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(Frascati-Roma-Padova-Maryland collaboration)

(The International Symposium on Electron and Photon Interactions at High Energy", Ithaca, August 23-27, 1971).

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With the apparatus shown schematically in Fig. 1 we have studied the production of hadrons in $e^+e^-$ collision at a total energy (2E) ranging from 1.4 to 2.0 GeV, using the Frascati storage ring, "Adone".

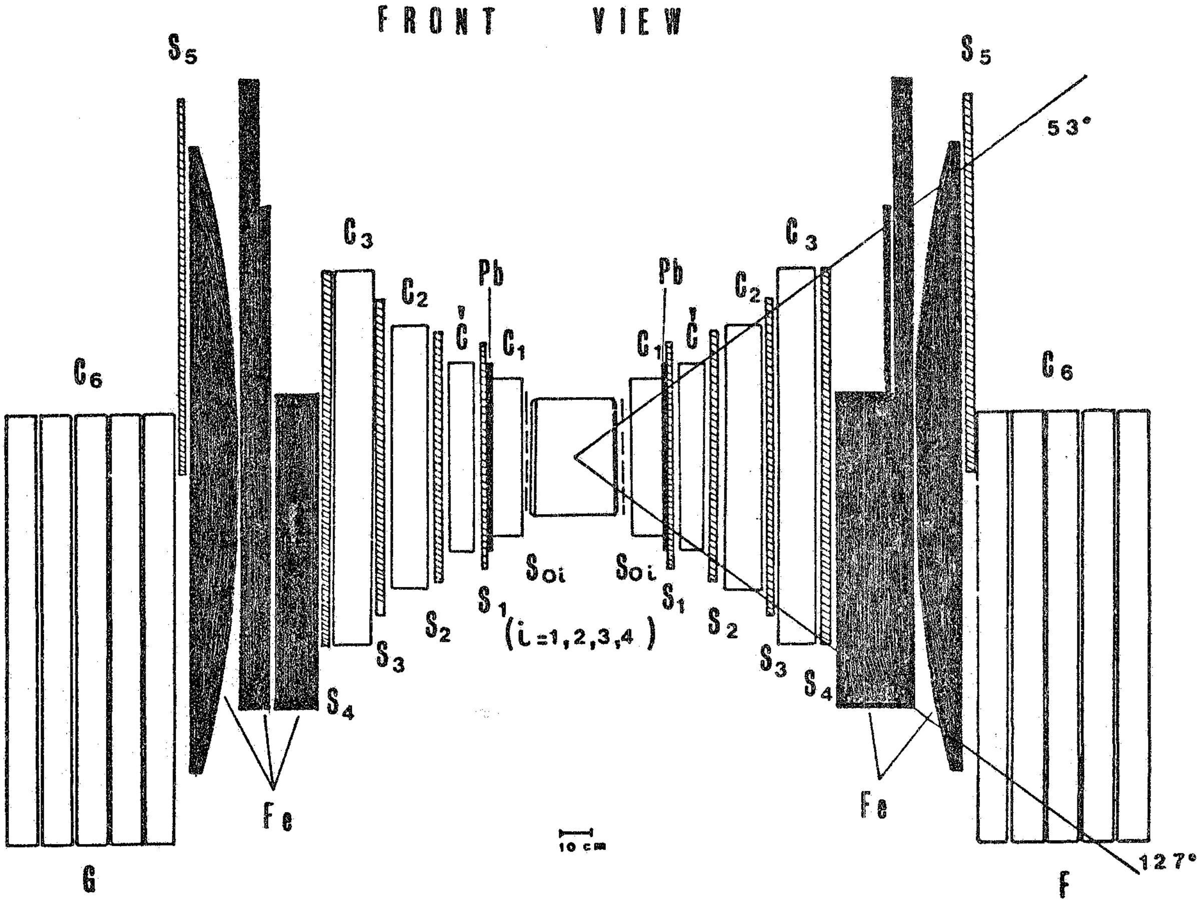

FIG. 1

Previous data on hadron production, which were reported at the Kiev conference, are essentially confirmed with the present larger statistics.

