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MULTIHADRON PRODUCTION IN e^+e^- COLLISIONS UP TO 3 GeV TOTAL C.M. ENERGY

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New results on the multihadron production by electron and positron beams colliding with a total energy of up to 3 GeV are reported. Disregarding possible kaon final states, the ratio $\sigma_{mh}/\sigma_{\mu\mu}$ of the total multihadron cross-section to the point-like cross section for process $e^+e^- \to \mu^+\mu^-$ has an average value of 1.58 ± 0.25 in the energy interval 2.6 – 3.0 GeV. The average charged multiplicity over this energy range is $\langle n_c \rangle = 2.9 \pm 0.3$.

The investigation of the electron-positron annihilation into multihadron final states has provided some of the most interesting results achieved with e^+e^- colliding beams. The final state hadrons are believed to be mostly pions [1] and a first result of great interest, also for its possible connections to the results on the deep e-p inelastic scattering, is the comparatively large value of the total cross section, σ_{mh}, observed at c.m. energies $E_+ + E_- = 2E \equiv \sqrt{s} \gtrsim 1.5$ GeV for the multihadron reactions

$$e^+e^- \to \tfrac{1}{2}n_c\pi^+ + \tfrac{1}{2}n_c\pi^- + n_o\pi^o \,. \qquad (1)$$

These involve n_c (= 2; 4; 6...) charged pions and n_o (= 1; 2; 3...) neutral pions, with the condition (since we want to exclude all two-body processes) $n_c + n_o \geqslant 3$. With reference to the point-like cross section, $\sigma_{\mu\mu}$ ($\sigma_{\mu\mu} = 21\ \mathrm{nb}/E^2_{\mathrm{GeV}}$), of the annihilation process

$$e^+e^- \to \mu^+\mu^- \qquad (2)$$

values as large as 1.5 – 4 have been reported for the ratio $\sigma_{mh}/\sigma_{\mu\mu}$ by various groups [1–3].

The average charged multiplicity, $\langle n_c \rangle$, and total multiplicity, $\langle n_c + n_o \rangle$, have been also determined at various energies [2–4].

We report in this letter new data on the total cross-section of processes (1) obtained at $\sqrt{s}$ = 2.6, 2.8 and 3.0 GeV. When corrected for a small contribution due to the two photon annihilation reaction

$$e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X \qquad (3)$$

(in which the two γ^*'s are "quasi real" photons and X represents a lepton pair or any hadron final state with $C = +1$) the average value of σ_{mh} in the energy interval 2.6 – 3.0 GeV is found to be $\sigma_{mh} = (1.58 \pm 0.25)\ \sigma_{\mu\mu}$.

The "main apparatus" (MA) employed in the measurements reported here consists of two wide-angle counter-chamber telescopes (fig. 1) and can be regarded as an improved version of one previously described [1]. In particular thick concrete absorbers and huge hodoscope chambers (of 2m × 4m sensitive area) were added to the previous apparatus in order to observe the muon stop from process (2), which however, like all other two-body reactions, will be disregarded in the present paper. The effective solid angle of the MA for the hadronic events discussed in this paper was about 1/4 of 4π from the center of the e^+e^- interaction region.

Events were analyzed and identified starting from the chamber photographs of the MA. In addition to the MA, however, two auxiliary pieces of apparatus were also installed over the same straight section of Adone: 1) A monytoring system [5] yielding with an estimated ±5% accuracy the machine luminosity from the measured rate of Bhabda scattering events

