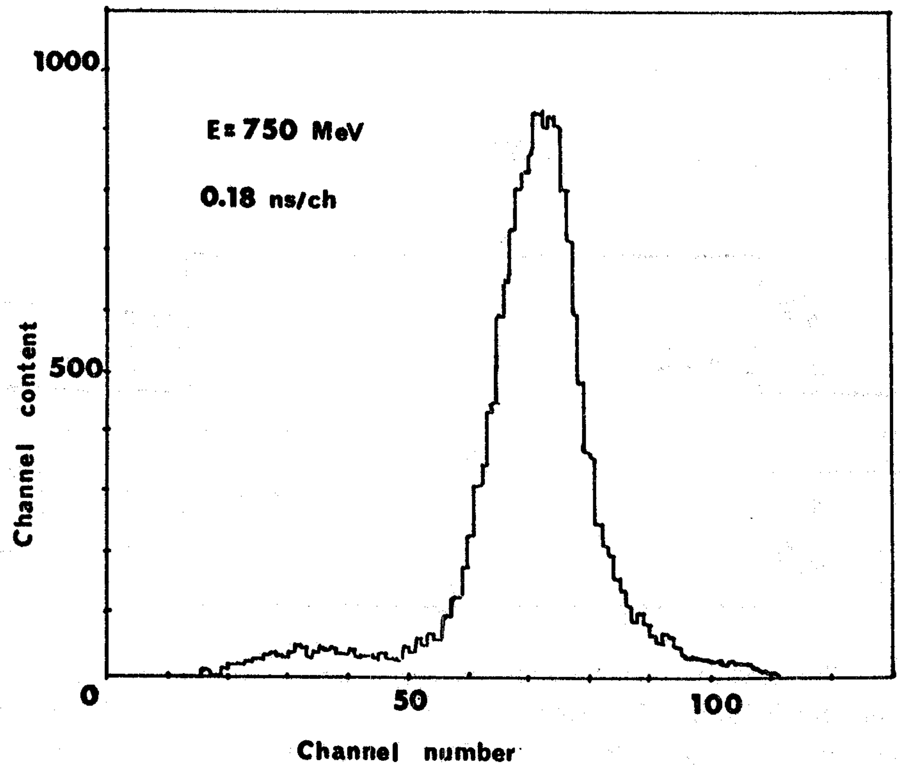

FIG. 4 - Time-of-flight distribution of pulses from counters G_1, G_3 of the monitoring system. It is clear from this sample the contribution of background events, which are identified by being far from the central part of the spectrum.

We recall here two important features of the system:

(i) The small scattering events are recorded as fivefold coincidences of the type $P_iG_iS_iG_{i\pm2}S_{i\pm2}$ (i = 1,2,3,4) for which the solid angle is determined by the small scintillation counters P_i (counters G and S having a much larger section). The sum of the counting rates for any pair of fivefold coin cidences corresponding to counters on opposite sides of O (Fig.3), is then stationary for small displacements of the e^+e^- interaction point[8]. This is because a displacement which produces an increase of the flux of scattered particles through, say, counter P_1, causes correspondingly a decrease of the flux through the opposite counter, P_3.

(ii) Counters S_i are "sandwiches" made up of .5 cm thick Pb plates, alternated with .3 cm thick plastic scintillator plates, for a total of about 13 radiation lenghts. As shown by measurements carried out with monoenergetic electrons of various energies[8] they can be used, in combination with an appropriate electronics, to detect with high efficiency energetic electrons, while rejecting with increasing efficiency electrons of lower and lower energy. For example, one can set the voltages of the photomultipliers viewing counters S_i so that electrons of energy greater than 500 MeV are recorded with $\sim$ 100% efficiency, whereas electrons of energy smaller than $\sim$ 100 MeV are rejected with $\sim$ 100% efficiency. As an illustration we reproduce in Fig.5 one of the many pulse-height distributions recorded during the runs to check the correct behaviour of these sandwich counters.

The rejection power of counters S_i, combined with the G_1G_3 and G_2G_4 time-of-flight measurements mentioned above, reduces to a negligible value the contribution to the fivefold coincidencies due to other than the e^+e^- genuine scattering events. Another small contribution to these events is given, however, by random coincidences between pulses produced by e^+ and e^- scattered by the residual gas in the interaction region. This contribution (usually smaller than 1%) was determined by suitable "delayed" fivefold coincidences.

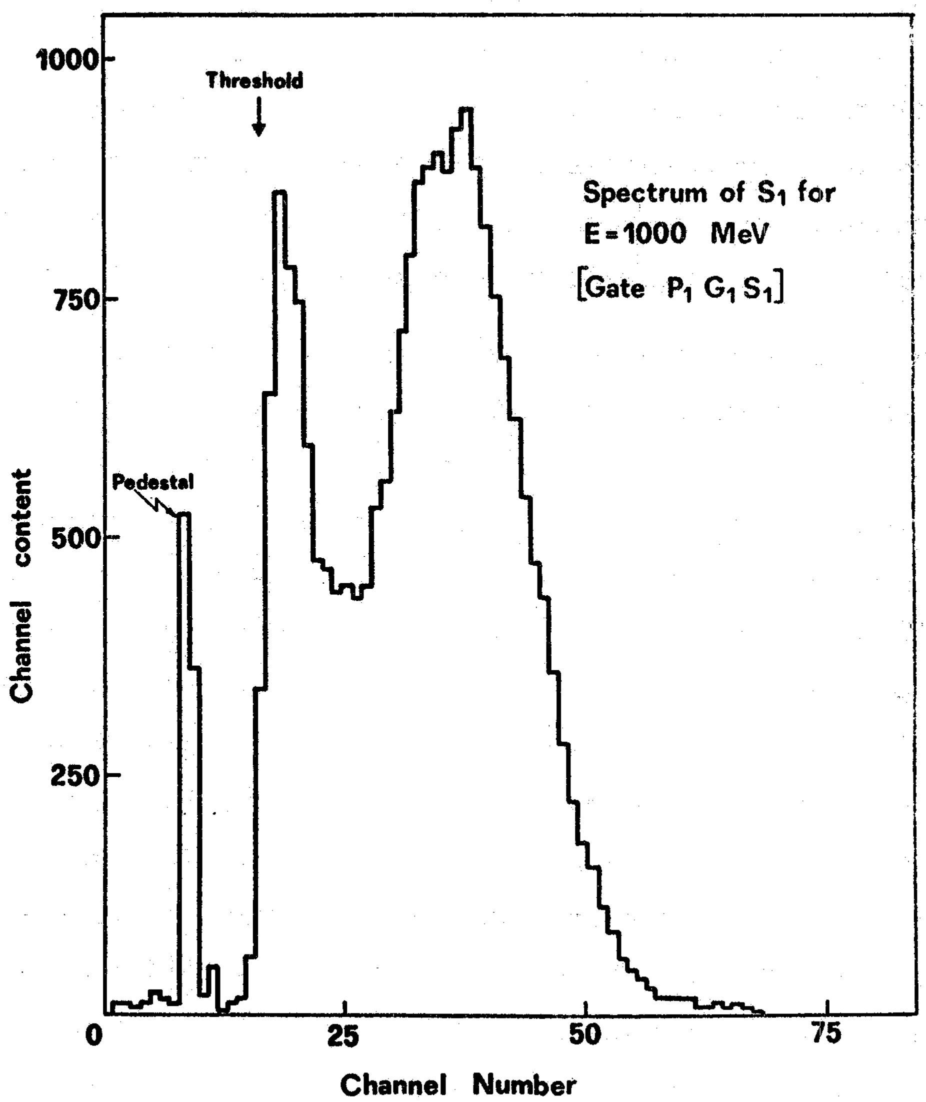

FIG. 5 - Example of a pulse height distribution relative to counter S_1 of the monitoring system, obtained in a run with 1 GeV e^+, e^- circulating in Adone. (Note that the pulse-height analyzer was gated by three-fold coincidences, P_1 G_1 S_1, rather than by fivefold coincidences: $P_1G_1S_1G_3S_3$, which would give a "cleaner" spectrum but have a much smaller counting rate).

These various coincidences were recorded by scalers, simultaneously with all relevant information regarding data and events selected by the main apparatus (Sec. 2). A number recording the luminosity integrated in time, was recorded on the film picture at the occurence of each event.

4. - Analysis of events and results.

Asmentioned in the previous Section, all the relevant information concerning the events was recorded on the film pictures. All pictures were scanned systematically to select candidates for "good events" (i.e. events due to any reaction produced in the e^+e^- collisions). The selection was only based, at this stage, on the requirement that the tracks met a fiducial region covering with some redundancy the interaction region of the colliding beams. The pictures thus selected were then analyzed individually. In order to be accepted as an elastic e^+e^- scattering event, a candidate had to fullfill the following conditions:

(i) Two particle trajectories - one in each telescope - are seen in the directional chambers C_1 coming from the fiducial region mentioned above;

(ii) particles appear as electrons by the development of cascade showers in chambers C_2 C_3 of at least one of the two telescope E,I;

(iii) no track is present in the final chambers (C_6).

For the events thus selected the distribution of the e^+e^- interaction points along the vertical coordinate (x, with the origin at the average position of the beam line) was derived and found to contain (in all cases corresponding to the various beam energies) $\sim$ 95% of the events with $|x| < 15$ mm, One such distribution is reproduced in Fig.6.

Fig.7 gives the longitudinal distribution of the e^+e^- interaction points for events obtained with a beam energy of 825 MeV.