The apparatus, already described elsewhere$^{(1,2)}$, consists of two identical telescopes located on opposite sides of the $e^+e^-$ interacting region, in the horizontal plane. The first spark chambers, C1, are thin-plate chambers used for spatial reconstruction of the events. Spark chambers C2 (15.4 $g/cm^2$, Fe) and C3 (36.3 $g/cm^2$, Fe) are employed to identify particles by their behaviour (e.m. showers, nuclear interactions). Water Cerenkov counters, $\check{C}$, (with a threshold of $\beta = .75$) separate K's of process $e^+e^- = k^+k^-$, from the other two-body final state processes ($\mu^+\mu^-$, $e^+e^-$, $\pi^+\pi^-$), for $2E \leq 1.5$ GeV. The end spark chambers, C6, serve to stop $\mu$'s from the reaction

$e^+e^- = \mu^+\mu^-$.

The master coincidence used to trigger the spark chambers and the film advance was defined as follows :

i) for $\pi^+\pi^-$ colinear events: one charged particle in each telescope, the first one with kinetic energy $T \geqslant 125$ MeV, the other one with $T \geqslant 180$ MeV;

ii) for multipion events : one charged particle in each telescope, one with kinetic energy $T \geqslant 90$ MeV, the other with $T \geqslant 180$ MeV ; any additional particle must have $T \geqslant 30$ MeV in order to be recognized.

The events, on which the following discussion is based, satisfy all the criteria necessary to insure that the events are due to $e^+e^-$ collisions(1). These criteria involve essentially the source spatial reconstruction and the correct time with respect to the instant of beam-beam collision.

The results have been corrected for possible machine background, using runs with only one beam circulating in Adone. No event with three or more tracks was seen in these background runs. A correction of less than 10% was required only in the case of two track non-collinear events.

We shall consider separately the two body hadronic process

(1) $$e^+e^- = h^+ + h^-$$

and multibody reactions

(2) $$e^+e^- = n\,h \qquad (n \geqslant 3, \text{ with at least 2 charged hadrons}).$$

The separation between these two classes of events was based on their appearence in the thin foil spark chambers, C1. Two-track events are considered as due to process (1) if the tracks are collinear within $10^o$. Events with larger non collinearity angle are interpreted as due to either radiative corrections or multibody events, in which only two tracks are observed(x). It should be pointed out, moreover, that multibody events appear with more than two prongs in ~70% of the cases.

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(x) - The multiplicity (number of tracks, T) is defined, for each event, as the number of prongs observed in the two chambers C1 originating from a point in the $e^+e^-$ collision region.

The possibility of identifying the secondary particles in these events lies, pratically, in the discrimination between electrons and hadrons. The criteria adopted for this discrimination were based on calibration measurements of our apparatus made with electrons of different energies (0.1 to 1.2 GeV)(3).

In the following tables and discussion we report only events classified as hadronic. One evidence that the tracks from these events are indeed mostly hadrons comes from the agreement between the expected and observed numbers of nuclear interactions, assuming that the secondary particles are pions, as it appears from the Table I.

TABLE I

Frequency of nuclear interactions
(observed in 3-track events)

| 2E (GeV) | Predicted value | Experimental value |
|---|---|---|
| 1.5 | $(50 \div 70)\%$ | $(66 \pm 8)\%$ |
| 2.0 | $(40 \div 50)\%$ | $(49 \pm 7)\%$ |

The "Predicted value" were obtained using known experimental data on pion absorption in nuclear matter and a pion energy spectrum as derived from phase space calculations, assuming that only processes $e^+e^- \to 2\pi^+ + 2\pi^- + n\pi^0$ $(n = 0, 1, 2)$ occur.

