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C. Bacci, G. Penso, G. Salvini, B. Stella, R. Baldini Celio, G. Capon, C. Mencuccini, G. P. Murtas, M. Spinetti and A. Zallo :
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MULTIHADRONIC CROSS SECTIONS FROM $e^+ e^-$ ANNIHILATION UP TO 3 GeV c.m. ENERGY

C. BACCI, G. PENSO, G. SALVINI and B. STELLA
Istituto di Fisica dell'Università di Roma, Italy
Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Italy

R. BALDINI CELIO, G. CAPON, C. MENCUCCINI, G.P. MURTAS, M. SPINETTI and A. ZALLO
Laboratori Nazionali del CNEN, Frascati, Italy

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With an apparatus slightly improved with respect to a previous one we have studied multihadronic production at the Adone e^+e^- storage ring up to a maximum center of mass energy of 3 GeV.

We have studied the reactions

$$e^+ + e^- \to \text{multihadronic production} \quad (1)$$

at the highest total center of mass energies ($2E$) of the Adone storage ring, 2.8 and 3.0 GeV. New data have also been obtained, with more limited statistics, at total c.m. energies of 1.35, 1.65 and 1.98 GeV.

Our results may be summarized as follows:

There is a relatively abundant multiple hadronic production at 2.8 and 3 GeV. The observed events have three or more hadrons in the final state, and electromagnetic showers (neutral pions) are present in a large percentage of the cases.

The total cross section at the highest energies (fig. 1 and table 2) is larger than the total cross section for μ-pair production at the same energies.

Some new data at lower energies confirm the multihadronic production as already found at Frascati [2–5].

We give in the following some experimental details and possible interpretations.

The apparatus (fig. 1 of ref. [6]) is the same one as reported in the preceeding letter [6]. The main improvement with respect to previous apparatus [1] is the addition of the thin cylindrical spark chambers C_1, C_2, which make easier the identification of good events and the discrimination between charged and neutral particles.

The apparatus was triggered whenever a total of three charged particles or showers had been detected in three out of four blocks A, B, D, S, and counter α or β gave a signal (fig. 1 of ref. [6]); i.e. one of the particles had to be charged.

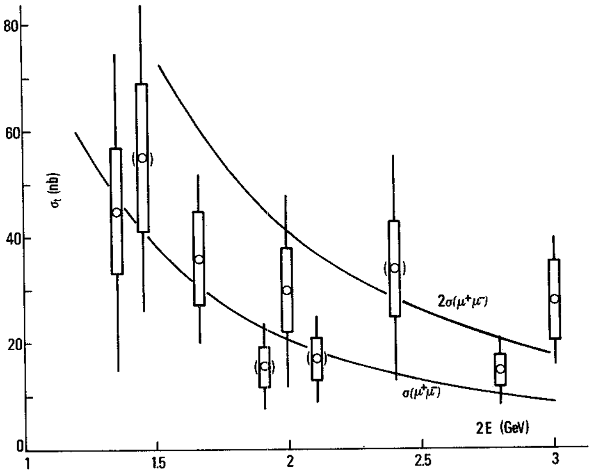

Fig. 1. Experimental results for the total cross section for reaction (1) versus the total energy in the c.m.. E is the energy of a single beam. The rectangles represent the systematic uncertainty, and the vertical lines represent the statistical errors. The points in parentheses were obtained without the cylindrical spark chambers C_1, C_2 (fig. 1 of ref. [6]). The solid lines represent the cross section $\sigma(e^+ + e^- \to \mu^+ + \mu^-)$ and $2\sigma(e^+ + e^- \to \mu^+ + \mu^-)$.

A pion (kaon) must have at least 95 MeV (145 MeV) kinetic energy in order to trigger the electronics, and at least 55 MeV (95 MeV) to give a recognizable track in the spark chambers.