Events ful filling condition (ii) produced in counters 2, 3 pulse heights the sum of which ($E_2 + E_3 + I_2 + I_3$) had

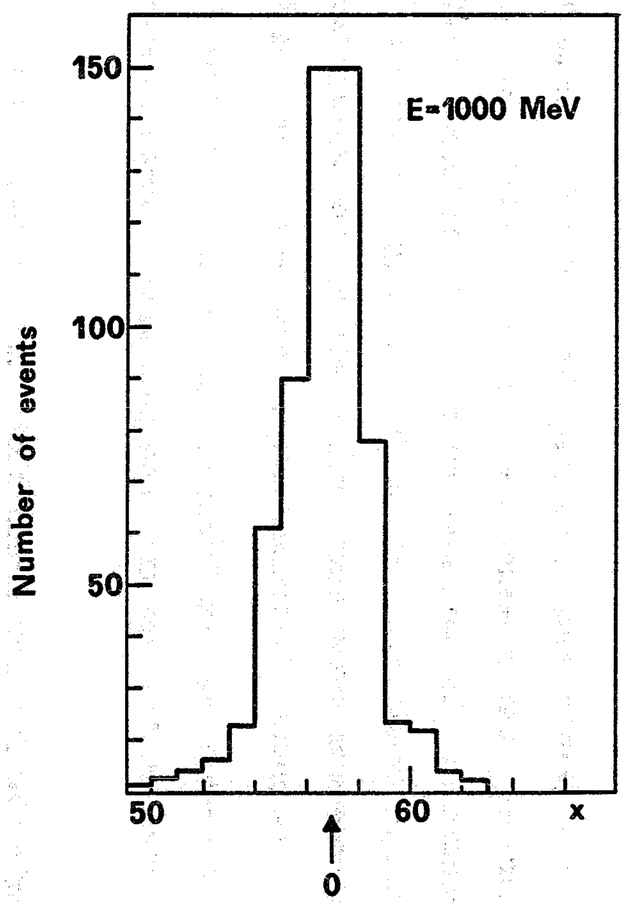

FIG. 6 - Vertical distribution of e^+e^- collision points at E = 1000 MeV.

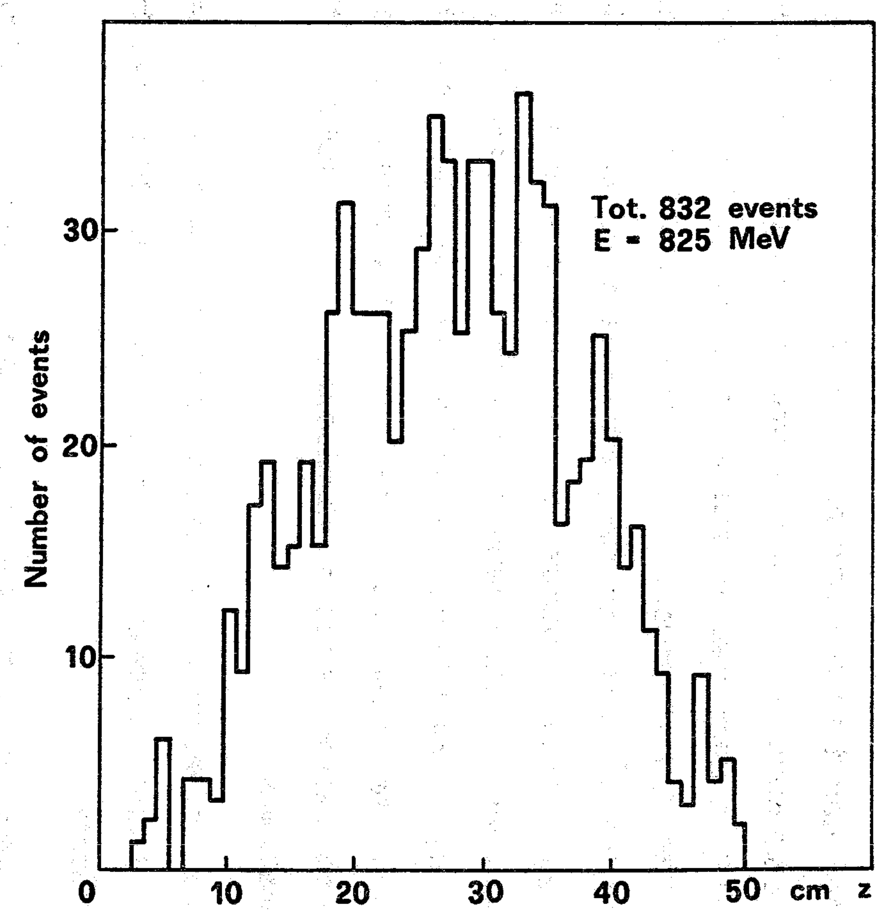

FIG. 7 - Longitudinal distribution of e^+e^- collision points at E = 825 MeV.

a mean value 2.5 times that expected for minimum ionizing particles. This is consistent with the expected behaviour of high energy electrons emitted from S.

Since the measurement of the scattering angles ϑ is not completed as yet, the solid angle was determined by the geometry of the spark chambers and counters. This criterium may introduce some loss (due to border effects on the counter efficiency) and will be therefore replaced (as soon as the measurement of the events is completed), by the condition of ϑ being smaller than a given limit, depending on the longitudinal coordinate z.

A few corrections need to be applied to the numbers of events obtained, at each energy, by applying the selection criteria listed above. The most important are related to the trigger loss of the e^+e^- events and to a 3.3 sec dead-time used to recover the high voltage onto the spark-chambers after the occurence of an event. Some of these corrections are slightly dependent on the beam energy E. By neglecting second order effects due to this dependence, we give here an average value of the over-all efficiency, which from the preliminary analysis of our data turns out to be ~ 0.85.

The monitoring events need also to be corrected for random ($\sim 1\%$) and background events ($2\% \div 5\%$, identified by time-of-flight among pairs of opposite G counters of the monitoring system, see Sec.3). In deriving the effective luminosity of Adone, it is essential, of course, to take into account the effect of the length of the "source" which, as already mentioned, depends on E.

When all corrections are applied, one obtains the experimental cross section, $\langle \sigma_{exp} \rangle$ of process (1) reported in the last column of Table 1 for the seven beam

TABLE 1 - Results on Bhabha scattering at total energies (2E) ranging from 1.6 to 2 GeV.

E (MeV)	$\int Ldt$ ($10^{33} cm^{-2}$)	Corr. Number of e^+e^- events	$\langle \sigma_{exp} \rangle$ (nbarns)
800	5.32	308 ± 18.5	58 ± 4.5
825	7.85	478 ± 28.5	61 ± 5
850	4.85	220 ± 13	45 ± 4
875	9.50	430 ± 25	45.5 ± 3.5
900	5.21	187 ± 11	36 ± 3.5
950	5.98	225 ± 13.5	37.5 ± 3.5
1000	16.65	506 ± 30	30.5 ± 2

energy values listed in the first column. The values of $\langle \sigma_{exp} \rangle$ are obtained merely as a ratio between the corrected numbers of $e^+ e^-$ events (3rd column) and the corresponding luminosity values integrated overthe effective duration of the measurements (2nd column). The quoted errors are obtained by adding to the statistical uncertainty a 5% systematic error due to uncertainty in the present luminosity measurements.

The results are plotted in Fig. 8.

The curves represent - for three values of the parameter Λ appearing in Eq (2) - the function $\langle \sigma_{th}(E) \rangle$, which is obtained integrating Eq (3) over the solid angle of our apparatus with the longitudinal distribution of the source folded in.

No radiative correction have been applied to the results, since $e^+ e^-$ events have been accepted with practically no requirement on energy or angle between the two tracks.

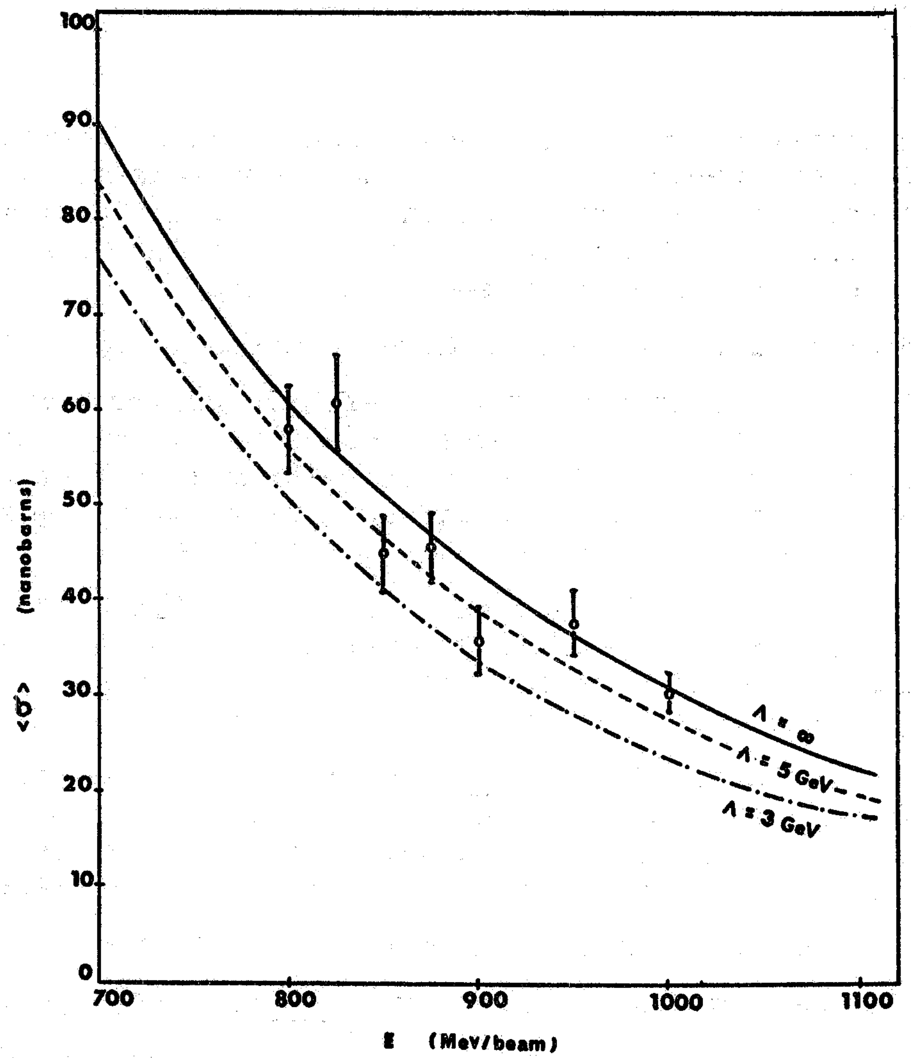

FIG. 8 - Integrated Bhabha scattering cross-section as a function of beam energy.