## I. - RESULTS ON $e^+e^- = \pi^+\pi^-$. -

The criteria adopted to select this process are:

a) - Collinearity of the two tracks within $10^o$ degrees (as mentioned previously);
b) - Correct time-of-flight between counter pairs 3 placed symmetrically on opposite sides of the beam interaction region at 60 cm(x);
c) - No pulse in counter 5, placed at about 250 g/cm$^2$ (Fe) from the interaction region;
d) - No track in the range chambers $C_6$;
e) - No shower observed along the path of the two particles, which

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(x) - Correct time-of-flight is required also for the two counters 4 (at 80 cm from the interaction region) when they are both reached by the particles.

must reach counter 3 in one telescope (placed at 1 radiation length from the source) and counter 4 (at 3.5 R.L.) in the opposite telescope;

f) - Pulse height in either of the two range telescopes less than twice the minimum value.

Criteria b) e) d) strongly reject cosmic rays; c) and d) allow one to recognize muon pairs from $e^+e^-$ annihilation(4).

On the basis of the above criteria and of the electron calibration previously mentioned, we estimate that wide angle scattering events (WAS-events) can contribute at most a 12% contamination to process (1).

The results have been divided into three energy groups. The detection efficiency for a pion pair has been calculated taking into account the nuclear absorption of the pions, as known from experimental data(5).

On the basis of the calculated efficiency we obtain the actual corrected numbers of $\pi^+\pi^-$ pairs in the solid angle of our apparatus. It is interesting to note that this efficiency result to be nearly the same over the energy range of our measurements. So, as we see from the Table II, both the observed and corrected $\pi\pi$/ee ratios show the same energy dependence. This ratio should not vary with the total energy 2E if the $\pi\pi$ production cross section has a 1/s energy dependence. Our data indicate, therefore, an energy dependence steeper than 1/s.

We notice, furthermore, that in the case of a point-like pion the ratio ($\pi\pi$/ee) should be about 2.5%. These results are summarized in Fig. 2.

During part of the runs at 1.5 GeV we have measured separately K pair from $\pi$ pair, exploiting the information from the Cerenkov counter, C (Fig. 1). The detection efficiency for kaon pairs is comparable to that for pion pairs. Only 1 $K^+K^-$ event was found out of observed 16 hadron pairs ($\pi$ - $\pi$ events).

Possible contamination in the two body hadronic events from different processes (radiative corrections to $\mu$ pairs, or $\pi^+\pi^-$ production from $\gamma\gamma$ annihilation processes(6)) have been considered. They are estimated to be less than 10%.

In summary, the most interesting results appear to be the energy dependence of the pion pair cross section and the small ratio between kaon and pion pairs. We stress that both results are not critically dependent on the absolute value of the efficiency of the apparatus.

### TABLE II

Results on $\pi^+\pi^-$ pairs

| 2E (GeV) | Associated $e^+e^-$ pairs (WAS) Observed | Corrected | Observed number of $\pi^+\pi^-$ pairs | Estimated contamination from WAS |
|---|---|---|---|---|
| 1.5 | 3197 | 3385 | 26 ± 5 | .3.5 |
| 1.9 | 1572 | 1625 | 7 ± 2.6 | 1.0 |
| 2.1 | 3643 | 3795 | 12 ± 3.5 | 1.0 |

| 2E (GeV) | Actual number of $\pi^+\pi^-$ pairs Observed | Corrected | $(\frac{\pi^+\pi^-}{e^+e^-})$ observed (x $10^3$) | $(\frac{\pi^+\pi^-}{e^+e^-})$ corrected (x $10^2$) |
|---|---|---|---|---|
| 1.5 | 22.5 | 93 | 7.0 ± 1.6 | 2.7 ± .6 |
| 1.9 | 6 | 27 | 3.8 ± 1.7 | 1.6 ± .6 |
| 2.1 | 11 | 50 | 3.0 ± 1.0 | 1.3 ± .4 |