We have obtained 112 multiple hadronic events at 3 GeV total c.m. energy with a total integrated lumi-

Table 1
Distribution of events according to the number of tracks (T) and neutral showers (S) detected at 3.0 and 2.8 GeV total c.m. energy; for instance 2T 3S means events with 2 tracks and 3 neutral showers observed.

Category c:	Number of events at 3 GeV (L=249 nb^{-1})	Number of events at 2.8 GeV (L=158 nb^{-1})
1T 2S	7	9
2T 1S	39	14
2T 2S	15	9
2T 3S	4	2
3T	16	4
3T 1, 2S	14	16
4T	10	1
1T 3, 4, 5S	3	6
4T 1, 2S	3	3
5T 0, 1S	0	1
0T 4, 5, 6S	1	2
total	112	67

Table 2
Total and partial cross sections at different c.m. energies, for processes $e^+ + e^- \to$ multihadronic production. σ_t is the total cross section for processes (1). σ_4 is the sum of the cross sections for reactions (5) and (6). The values in parentheses were obtained without the cylindrical spark chambers C_1, C_2 (fig. 1 of ref. [6]).

Total c.m. energy $2E$ (GeV)	σ_t (10^{-33} cm^2)	σ_4 (10^{-33} cm^2)	($e^+ + e^- \to \pi^+ + \pi^- + \pi^0$) ($10^{-33}$ cm^2)
3.0	28±4.5 (±7.5)	16±2.5 (±3.5)	5±3
2.8	15±3.5 (±3)	11±2.5 (±2.5)	0–2
(2.4)	34±12 (±9)	7±5 (±2)	
(2.1)	17± 4 (±4)	8.5±3 (±2)	
1.98	30±10 (±8)	} 7±2 (±1)	} ≤5±2 [1]
(1.90)	15.5± 4 (±4)		
1.65	36± 7 (±9)	17±5 (±4)	
(1.45)	55±15 (±14)	} 28±10 (±6)	
1.35	45±18 (±12		

nosity L of 249 × 10^{33} cm^{-2} and 67 multiple hadronic events at 2.8 GeV c.m. with a luminosity L = 158 × 10^{33} cm^{-2}. These events have been distributed in categories c (table 1) according to the number of neutral showers and charged particles (tracks) identified in the four blocks A, B, D, S. The luminosity L has been measured by using as a monitor the scattering $e^+ + e^- \to e^+ + e^-$ at small momentum transfer [7].

Using known arguments [1], we assume in the following that the multiple events are of hadronic nature, with the particles directly produced being primarily pions. We also assume that the well known one photon annihilation channel is the source of these processes. This last assumption, though very plausible, is not strictly verified in this analysis.

Processes:

$$e^+ + e^- \to e^+ + e^- + \text{hadrons } (\gamma\gamma \text{ interactions}) \qquad (2)$$

which have been studied by many authors [8] may contribute to only a small fraction (less than 5%) of our events.

In order to obtain the total cross section of process (1), we have assumed that the most important processes which contribute to our events are the following:

$$e^+ + e^- \to \pi^+ + \pi^- + \pi^0 \qquad (3)$$

$$e^+ + e^- \to \pi^+ \pi^- + n\pi^0 \; (2 \leqslant n \leqslant 6) \qquad (4)$$

$$e^+ + e^- \to m\pi^\pm + n\pi^0 \; (m = 4,6,8); (4 \leqslant (n+m) \leqslant 8) \qquad (5)$$

$$e^+ + e^- \to 10\,\pi^\pm \qquad (6)$$

This corresponds to the assumption that disregarding processes with more than 8–10 pions or with kaons, does not appreciably affect our final results on the total cross section. This hypothesis is consistent with the hadronic multiplicities observed in $p+\bar{p}$ [10] annihilation at the same c.m. energies