Angular distributions in the scattering angle θ are now being derived to try to obtain another test of the validity of QED at the high space-like momentum transfers involved in this experiment.

References

(1) Experimentation with Adone has begun late in November 1969, after two-beam operation had been successfully achieved with head-on collision of the e+, e⁻ bunches. [See ref.(2)] . This mode of operation ("zero angle crossing") has been mantained since then.

(2) F.Amman et al.: Lettere al Nuovo Cimento, 1, 729 (1969)

(3) W.C.Barber, B.Gittelman, G.K.O'Neil and B.Richter: Proceedings of XIV International Conference on High Energy Physics, Vienna (1968). Results on Bhabha scattering at a total energy of 600 MeV had been previously reported by the same authors in P.R.L. 16, 1127 (1966).

(4) J.E.Augustin et al.: Internal note n.91, Orsay (1968)(*). See also J.Perez-y-Jorba: Proceedings of the 4th International Symposium on Electron and Proton Interaction at High Energies, Liverpool, p.213 (1969)

(5) N.M.Kroll: Nuovo Cimento 45A, 65 (1966). For a recent review on the status of QED see S.J.Brodsky: Proceedings of the 4th International Symposium on Electron and Photon Interactions at High Energies, Liverpool, p.3 (1969).

(6) T.D.Lee and G.C.Wick: Nucl.Phys. B9, 209 (1969).

(7) H.J.Bhabha: Proc.Roy.Soc.(London) A154, 195 (1935).

(8) G.Barbiellini et al.: Atti dell'Accademia Naz.dei Lincei XLIV, 233 (1968) -(presented by M.Conversi). See also: R. Santonico: Thesis, University of Rome (1967) (unpublished).

(9) B.Borgia et al.: Proc.Symp.Intern.sur les Anneaux de Collision, Saclay 1966, VIIa - 4-1 (presented by M.Conversi).

(10) M.Grilli et al.: Proc.Symp. Intern.sur les Anneaux de Collision, Saclay 1966, VIIa-2-1 (presented by M.Grilli).

(11) B.D'Ettorre Piazzoli and R.Visentin, LNF 69/65 internal report (unpublished).

(12) L.Paoluzi and R.Visentin: Nuclear Instruments and Methods 65, 345 (1968).

(13) For further details see: W.Scandale, Thesis, University of Rome, (1970) (unpublished).

(*) See also P.L. 31B, 673 (1970)

MUON PAIR PRODUCTION BY e^+, e^- COLLIDING BEAMS IN THE GeV REGION[x]. -

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Electron positron annihilation into muon pairs

(1) $$e^+e^- \longrightarrow \mu^+\mu^-$$

has been investigated with the Frascati storage ring, Adone, to test electron-muon universality[1] and the validity of quantum electrodynamics (QED)[2] at the large time-like momentum transfers involved. Process (1) was first observed at ACO[3]. The preliminary results reported here[x] extend these measurements to $q^2 = 4\,E^2 \sim 4\,(\mathrm{GeV})^2$.

The operating conditions of Adone (head-on collision of the bunches, etc), as well as the main characteristics of the apparatus, were reported in a previous paper[4] (referred to as I in what follows),

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(x) - The results reported in this paper are based on the analysis of events as of June 30, 1970 and are subject to possible changes as further refiniments are introduced.

in which preliminary results on Bhabha scattering

(2) $$e^+e^- \rightarrow e^+e^-$$

were also given.

Events due to processes (1) and (2) were recorded simultaneously by the same apparatus. This allowed a direct comparison of the e^+e^- interaction in the time-like and space-like regions, since in the effective angular interval $53^o < \theta < 90^o$ (see I), process (2) involves essentially space-like momentum transfers.

Small angle Bhabha scattering ($3.5^o < \theta < 6.1^o$) was also recorded simultaneously by an additional set-up(5) (I, Sec. 3), and was used to measure the absolute luminosity, L, of Adone. Absolute values of the cross-sections of processes (1) and (2) can thus be obtained.

In terms of the form factor(6)

(3) $$F(q^2) = 1/(1 + q^2/\Lambda^2)$$

where Λ is a cut-off parameter, the differential cross-section of process (1)(7) can be written (for $\gamma \gg 1$) as

(4) $$\left(\frac{d\sigma}{d\omega}\right)_{th} = \left(\frac{r_o}{4\gamma}\right)^2 \left\{1 - (\rho/\gamma)^2\right\}^{1/2} \left\{1 + \cos^2\theta + (\rho/\gamma)^2 \sin^2\theta\right\} \cdot F^2(q^2)$$

where

$$r_o = e^2/m_e c^2 = 2.82 \cdot 10^{-13}\,\mathrm{cm}, \quad \gamma = E/m_e c^2 \text{ and } \rho = m_\mu/m_e = \sim 207$$

The identification of muon pairs is made easier by the fact that muons behave as "heavy electrons", i.e. in crossing the apparatus (see Fig. 2 of I) they do not irradiate energetic photons (as electrons do) or loose energy through nuclear interactions (as pions or kaons may do).

Special care must be taken, however, in rejecting cosmic ray muons, since these cross the solid angle of our apparatus at a rate of more than 1 per sec. If one assumes a luminosity value of $3 \cdot 10^{32}$ $hr^{-1} cm^{-2}$ and takes into account the spatial distribution of the "source", S, of the "good" events, this rate is $\sim 10^4$ of the rate for events expected from process (1) at E = 1 GeV. A total rejection factor, $R_{tot} = \sim 5 \cdot 10^4$ was achieved by the following requirements:

(a) correct timing of the electronic coincidences relative to the bunch collision time (partial rejection factor: $R_a = \sim 4$);

(b) correct time-of-flight between counter pairs E_3, I_3 and E_4, I_4 to exclude cosmic ray muons ($R_b = \sim 50$);

(c) point of coincidence of track lines in the two directional chambers (C_1) should lie within a fiducial region defined by the source S - ($R_c = \sim 10$);

(d) a track must come at the end of its range in one of the chambers C_6 and the other must traverse counter 5 of the opposite telescope (see Fig. 2 of I). Notice that the chambers C_6 cover only half of the solid angle of the apparatus, so that one track must stop in one only of the two range telescopes ($R_d = \sim 25$).

Condition (d) is energy dependent in that there is a probability of $\sim 95\%$ for muon stop in C_6 for $.850 \text{ GeV} \leq E \leq .975$ GeV which drops to 85% at E = 1 GeV and to 75% at E = .800 GeV.

Conditions (c) and (d) were introduced during the analysis after the photographs of each event had been scanned and measured. Conditions (a) and (b) were imposed in a non-stringent way to the master coincidence used to trigger the spark chambers and to advance the film. The trigger rate due to cosmic ray muons was thus reduced to below 1 per min. A more stringent application of these conditions became possible, however, during the analysis as this information was also recorded in digital form on each photograph.

The time-of-flight technique[8] mentioned in (b) enables one to recognize whether the pulses from counters placed on opposite sides of S are nearly simultaneous (as in the case of two body events coming from the crossing region) or occur at different times (as in the case of cosmic-ray muons entering on either side of the apparatus). In practice the time T_3 (or T_4) elapsing between the instants of traversal of say counter E_3 (or E_4) and I_3 (or I_4), is converted into a pulse of amplitude proportional to that time. The largest amplitudes are due to cosmic rays entering from counter E_3 (or E_4); the smallest due to cosmic rays entering from counter I_3 (or I_4); intermediate amplitudes are characteristic of "correct" T_3, T_4 values, as one would expect for "good" two-body events, in which charged particles emitted from the source S cross counters E_3 (or E_4) and I_3 (or I_4) at almost the same time.

Both T_3 and T_4 are digitized and recorded on the photographs as decimal numbers, no matter which type of trigger is used (sec. I). Other relevant informations, e.g. pulse heights of counters 2 and 3, integrated luminosity (I, sec. 3), frame number, etc. appear on each photograph.