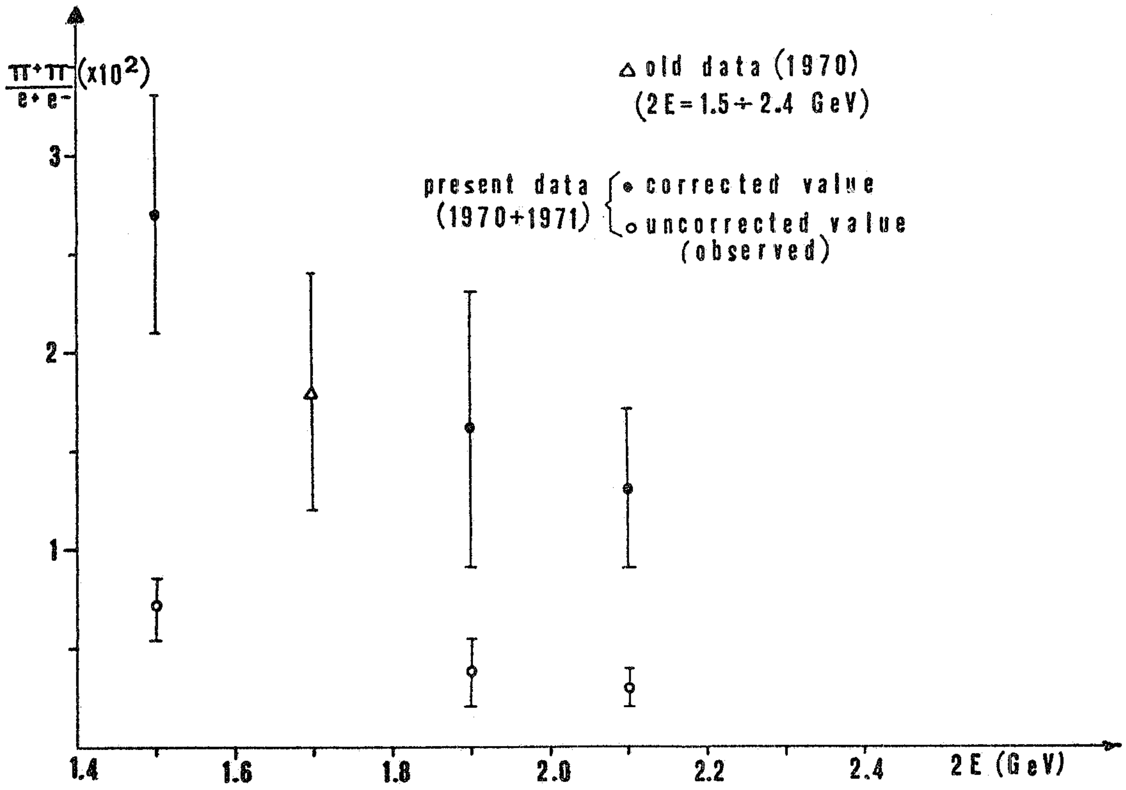

FIG. 2

## II. - RESULTS ON MULTIHADRONIC PRODUCTION. -

Our present evidence of multihadronic production is based on about 200 events.

The observed multiplicity distribution of these events, divided in three energy groups, is reported in the Table III. In this table we have also reported the frequencies of the different types of events (2, 3, 4 track events) relative to the associated WAS events and the numbers of events divided by the corresponding time-integrated luminosity.

From the definition of luminosity, it follows that these ratios are proportional to the corresponding cross-sections. We note that these ratios decrease (by a factor 2-3) in going from 1.5 to 2.0 GeV. For a detecting efficiency roughly constant with the total energy, this result would indicate a total hadronic cross section which decreases with increasing total energy.

The following discussion, which is made up of two parts, will be based essentially on events with 3 or more tracks.