An estimate of the cross section for process (3) at 3.0 GeV may be obtained directly from the analysis of the 39 events of category 2T 1S, and of the 15 2T 2S events. From the 2T 1S events we have selected those which may be due to reaction (3) on the basis of: range and coulomb scattering of the particles; absence of other tracks in the cylindrical thin spark chambers C_1, C_2; angle α of the shower respect to the plane of the two charged particle tracks. With these criteria we are left with seven events which may be due to reaction (3) and we may compare the distribution in angle α for these events with the Montecarlo predictions for processes (3) and (4). We also studied category 2T 2S, where we have looked for those events which may describe *completely* process $e^+ + e^- \to \pi^+ + \pi^- + \pi^0$. In this case one can calculate the two photon invariant mass m, and look for the events with $m_{\gamma\gamma} \approx m_{\pi^0}$.

Out of 15 events at 3.0 GeV, we found two such events with $m_{\gamma\gamma}$ = 180±35 MeV respectively. We also found one possible $\pi^+ \pi^- \eta$ ($\eta \to \gamma\gamma$) event with $m_{\gamma\gamma} \approx$ 550±50 MeV.

Finally, from 2T 1S and 2T 2S events we get for process (3) the result:

$$\sigma(e^+ + e^- \to \pi^+ + \pi^- + \pi^0) = 5 \pm 3 \text{ nb, at 3.0 GeV.} \quad (7)$$

We cannot exclude that part of the events interpreted as $e^+ + e^- \to \pi^+ + \pi^- + \pi^0$ are instead due to $e^+ + e^- \to \pi^+ + \pi^- + \gamma$ (these two processes have similar trigger efficiencies).

The same procedure has been used at 2.8 GeV. In this case we found no event which could be interpreted as due to reaction (3) (one event would correspond to 2 nbarn). We obtain:

$$\sigma(e^+ + e^- \to \pi^+ + \pi^- + \pi^0) = 0\text{–}2 \text{ nb, at 2.8 GeV.} \quad (8)$$

These are the only results one can obtain in a rather direct way for a single channel.

The values of cross sections for reaction (5), (6) and of the total cross section for reaction (1) have been estimated using the approach followed in previous publications [1]. The cross sections at a given energy for the processes (3)–(6) may be obtained from a system of relations of the type:

$$N_c = L \sum_i \sigma_i \epsilon_{ic} \quad (9)$$

where N_c is the total number of the events belonging to a given category c, characterized by the number of tracks and showers observed (table 1). L is the total luminosity. The σ_i are the cross sections for processes (3)–(6). ϵ_{ic} is the detection efficiency for events of category c coming from reaction i.

All the efficiencies ϵ_{ic} have been evaluated under the hypothesis of a pure invariant phase space momentum distribution [1].

Following this procedure, we have looked for the best solution to the relations (9) with the requirement that all the σ_i be positive or zero. For reaction (3) we introduce our measured value (7), (8).

Because of the poor statistics, each individual cross section has a large error. However it is possible to find reliable values for the sum of cross sections for processes with at least *four* charged pions and any number (including zero) of π^0. For σ_4, sum of the cross sections for processes (5) and (6), we obtain the following values from relations (9):

$$\sigma_4 = 16 \pm 2.5\ (\pm 3.5) \text{ nb, at 3.0 GeV;} \quad (10)$$

$$\sigma_4 = 11 \pm 2.5\ (\pm 2.5) \text{ nb, at 2.8 GeV.} \quad (11)$$

The first error is statistical only, calculated on the basis of Poisson fluctuations in N_c. The second error, in parentheses, is an estimate of the systematic uncertainties.

The determination of the cross section for process (4) is less direct, due to some criticality in the solution of system (9).

Therefore we have looked for different methods to evaluate σ_2, the cross section of channel (3) plus (4).

These include a) direct analysis of events 1T 2S and 2T 2C; b) analysis of the isospin relations among the multiplicities for charged and neutral pions [9].