To illustrate the correlation between time-of-flight and pulse height measurements[9] a three-dimensional distribution of cosmic ray events is represented in Fig. 1. It gives the number of events, on the z-axis, as a function of both, the sum of the pulse heights of the four counters 2, 3 (x-axis), and the time T_3 (y-axis) elapsed between traversals of counters E_3 and I_3. Since the bulk of the events recorded in this figure is due to fast cosmic ray muons (which are minum ionizing particles producing no secondaries) most events occur with relatively small pulse heights in counters 2, 3. Fig. 2 is a projection on the z = 0 plane of the previous distribution. The two visible lines parallel to the x-axis specify the range of T_3 requested in forming the master coin-

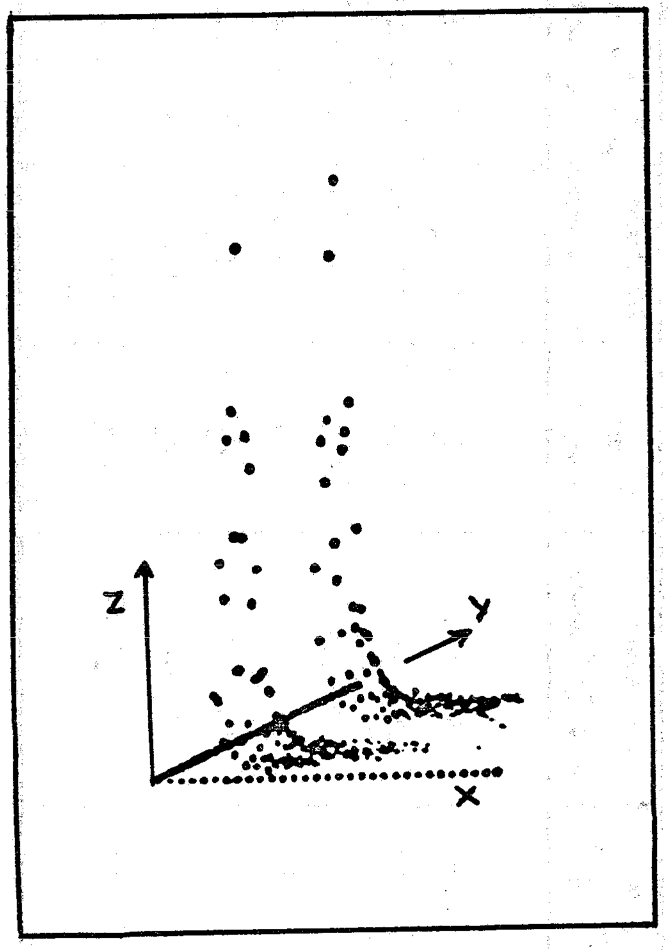

FIG. 1 - Sample of a three-dimensional distribution: number of events (z-axis) as a function of both the sum of pulse heights in counters 2, 3 (x) and time-delay relative to the passage of the particle in counters E_3, I_3 (y) for cosmic-ray muons entering the apparatus.

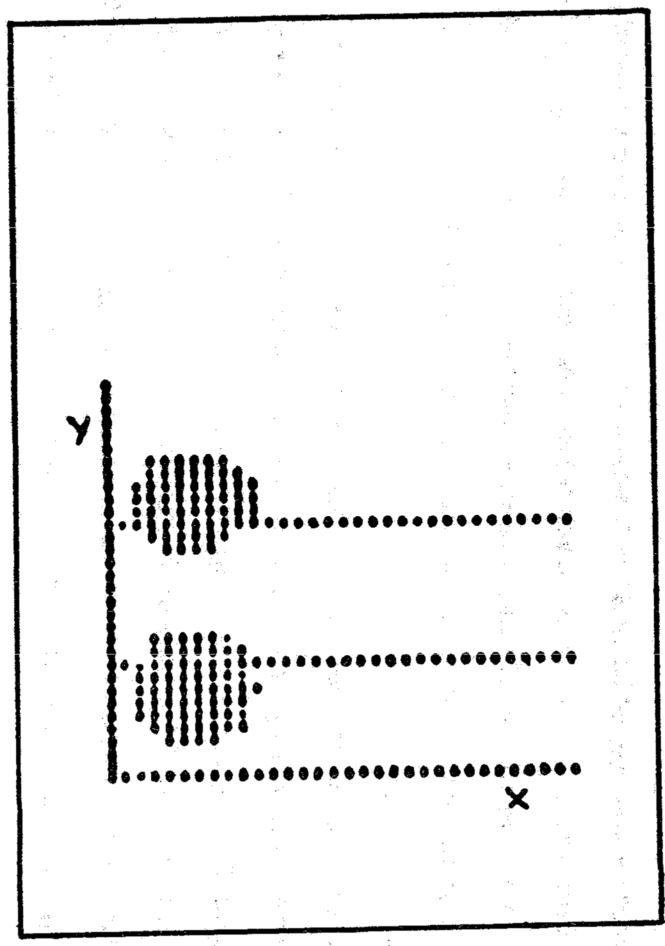

FIG. 2 - Projection on the z = 0 plane of the three-dimensional distribution given in Fig. 1.

cidence used for $\mu^+\mu^-$ events[10].

Finally a system of 12 scalers was used to check continuously the correct behaviour of the main apparatus and the monitoring system (I, sec. 3). The content of all the scalers (useful data, as well as the numbers of significant events occurring during the runs) was printed at the end of each run.

The preliminary results of this experiment are contained in Table I, where luminosity data (column 2) and numbers of $e^+e^- \rightarrow e^+e^-$ events (column 5) are also reported for various values of the beam energy E (column 1). The values of the quantity $\langle \sigma_{exp} \rangle$ are obtained from the ratio between the corrected numbers of $\mu^+\mu^-$ events and the corresponding values of the integrated luminosity. The "theoretical"

TABLE I

Results on the annihilation process $e^+e^- \rightarrow \mu^+\mu^-$ at total energies (2E) ranging from 1.6 to 2 GeV[x].

E (MeV)	$\int L \cdot dt$ (10^{33} cm^{-2})	Corr. Number of $\mu^+\mu^-$ events	$\langle \sigma_{exp} \rangle$ (nbarn)	Corr. Number of e^+e^- events	$\mu^+\mu^-/e^+e^-$ per cent
800	4.85	20.5±5.5	4.2±1.2	281±20	7.3± 2.0
825	7.85	25.5±6	3.2± .8	478±29	5.4±1.3
850	2.22	3.7±2	1.7±1.0	101±11	3.7±2.3
875	9.50	30.0±6	3.2± .7	430±25	7.0±1.5
900	5.21	15.5±4	3.0± .8	187±15	8.3±2.2
950	4.21	14.5±4	3.4± .9	160±14	9.1±2.5
1000	16.65	31.5±6.5	1.9± .4	506±30	6.2±1.3

(x) - The data assembled to form this Table do not exactly coincide with the data reported in Table I of I.

quantity $\langle\sigma_{th}\rangle$, which is to be compared with $\langle\sigma_{exp}\rangle$, is the integral of Eq. (4) over the solid angle of the apparatus with the spatial distribution of the source folded in. It is represented in Fig. 3 as a function of E, for three values of the parameter Λ appearing in Eq. (3).

The average weighted value of $\langle\sigma_{exp}\rangle$ is $\bar{\sigma}_{exp} = (2.7 \pm .4)$ nbarn. It corresponds to an average value for E of .91 GeV or $\langle q^2\rangle = 3.3\ (\mathrm{GeV})^2$. The corresponding value of $\langle\sigma_{th}\rangle$ computed with $\Lambda = \infty$, is 3.35 nbarn, which differs from $\bar{\sigma}_{exp}$ by 1.6 times the quoted error.

The ratio $\mu^+\mu^-/e^+e^-$ given in percent in the last column of Table I, is plotted in Fig. 4. Let us recall that the experimental points give the ratio of the numbers of muon to electron pairs recorded simultaneously by the same apparatus. The curve gives the expected absolute values and energy dependence of this ratio assuming that QED is valid and that the muon behaves as a heavy electron. It is computed of course taking into account the effect of the source length.

Our results are consistent with the hypothesis of muon-electron universality and the validity of QED at the large time-like momentum transfers involved in this experiment.

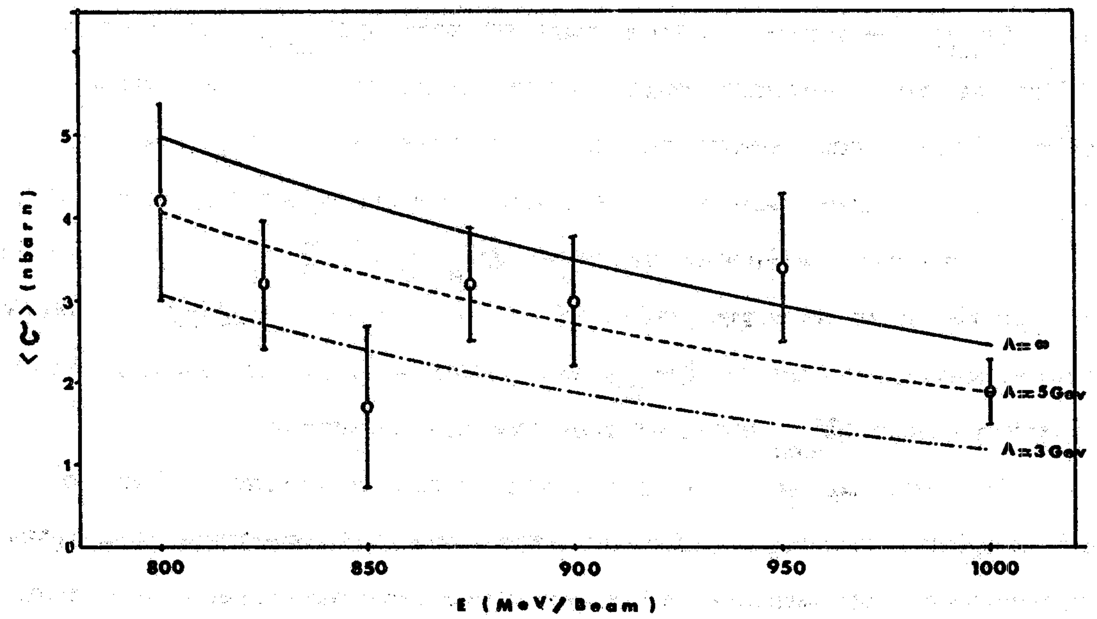

FIG. 3 - Integrated cross-section $\langle\sigma\rangle$ for the process $e^+e^- \to \mu^+\mu^-$ as a function of beam energy, E.