### II.1. - Some results on the production mechanism of multibody events. -

One of the problems to be solved is the mechanism by which hadronic events are produced. Until now, all observed angular distributions are consistent with isotropic emission and, therefore, with the predictions of a statistical model (SM), such as that proposed by Bjorken and Brodsky(7). We shall see, however, that the overall data collected in our experiment cannot be interpreted in terms of the statistical model alone

In Fig. 3 the distribution of the non collinearity angle ($\Delta\theta$), for two-track events, is compared with the predictions of the SM. In Fig. 4 the distribution of the angles between any two tracks of three-track events is compared with the prediction from the SM and also from a quasi-two-body final state, involving the $A_1\pi$ system(x) (i.e. $e^+e^- = = A_1^\mp \pi^\mp \to \pi^\pm \pi^+ \pi^- \pi^+$). In both cases the results are consistent with the SM predictions.

However, the 4-track events give angular correlations which cannot be explained by the SM alone. In fact, the frequency of the

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(x) - This possibility, which has its relevance in the existence of decay $A_1 = \rho\pi$, has been considered in several theoretical papers(8).

## TABLE III

Observed multiplicity distribution for multi-body hadronic events

| 2 E (GeV) | Associated $e^+e^-$ events (WAS) | Number of tracks | | | | $\frac{2T}{WAS}$ | $\frac{3T}{WAS}$ | $\frac{4T}{WAS}$ ($x10^2$) | $\frac{2T}{L}$ | $\frac{3T}{L}$ | $\frac{4T}{L}$ ($x10^{33}$ $cm^2$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2T | 3T | 4T | 5T | | | | | | |
| 1.5 | 1842 | 31 | 27 | 10 | 0 | 1.7 | 1.5 | 0.6 | 1.2 | 1.2 | 0.44 |
| 1.7 | 992 | -- | 12 | 9 | 0 | --- | 1.2 | 0.9 | --- | 0.44 | 0.33 |
| 2.0 | 2400<br>(920 for 2T) | (28) | 50 | 10 | 2 | 3.0 | 2.1 | 0.4 | 1.0 | 0.6 | 0.11 |

WAS = Wide angle $e^+e^-$ scattering events

L = Time-integrated luminosity ($cm^{-2}$).

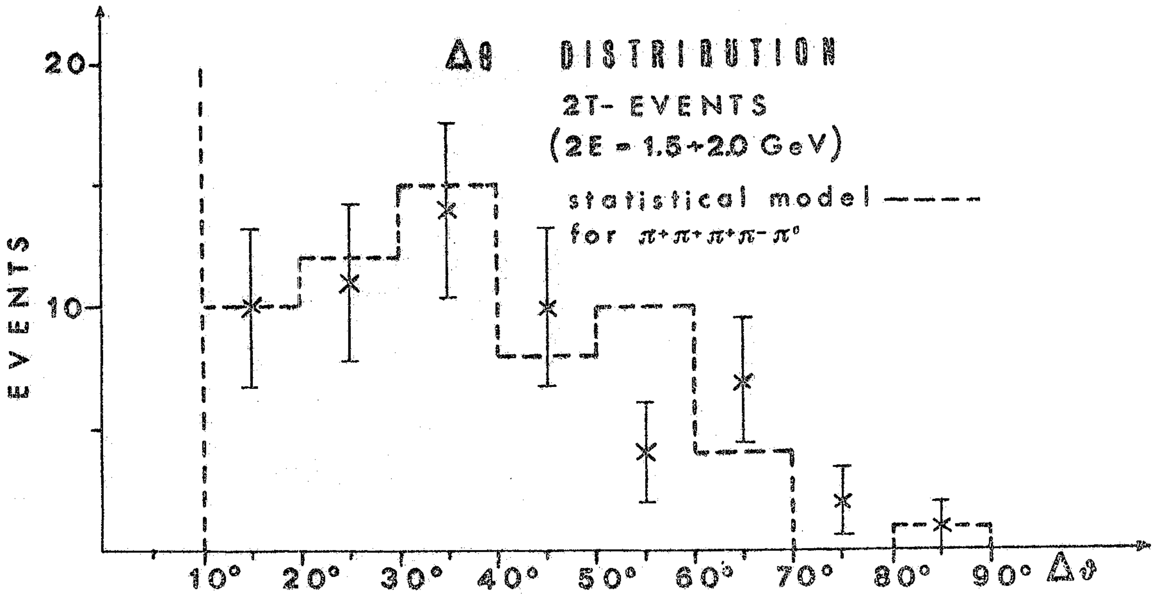
Δθ DISTRIBUTION
2T- EVENTS
(2E = 1.5÷2.0 GeV)
statistical model ----
for π+π+π+π-π0
EVENTS
20
10
10°
20°
30°
40°
50°
60°
70°
80°
90°
Δϑ