Using these methods we obtain:

$$\sigma_2 = 12 \pm 6 \text{ nb, at 3.0 GeV} \quad (12)$$

$$\sigma_2 = 4 \pm 2 \text{ nb, at 2.8 GeV} \quad (13)$$

where the errors in this case include the systematic uncertainties.

The total cross section σ_t has been obtained by addition of results (10) and (12) for 3.0 GeV, and (11) and (13) for 2.8 GeV.

$$\sigma_t = 28 \pm 4.5\ (\pm 7.5) \text{ nb at 3 GeV} \quad (14)$$

$$\sigma_t = 15 \pm 3.5\ (\pm 3) \text{ nb at 2.8 GeV} \quad (15)$$

where the quoted errors have been evaluated in a rather conservative way without taking account of the correlations between σ_2 and σ_4 imposed by relations (9).

In table 2 and fig. 1 we report our values of σ_t at 2.8 and 3 GeV together with some new results which we have obtained at lower energies. In addition we include our previously published results [1] at lower energies.

Alternatively we have tried to obtain the total cross section σ_t for multihadronic production assuming for the processes (3)–(6) the branching ratios A_i observed in $p+\bar{p}$ annihilation at the same c.m. energies [10].

The $p+\bar{p}$ annihilation data leave little room for the mode $p+\bar{p} \to \pi^+ + \pi^- + \pi^0$ and indicate a somewhat higher pion multiplicity than we observe. In this $p\,\bar{p}$ model, we have obtained the total cross section for process (1) through the relations:

$$N_c = \sigma_t \sum_i A_i \, \epsilon_{ic} \qquad (16)$$

where A_i is the branching ratio for the reaction i. We again assume efficiencies ϵ_{ic} given by our invariant phase space model. The results for the total cross section of process (1) obtained in this way are in general agreement with results (14) and (15). For instance we obtain $\sigma_t = 20 \pm 6$ nb at 3.0 GeV. This value become 25 ± 9 nb if we include a $\pi^+ + \pi^- + \pi^0$ contribution (absent in $p+\bar{p}$ data) using our result (7). We point out that $p+\bar{p}$ annihilation at high energy does not occur in a pure $J^P = 1^-$ states as in the $e^+ + e^-$ case. Therefore the interest of the comparison with $p+\bar{p}$ annihilation may be a question of taste.

The most interesting observation from our data is that the cross sections at 2.8 and 3 GeV appear to be remarkably high. Of course we cannot yet be certain whether the difference between 2.8 and 3 GeV in the c.m. is significant.

One point of reference for a comparison with theory is the cross section for muon pair (that is a pointlike fermion pair) production [11]. Our values for hadronic production cross section at the highest energies seem to be higher than $\sigma(e^+ + e^- \to \mu^+ + \mu^-)$.

At the recent Batavia Conference [2] a high value of σ_t was presented by CEA: at 4 GeV c.m. they found σ_t (multiple hadronic production) $\approx (3-5) \cdot \sigma(e^+ + e^- \to \mu^+ + \mu^-)$. If we consider these results at high energy as already "asymptotic" then some models are clearly more reasonable than others. In the simplest quark model [11]

$$\sigma_t(e^+ + e^- \to \text{hadrons}) \approx \tfrac{2}{3}\,\sigma(e^+ + e^- \to \mu^+ + \mu^-) \approx 7 \text{ nb at 3 GeV c.m.}$$

which is considerably lower than our value.

A recent prediction by Gell-Mann [12] gives instead

$$\sigma_t(e^+ + e^- \to \text{hadrons}) \approx 2\sigma(e^+ + e^- \to \mu^+ + \mu^-) \approx 20 \text{ nb at 3 GeV c.m.}$$

This case remains possible.

A recent theoretical analysis by Greco [13] seems to explain our experimental results on the basis of the existing vector bosons.

A new experimental apparatus is under construction, which will allow detailed analysis of the channels which contribute to multihadronic production.

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