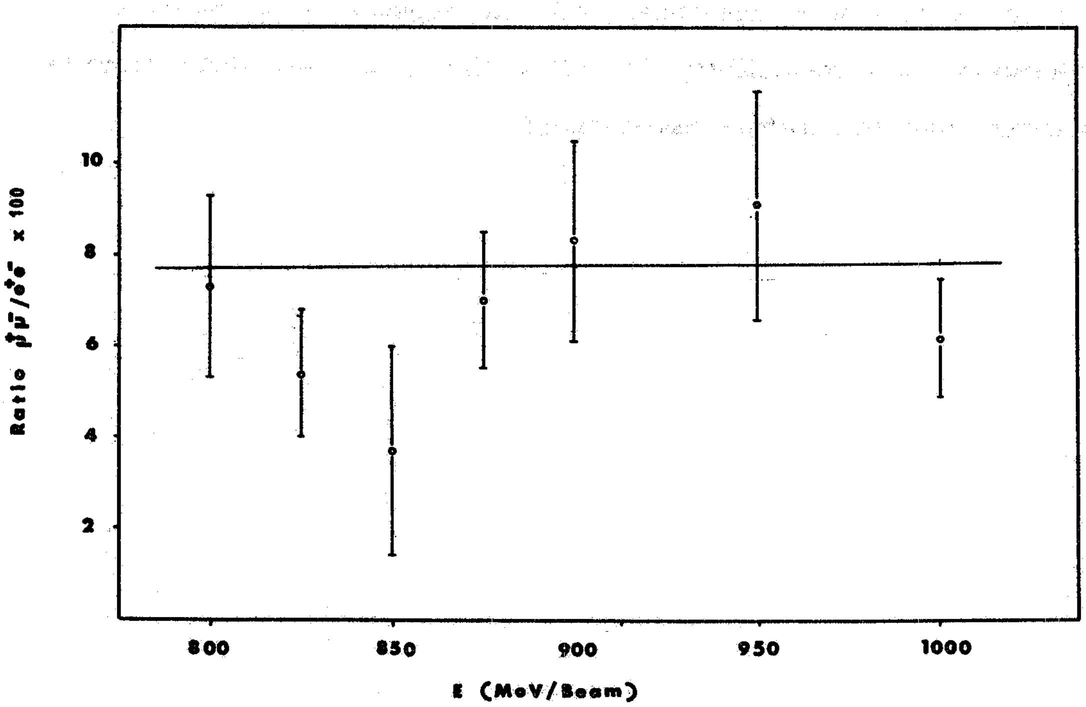

FIG. 4 - The ratio in percent of the rates for processes (1) and (2) as a function of beam energy, E.

REFERENCES. -

(1) - For a survey on the muon-electron problem see L. M. Lenderman in: G. Puppi (Ed.): Old and New Problems in Elementary Particles, Academic Press, p. 159 (1968).

(2) - For a review on the present status of QED see S. J. Brodsky: Proceedings of the 4th International Symposium on Electron and Photon Interactions at High Energies, p. 3 (Liverpool, 1969).

(3) - J. Perez-y-Jorba: Proceedings of the 4th International Symposium on Electron and Photon Interactions at High Energies, p. 213 (Liverpool, 1969).

(4) - B. Borgia et al.: Bhabha Scattering by e^+, e^- colliding beams in the GeV region, to be presented at the Kiev International Conference on High Energy Physics, Aug-Sept. 1970.

(5) - G. Barbiellini et al.: Atti dell'Accademia Naz. dei Lincei, XLIV, 233 (1968) - (presented by M. Conversi).

(6) - Sec N. M. Kroll: Nuovo Cimento 45A, 65 (1966); T. D. Lee and G. C. Wick: Nucl. Phys. 139, 209 (1969).

(7) - R. Gatto: Proceedings of the 1 st International Symposium on Electron and Photon Interactions at High Energies, p. 106 (Hamburg, 1965).

(8) - L. Paoluzi and R. Visentin: Nucl. Instr. Meth. 65, 345 (1968).

(9) - B. D'Ettorre and R. Visentin: LNF 69/65 internal report (unpublished).

(10) - For further details see: F. Ceradini, Thesis, University of Rome (1970) (unpublished).

HADRON PRODUCTION BY e^+-e^- COLLIDING BEAMS IN THE GeV REGION. -

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A. - INTRODUCTION. -

Hadron production in high energy e^+-e^- collisions has been investigated at the Frascati storage ring, Adone. The reaction that have been identified are :

(1) $$e^+ + e^- \rightarrow \pi^+ + \pi^-$$

(2) $$e^+ + e^- \rightarrow m\pi^+ + m\pi^- + n\pi^0$$

where $n \geq 0$ if $m > 1$ and $n \geq 1$ if $m = 1$, and where hadrons are indicated for simplicity as pions (π). We report here the results of a preliminary analysis(1) of data obtained during the period Jan.-March 1970 at e^+-e^- total energy ($E_+ + E_- = 2E$) of 1.6 - 2.0 GeV. This experiment was performed at the same time and with the same apparatus used to investigate the Bhabha scattering process(2),

(3) $$e^+ + e^- \rightarrow e^+ + e^-$$

and the e^+-e^- annihilation into muons[3],

$$(4) \qquad e^+ + e^- \rightarrow \mu^+ + \mu^- .$$

Frequent reference will be made to the two previous papers[1,2] - hereafter indicated as I and II - where the experimental apparatus, as well as the monitoring system used to determine the luminosity at Adone, are described. For convenience, a schematic drawing of the experimental arrangement is shown here in Fig. 1.

There is a close relation[4] between hadron production in high energy e^+-e^- collisions and electron-proton deep inelastic scattering. The exciting experimental finding in this field and the theoretical ideas put forward in attempts to interprete them[5] have stimulated further interest in the study of processes (1) and (2). It is also well known that process (1) may give information on the pion form factor at energies well above the region of the ρ-resonance[6].

We report here experimental evidence for the occurence of processes (1) and (2) at beam energies of E = 800, 825, 850, 875, 900, and 1000 MeV. We shall discuss separately the two-body and the multi-body processes, as the type of analysis required in the two cases is quite different.

We recall from I and II that all candidates for events produced in e^+-e^- collisions are required to come from a point in the region in which the e^+-e^- beams of Adone collide (see Fig. 3). Furthermore, they have to be in phase with the R. F. of the machine (a condition which is equivalent to requiring the presence of the two colliding bunches near the center of the straight section when the events occur). Additional selection criteria lead to unambiguous identification of events due to processes (3) and (4) as discussed in I and II. Reaction (3) is recognized by the appearance of a track associated with an electromagnetic shower in one of the shower spark chambers (C_2 and C_3) in at least one of the two telescopes E or I (see Fig. 1) and by the absence of associated tracks in the end range chambers, C_6. Reaction (4), on the other hand, is specified by requiring one track to stop in chamber C_6 of one telescope and the correct time of flight between counter pairs E_3-I_3 and E_4-I_4 expected for two-body events from the interaction region. Further information useful in the identification of these events is given by the pulse-height analysis of the two sets of counters 2 and 3. These counters are traversed by single minimum ionizing particles in the case of events of reaction (4) and usually by more than one particle (an e-m shower) in the case of events of reaction (3)[7]. For all two-body processes, the two secondary tracks observed in both views of the directional chambers C_1 must appear collinear within some angular interval which takes into account radiative effects and multiple coulomb scattering.