FIG. 3

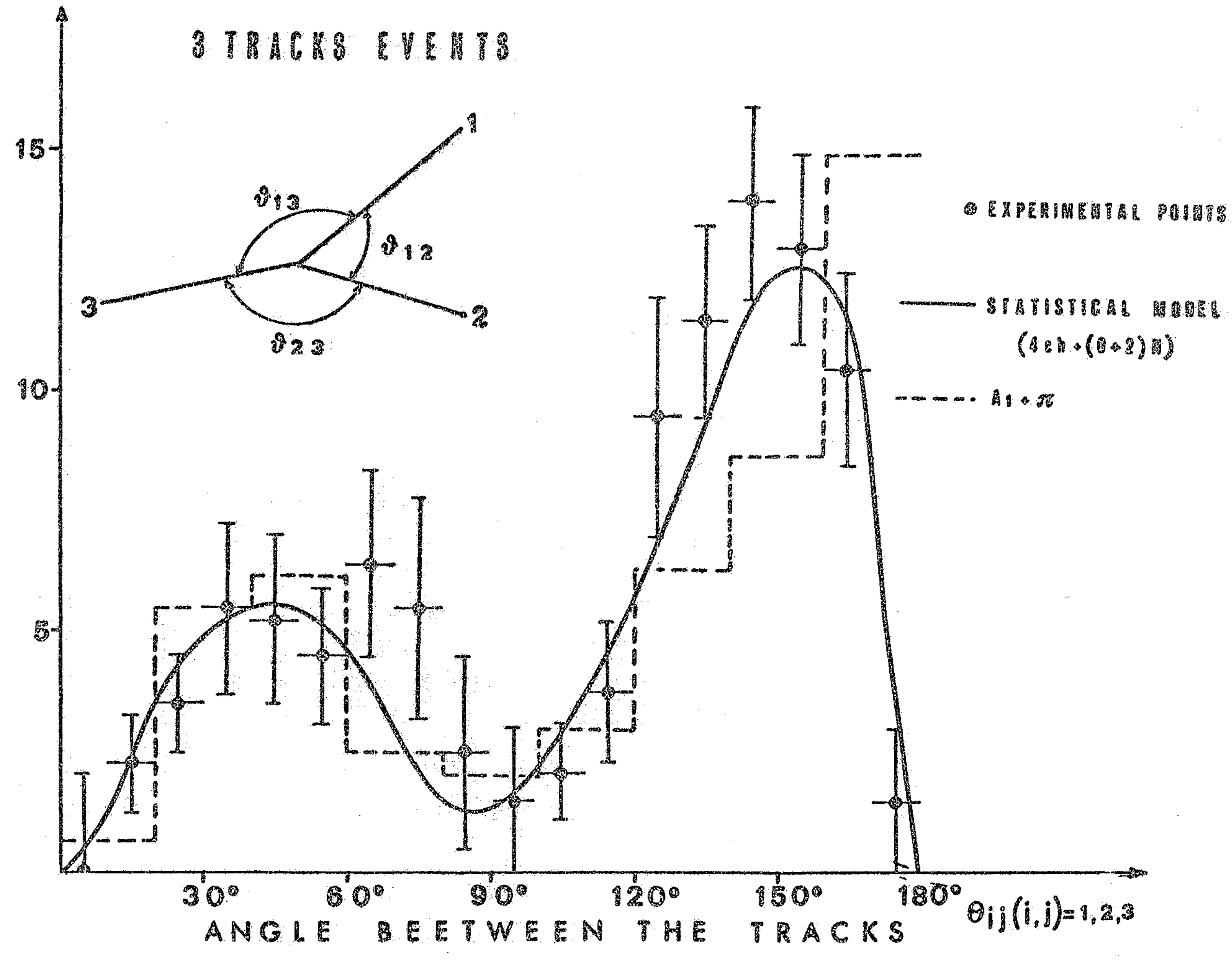
3 TRACKS EVENTS
1
2
3
ϑ13
ϑ12
ϑ23
⊗ EXPERIMENTAL POINTS
STATISTICAL MODEL
(4ch+(0÷2)N)
A1+π
15
10
5
30°
60°
90°
120°
150°
180°
θij(i,j)=1,2,3
ANGLE BEETWEEN THE TRACKS