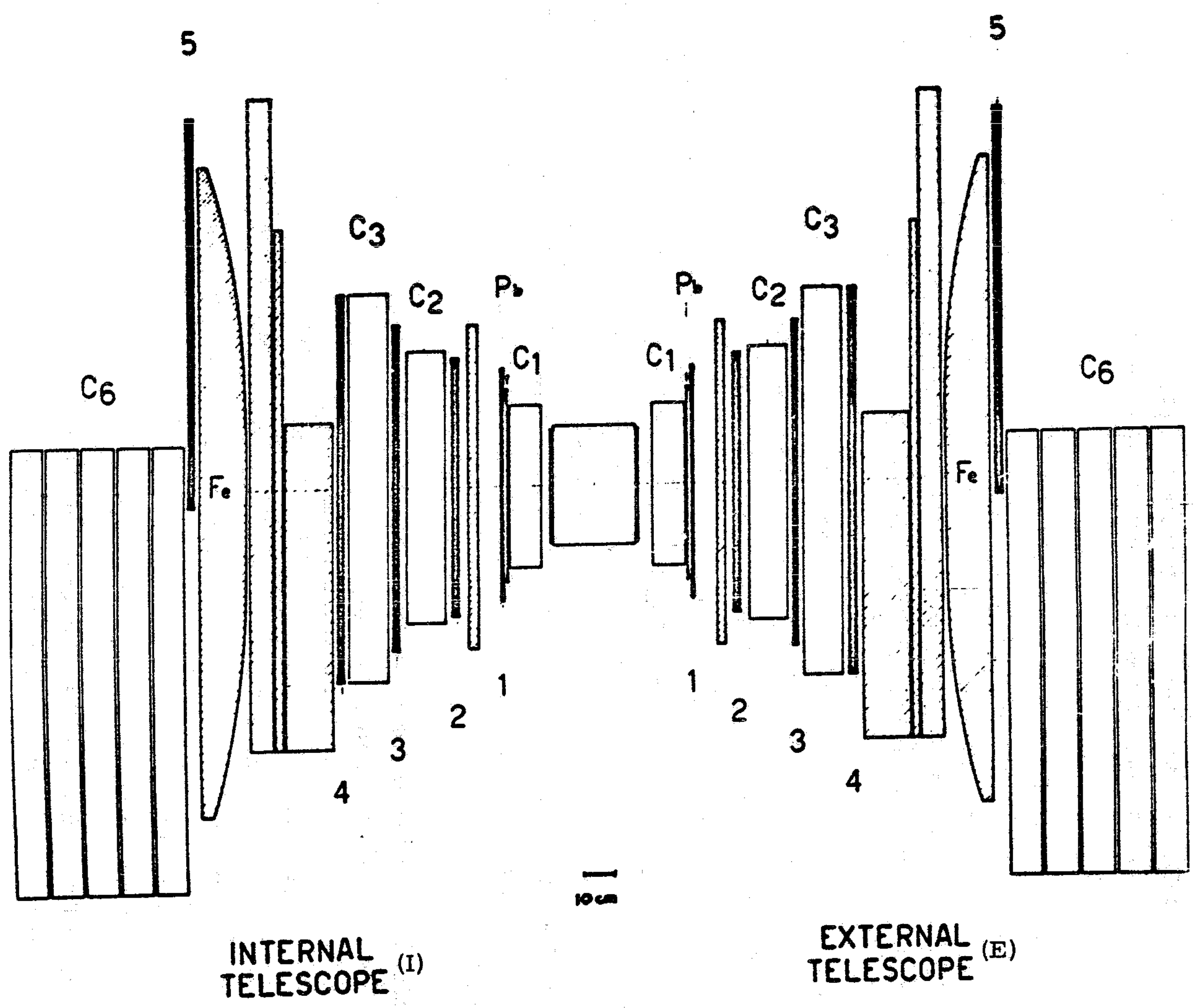

FIG. 1 - Experimental apparatus. 1, 2, 3, 4 are plastic scintillators; $C_1, C_2, \ldots C_6$ are spark chambers.

B. - TWO-BODY HADRONIC EVENTS. -

In brief one might consider events of reaction (1) as those two-body collinear events which are not identificable as being due to reactions (3) or (4). More specifically, in addition to the requirements of being produced in the e^+-e^- interaction region and in phase with the machine R. F., a two-body hadronic event has to satisfy the following conditions :

a) correct time of flight between counters E_3 and I_3;
b) absence of shower development in the shower spark chambers;
c) no coincident pulse in counters 5 placed at about 3 geometrical interaction lengths from the source i. e. 340 g/cm^2 of Fe;
d) no correlated track in the end chambers C_6, placed at $\sim$ 400 g/cm^2 of Fe;
e) the sum of the pulse heights for counters E_2, E_3, I_2, and I_3, $H = H_{E1} + H_{E_2} + H_{I_1} + H_{I_2} = H_E + H_I$ being less than 1.7 of the value expected for a minimum-ionizing particle.

In Table I, the results of the preliminary analysis of some 20,000 photographs are given. Only two-body events which were collinear within 5^o have been considered (and no attempt will be made at this time to apply radiative corrections). In these photographs, 1290 e^+-e^- elastic scattering events, about 90 events due to $e^+ + e^- \to \mu^+ + \mu^-$ and 6 events fulfilling all the conditions specified above for a hadron pair, were identified.

TABLE I - Preliminary results on the production of hadrons in e^+-e^- annihilation.

Reaction	Number of events observed	Number of events corrected
$e^+ e^- \to e^+ e^-$	1290 $\pm$ 36	1390 $\pm$ 58
$e^+ e^- \to \pi^+ \pi^-$	6 $\pm$ 2.4	13 $\pm$ 7.5

The last column of the Table contains the corrected numbers of events. These are obtained from the observed numbers by taking into account detection efficiency and contamination from improperly identified events. In the case of $e^+e^- \to e^+e^-$ events the detection efficiency for secondary electrons in our solid angle is 93% (see I) and there is no appreciable contamination from other events. The correction in the case of $e^+e^- \to \pi^+\pi^-$ will now be briefly discussed.

No appreciable contamination of these events is expected from cosmic-rays or from $e^+e^- \to \mu^+\mu^-$ events, which are rare and are detected with a clear signature by our apparatus[(8)]. A few of the 6 events interpreted as due to process (1) may well have been due to process (3) (which occurs at a much higher rate) in spite of the strong discrimination introduced by conditions b) and e) which are imposed in the selection of two-body hadronic events. The probabilities that an electron simulates these conditions have been measured directly on well identified electrons from collinear e^+e^- pairs one associated e-m shower.

The combined probability that an electron pair from process (3) fulfills both conditions b) and e) leads to an expected background contamination of 1.7 ± 0.8 events. Thus we conclude that 4.3 ± 2.5 events out of the 6 observed are actually due to process (1).

The above number, however, has to be considerably increased because of detection inefficiencies. These are caused mostly by nuclear interactions which prevent pions from reaching counters 3 and 4 placed at 49 g/cm^2 and 88 g/cm^2 respectively from the source. (We recall from I that counters 3 and 4 are both involved in the master coincidence). These losses have been estimated in a Monte Carlo simulation of the experiment which takes into account the attenuation of pions as given by experimental measurements up to 1 GeV in various materials[9]. The result is that $\sim$ 40 % of two-hadron events should have produced a master coincidence. A further reduction in the number of events occurs in the analysis by the imposition of conditions a) through e)[10]. We are left with an estimated efficiency for the detection of hadron pairs of (33 ± 3.5) %. Thus from the number of 4.3 ± 2.5 events we obtain a total of 13 ± 7.5 two-body hadronic events.

It is concluded that the ratio of pion to electron pairs produced in the solid angle of our apparatus is between 0.4 % and 1.5 % at confidence level of 68 %. It is to be noted that the ratio expected for a hypothetical point-like pion is $\sim$ 3 % and that the ratio of muon to electron pairs is 7.5 % (see Fig. 4 of II).

C. - MULTI-BODY HADRONIC EVENTS. -

Multi-body hadronic events can appear either as two-track events which are not coplanar with respect to the beam[11] or as multi-track events. In either case each particle track is required to satisfy the conditions for the selection of hadrons, listed in section B of this paper, with the exception of a) and e), which are more directly related to the selection of two-body hadronic events[12].

The analysis of some 30,000 photographs taken at beam energies between 0.8 and 1.0 GeV has lead to the identification of 88 events. The number of events seen at various beam energies are given in Table II. In Table III the multiplicity distribution of the events is given. As will be discussed later, two-track events are classified as multi-body

TABLE II

Energy distribution of observed multi-body hadronic events. The corrected numbers of e^+e^- elastic scattering events are also given for reference.

Beam energy E (MeV)	Number of observed hadronic events	Number of associated wide-angle Bhabha scattering events.
800	18	264
825	19	487
850	9	204
875	15	324
900	5	160
1000	22	465
	tot. 88	1904

TABLE III

Observed multiplicity distribution for multi-body hadronic events.

Number of tracks	2 ($\Delta\varphi \geq 20^{o}$)	3	4	5
Number of events observed with two beams ($T_1 = 130 x 10^6$)	46	32	9	1
Number of events observed with one beam ($T_1 = 110 x 10^6$)	3	--	--	--
Corrected number of events	43	32	9	1

hadronic events only if the non-coplanarity angle, $\Delta\varphi$, is greater than 20^o. $\Delta\varphi$ is defined as the angle between the planes formed by each track and the beam.

In order to be able to estimate the cross sections for multi-hadron production (reaction (2)) it is necessary to known the number of background events included in our sample due only to the collision of the beams with residual gas in the vacuum chamber. This background has been measured in special runs in which only one beam circulated in Adone. The normalization between these runs and those for colliding beams was made using the ratio of the threefold coincidences, T_1, registerd in one of the four telescopes of the monitor system ($T_1 = P_1 G_1 S_1$)[14]. These coincidences are essentially due to electron scattering on residual gas nuclei.

It is seen from Table III that there is only a very small background to be subtracted from multi-track events. Relevant information concerning these background events is given in Fig. 2, 3 and 4 where their characteristics are compared with those of the hadronic events produced in the e^+e^- collisions.

The $\Delta\varphi$ distribution for two-track events are presented in Fig. 2. Fig. 2a gives the distribution for colliding-beam events satisfying all criteria, b) through d), required for hadronic events. In Fig. 2b the $\Delta\varphi$ distributions is shown for background events obtained with only one e^--beam circulating in Adone. The events with no shower are actually those which simulate hadronic events. Fig. 2c gives the $\Delta\varphi$ distribution for electron-like events (i. e. where at least one e. m. shower is present) obtained with two circulating beams. The last figure (Fig. 2c), as well as the distribution of one-beam background events with an associated e-m shower in Fig. 2b, are given only to complete the experimental picture, as they are not required in a straightforward background subtraction. Among the sample of events with one associated e-m shower, those which are kinematically consistent with an electron-proton quasi-elastic scattering are explicitely shown. Thus it is seen, from Fig. 2b, that a part of the background is due to e-p scattering. The remainder is presumably due to pion electroproduction on the residual gas. It also follows, from Fig. 2b and 2c, that the number of e-p events observed with colliding beams and with one beam are, approximately, equal, in agreement with the previous T_1 normalization.

In order to further reduce the one-beam background as well as possible contamination from other spurious events, preferentially occuring at small $\Delta\varphi$[15], it was decided, on the basis of Fig. 2b and 2c, to exclude two-track hadronic events with $\Delta\varphi < 20^o$.

Fig. 3 shows that both source and time distributions are essentially the same for hadronic and Bhabha-scattering events.

Fig. 4 gives the pulse-height distribution for $H_E = H_{E_2} + H_{E_3}$

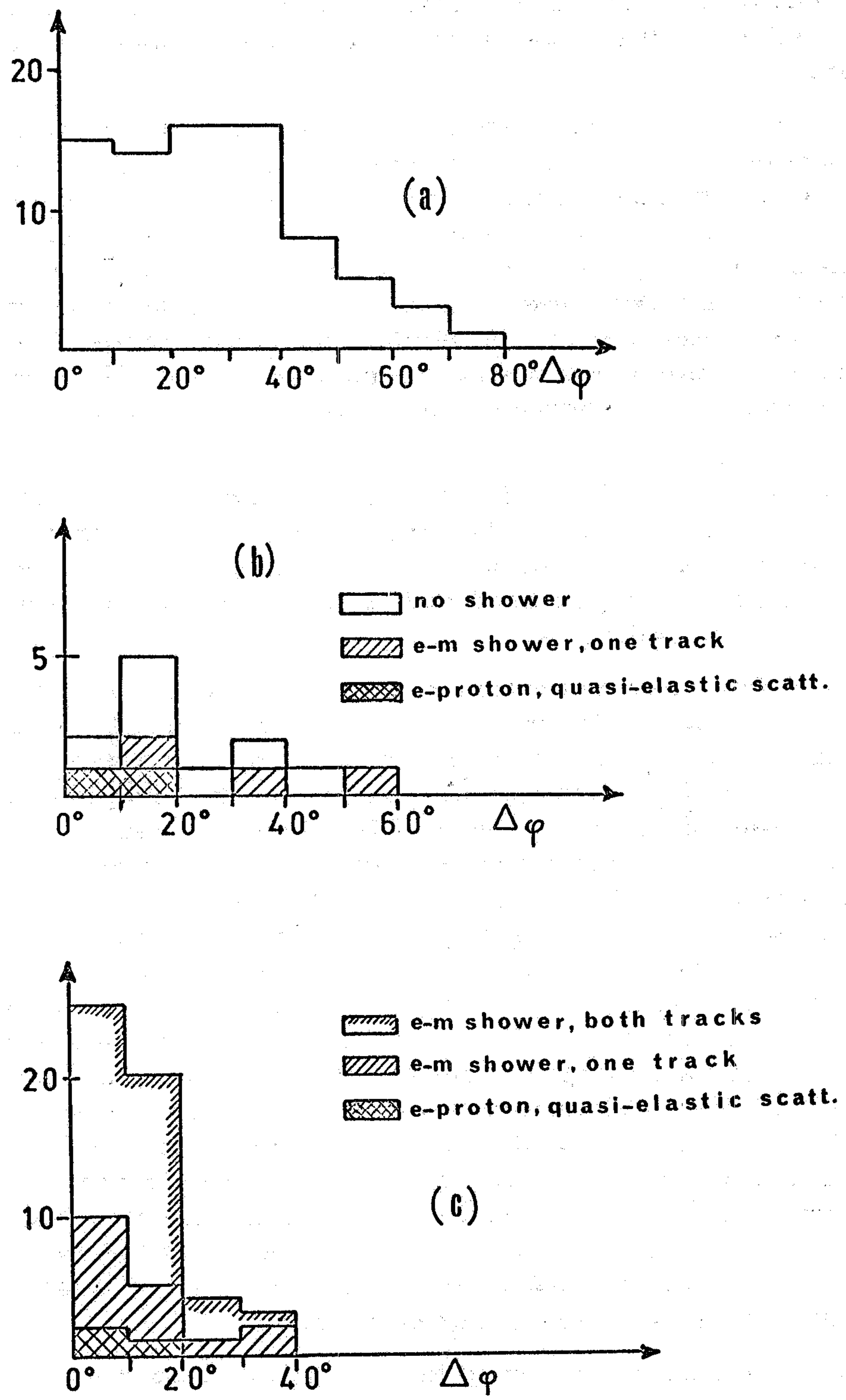

FIG. 2 - Distribution for the angle of non coplanarity, $\Delta\varphi$, for events with two visible tracks; a) hadronic events; b) one-beam background events; c) electron-like events with at least one associated e-m shower. Events of distributions a) and c) were obtained in colliding-beams runs. Those events, wich are kinematically consistent with an electron-proton quasi elastic scattering, are indicated.

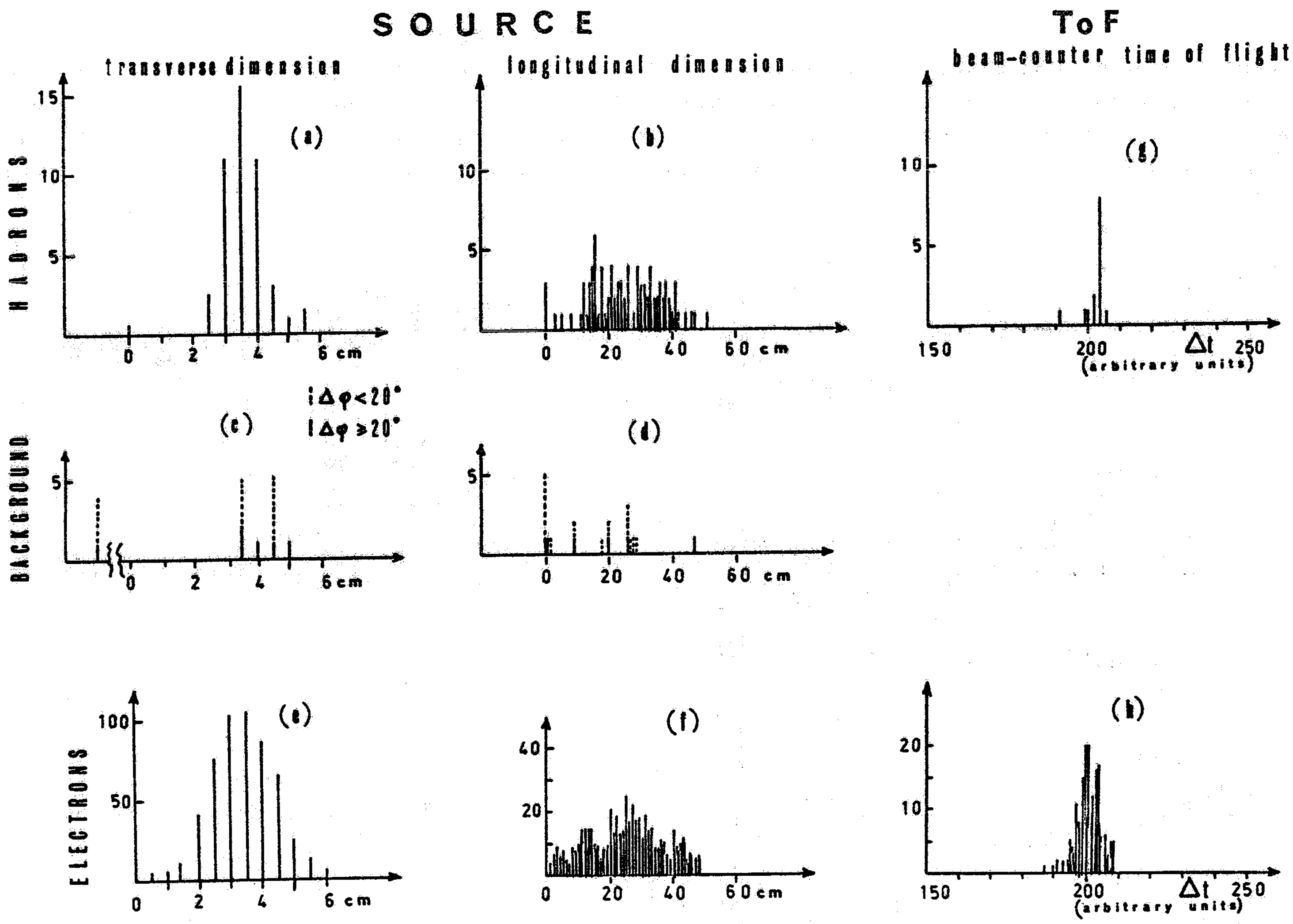

FIG. 3 - Distribution of event origins along and transverse to the interaction region (source): a) and b) for accepted hadronic events; c) and d) for one-beam background events (including those with $\Delta\varphi < 20^{o}$); e) and f) for large-angle e^+e^- scattering events. Also given are the distributions for the time of flight (TOF) relative to the beam for events where TOF informa_ tion was available. (These TOF measurements were introduced only recently).