FIG. 4

symmetric track configurations (i. e. 2 tracks on each telescope) is larger than expected from the SM as shown from the data given in Table IV.

## TABLE IV

4-Tracks events configurations: $\frac{\text{Number of events with a (3/1) configuration}}{\text{Number of events with a (2/2) configuration}}$

| 2 E (GeV) | Experimental value | Expected value | | | |
|---|---|---|---|---|---|
| | | Statistical model | | | $A_1^{\pm}\pi^{\mp}$(x) |
| | | 4 Ch + (0-1) $\pi^o$ | 4 Ch + 2 $\pi^o$ | 6 Ch | |
| 1.5 ÷ 2.4 | .13 $\pm$ .06 (34 ev) | .4 | 1 | 1 | .1 |

In this table are reported the ratio between number of events with a 3/1 configuration (asymmetric configuration) and of events with a 2/2 configuration (symmetric). It appears that the experimental value may be better explained by the inclusion of the $A_1\pi$ channel.

Furthermore, if one retains the SM, the data of the table indicate that the processes in which 6 pions are produced are unimportant.

Indications against a dominance of channels with six pions (charged or uncharged) come also from the following facts:

1) - the small observed number of events with 5 prongs. Only two events were observed and they yield $\sigma$ ($e^+e^- = 3\,\pi^+ + 3\,\pi^-$) = 2 nb;
2) - the relative frequency of 3-prong to 4-prong events, which is higher by a factor ~3 than expected, assuming that the 6-body channel is dominant. Also this result could be better explained with the inclusion of $A_1\pi$ (or similar processes);
3) - the frequency of e. m. showers present in the 3 or 4-prong events, which can be ascribed to $\pi^o$'s, is smaller that expected from channel $e^+e^- \rightarrow (2\,\pi^+ + 2\,\pi^- + 2\,\pi^o)$.

Most of the preceeding conclusions are not so strongly dependent on the absolute values of the detection efficiencies, as are those reported in the following section.

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(x) - In this calculation the $A_1$ was assumed to decay in a statistical way (into three pions).

## II.2.- Evaluation of cross sections.-

From the observed 3- and 4-track events we have calculated the cross sections for the processes :

(3) $$e^+e^- = 2\pi^+ + 2\pi^-$$

(4) $$e^+e^- = 2\pi^+ + 2\pi^- + \pi^0$$

(5) $$e^+e^- = A_1^{\pm,0} + \pi^{\mp,0}$$

We have assumed that only one reaction at a time was responsible for all of the observed events, so that the calculated values have to be regarded as upper limits for each channel. The results are reported in Fig. 5.

The efficiencies of the apparatus for the different reactions, used to derive the cross sections of Fig. 5, have been computed (by a Montecarlo calculation) in the hypothesis of a statistical production mechanism (isotropy, phase-space momentum distribution) for (3), (4),

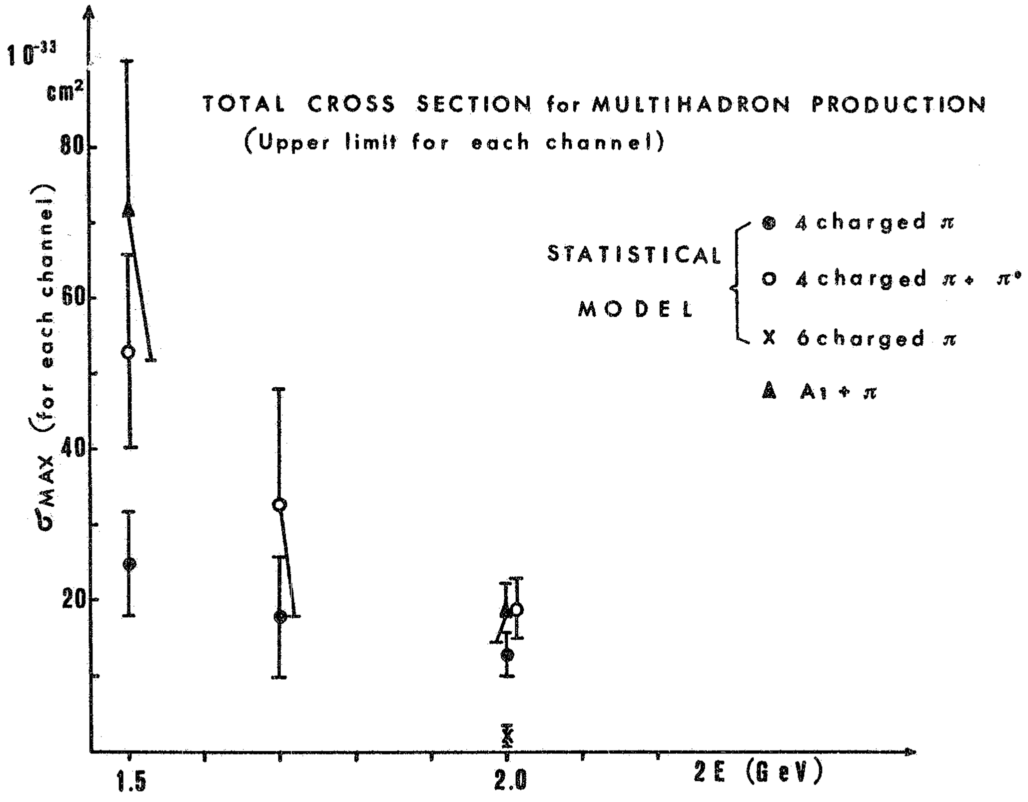

FIG. 5

and assuming for reaction (5) that :

$$\frac{A_1 \rightarrow 2\pi^+ + 2\pi^-}{A_1 \rightarrow \text{all}} = 1$$

Channel ($2\pi^+ + 2\pi^- + 2\pi^0$) has not been considered because it appears to be unimportant as mentioned above. The cross section for 6 charged pions is derived from the two 5-track events which were observed.

From Fig. 5 we see that in all cases the upper limit of the cross section for each channel clearly decreases in going from 1.5 to 2.0 GeV. Obviously in order to obtain the true energy variation of the multihadronic cross sections, we should know the relative weight of the different channels at each total energy. This analysis is now in progress.

The values reported here for the cross sections are, clearly, model dependent. Nevertheless, at 2E = 2 GeV, for any choice of the relative percentage of the various channels, the cross section for multihadron production (with 4 charged pions) is about 15 nb.

In summary the conclusions of our present analysis on multihadron production are:

1) - in the total energy range 1.5 ÷ 2.0 GeV the contribution from processes in which 6 pions are produced seems to be small;
2) - the upper limit of the cross section for each separate channel (4 charged $\pi$, 4 $\pi$ + 1 $\pi^0$, $A_1\pi$) decreases with increasing total energy;
3) - the cross section for multihadron production at 2 GeV is ~ 15 nb and almost model independent;
4) - some results are not explained if we assume that a statistical mechanism alone is operating. These results can better be explained if we assume that also a quasi-two-body reaction, like the $e^+e^- \rightarrow A_1\pi$, is present.

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(7) - J.D. Bjorken et al., Report SLAC-PUB-662 (1969).

(8) - See for example: J. Layssac et al., Report PM/71/2 (1971).