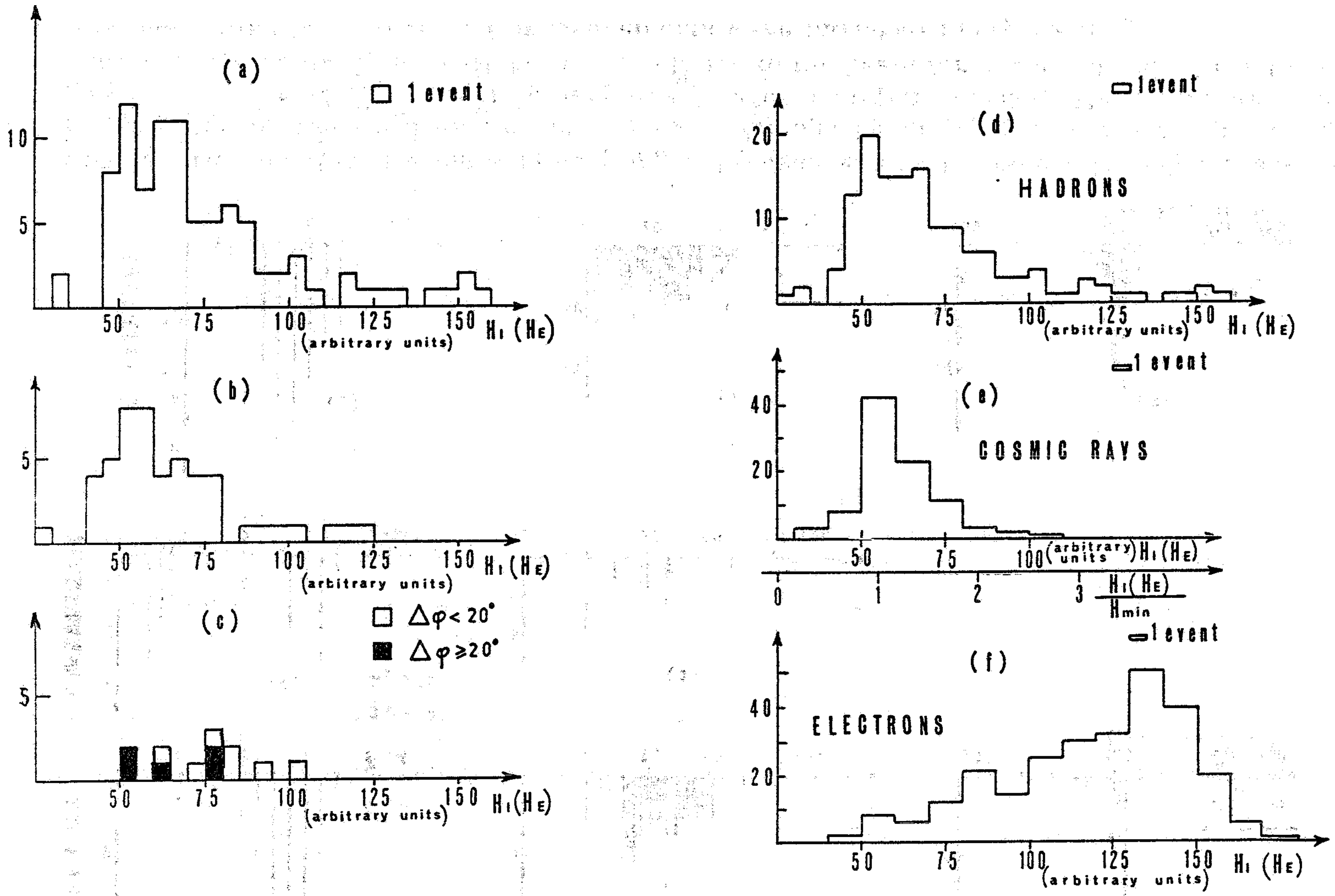

FIG. 4 - Pulse-height distributions for counters 2 and 3 of telescopes I or E: a) for hadrons of two-track events with $\Delta\gamma > 20°$; b) for single tracks hadronic events with more than two visible tracks; c) for one-beam background events, including in this case events with e-m showers and events with $\Delta\gamma < 20°$; d) for the sum of the distributions of a) and b); e) for cosmic rays; and f) for large-angle electron pairs.

or $H_I = H_{I_2} + H_{I_3}$. The distribution for two-track events is presented in Fig. 4a, that for events with greater than two-tracks in Fig. 4b and their sum in Fig. 4d. In Fig. 4c the distribution for one-beam background events is given and, finally in Fig. 4e and 4f, cosmic ray and e^+e^- scattering events are reported.

From a comparison of Fig. 4d and 4e it is seen that most particles in hadronic events are minimum ionizing and, from Fig. 4d and 4f, that they have a pulse height quite different from that observed for electrons. There is, however, an appreciable fraction of the particles with greater specific ionization than the minimum(16). This observation is in line with what one would expect from the fact that pions in these events are emitted with a continuous energy spectrum. Direct evidence for this interpretation is obtained from the pulse-height analysis for counters 2 and 3 which show that larger pulse heights occur for those events in which one track does not reach counter 4. (We recall that 39 g/cm^2 of Fe are placed between counters 3 and 4). It should be pointed out, neverthless, that a contribution to large pulse heights, may be due to showers from decay of π^0 mesons emitted in the same reaction i. e. reaction (2). Evidence for this interpretation is also found in some of the photographs, where showers which are not correlated with the charged particles, are seen.

In order to obtain an estimate of the total cross section for the multi-body process (2) from the measured numbers of hadrons and e^+e^- elastic scattering events, the detection efficiency, $\mathcal{E}$, of the apparatus must be known for both processes. The efficiency for detection of reaction (3) was estimated previously (see I). For multi-body processes the efficiency depends, of course, on the kinematics of the specific process assumed in its calculation, i. e. values of m and n in reaction (2). A Monte Carlo calculation of $\mathcal{E}$ for different values of m and n is now in progress.

A preliminary estimate of $\mathcal{E}$ made for the particular case $m = 2$, $n = 0$, indicates that the average total cross section for multi-body hadronic production, for the energy range 2E = 1.6-2.0 GeV, is of the same order of a magnitude as that for e^+e^- annihilation into muon pairs, namely $\sim 2 \times 10^{-32}$ cm^2.

REFERENCES AND FOOTNOTES. -

(1) - The results reported in this paper are based on the analysis of events as of June 30, 1970. They are subject to possible changes as further refinements are introduced.

(2) - B. Borgia et al., Bhabha scattering by e^+, e^- colliding beam in the GeV region, to be presented at the Kiev Intern. Conf. on High Energy Physics, Sept. 1970 (see pag. 3).

(3) - B. Borgia et al., Muon pair production by e^+, e^- colliding beam in the GeV region, to be presented at the Kiev Intern. Conf. on High Energy Physics, Sept. 1970 (see pag. 21).

(4) - S. D. Drell, D. J. Levy and T. M. Yan, Phys. Rev. Letters 22, 744 (1969); S. D. Drell, D. J. Levy and T. M. Yan, SLAC-PUB-606 (1969) (unpublished); Phys. Rev., 187, 2159 (1969).

(5) - E. D. Bloom et al., Phys. Rev. Letters 23, 930 (1969); M. Breidenbach et al., Phys. Rev. Letters, 23, 935 (1969).

(5bis) - J. D. Bjorken and E. A. Poschos, Phys. Rev., 185, 1975 (1969); S. D. Drell and T. M. Yan, Phys. Rev. Letters 24, 855 (1970).

(6) - $e^+e^- = \pi^+\pi^-$ in the ρ region has been studied experimentally at Orsay: G. E. Augustin et al., Phys. Letters 28B, 508 (1969); and at Novosibirsk: V. L. Auslander et al., Investigation of the meson resonance with electron-positron colliding beam, Novosibirsk, Preprint 263.

(7) - As an illustration of use of correlated information on pulse height and time of flight see Fig. 1 and 2 of II.

(8) - A strong discrimination against the detection of $\mu^+\mu^-$ events comes from conditions c) and d) above. In the worst case, corresponding to 800 MeV/beam, the muon pair contamination is 0.5% as deduced from a Monte Carlo calculation which gives the probability for a muon-pair to give no pulse in one of the counters 5 and no track in an opposite chamber C_6.

(9) - D. H. Stork, Phys. Rev. 93, 868 (1954); A. E. Ignatenko et al., Sov. Phys.-JEPT 4, 351 (1957); J. C. Caris et al., Phys. Rev. 126, 295 (1962); M. Cruzon et al., Nuclear Phys. 64, 567 (1965); J. W. Cronin et al., Phys. Rev. 107, 1121 (1957).

(10) - These losses are mostly due to pions reaching counters 5 (estimated loss = 7%) or producing pulse-heights above 1.7 minimum (loss = 10%). The loss due to shower development from the decay of a π^0 produced in a charge exchange reaction is estimated to be small.

(11) - Except in the case m = n = 1 in reaction 2, where the three particles are emitted preferentially in a plane containing the beam direction.

(12) - In the case of non-collinear events the time of flight requirement, a), may not be satisfied(13). Clearly condition (e) can not be strictly be satisfied by pion belonging to a continuous energy spectrum.

(13) - L. Paoluzi and R. Visentin, Nuclear Instr. and Meth. 65, 345 (1968).

(14) - See section 3 of I for a description of the monitor system (Fig. 6).

(15) - At the present stage of this preliminary analysis the nature of non coplanar events, with $\Delta\varphi \gtrsim 5^{o}$, and with two associated e-m shower has not been established. Calculations are now in progress, to acertain if they can be explained in therms of radiative corrections to reaction (3).

(16) - About 25% of the hadrons have an average ionization larger than 1.7 times the minimum.