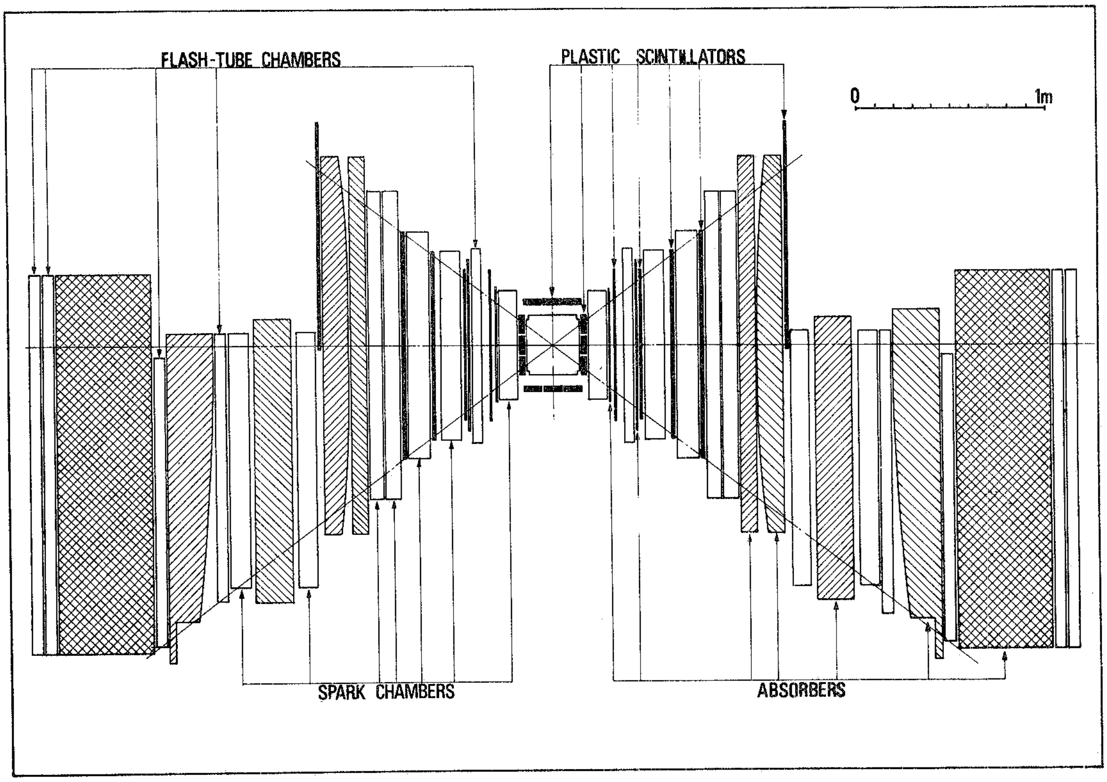

Fig. 1. Cross sectional view of the "main" apparatus (MA). The e^+ and e^- bunches travel perpendicularly to the figure plane. The flash-tube and spark chambers placed externally, after the last plastic scintillators, were only used to observe the stop of muons from process (2).

at small angles; 2) A tragging counter system which exploited the two bending magnets adjacent to the straight section [6] in order to determine, with a typical accuracy of ±4%, the energy of the e^+ and/or e^- emitted forward in processes (3).

The tagging system was particularly useful for identifying events from process (3) which otherwise would appear in the MA as events from process (1) with two non collinear tracks (2T events as defined below). The corresponding correction to the recorded number of 2T events (a correction which in the absence of the tagging system should be introduced on the basis of a calculation) is less than 10% at all energies, but it corresponds to a nearly 30% correction to the partial cross section (σ_2) relative to channels with two charged hadrons and any number of neutrals in final state.

For an event to be recorded by the MA the following conditions had to be fulfilled:

a) At least one charged particle had to be emitted in each telescope of the MA.

b) The charged particles had to penetrate at least 36 g/cm^2 of iron equivalent in one telescope (correspnding pion kinetic energy E_π = 95 MeV) and at least 75 g/cm^2 in the other telescope (E_π = 155 MeV).

c) The event had to be within ± 10 nsec in time with respect to the instant of collision of the e^+ and e^- bunches at the center of our straight section‡1.

Counters placed at a depth of 380 g/cm^2 of iron equivalent (E_π = 605 MeV) were used to veto cosmic ray events. "Good events", originated at the interaction region near the center of the straight section, were not rejected, however, by these counters, since they could be distinguished from cosmic rays on the basis of a time-of-flight technique [7]. Other counters

‡1 The collision time of Adone's bunches is about 2 nsec and the time between two consecutive collisions is 117 nsec.

placed, at a distance of $\sim 1-2$ m, on opposite sides of Adone's vacuum chamber, were used for this purpose.

At the occurrence of an event fulfilling the above listed conditions all chambers were triggered and the film was advanced soon after the recording, on a sinlge 70 mm × 100 mm frame, of two orthogonal views of the chambers and of a "data box". The latter contained all data relevant for the event (data and time, event number, integrated luminosity, counter pulse heights and times-of-flight, etc.) given in digital form by nixie lamps.

Let $\sigma_{r,s}$ be the partial cross section of the particular multihadron reaction which involves $r \equiv n_c$ charged hadrons and $s \equiv n_0$ neutral hadrons [$n_c \geqslant 2$, $n_0 \geqslant 0$, $n_c + n_0 \geqslant 3$, see eq. (1)]. The corresponding event, consisting of n_c charged particles and n_0 neutral pions, may be recorded by the MA in any configuration, $c \equiv nT$, with $n \leqslant n_c$ single tracks (T). (The inequality sign arises of course from the fact that the MA has a detecting solid angle $\omega < 4\pi$.)

By means of special runs in which the machine was operated with a single beam, or with two beams separated so as to exclude collisions of the e^+ and e^- bunches, we proved that the numbers of events recorded in the configuration c, N_c, need not to be corrected for any background contribution, except in the case of the particular configuration c = 2T. Two-track events were accepted in the 2T configuration of the hadronic events if the angle between the planes identified by each track and the beams was greater than 10°. With this condition the background contribution, to be subtracted statistically to the recorded numbers of events in the 2T configuration, was found to be smaller than 10% at all energies.

Each 2T event was further required to have not a coincident pulse in any of the two counters of the tagging system. Under these conditions there remains only a small background contribution to the 2T events, which is made up of two small terms of opposite signs. One due to $\gamma\gamma$ events [process (3)] whose secondary e^+ and e^- have both missed the tagging counters; the other one due to an accidental coincidence of a genuine 2T event in the MA, with an uncorrelated pulse from either tagging counter. At all energies this residual background contribution is represented by less than 1 event, out of the numbers of 2T events reported in table 1. It has been there-

Table 1
Numbers of multihadron events in various configurations. $(4T)_{rec.}$ are 4T events for which it is possible a kinematical reconstruction based on the measured directions of the four tracks. 2T events are corrected as explained in the text.

2E	$\int L\,dt$	Number of events in the configuration				
(GeV)	(nb^{-1})	2T	3T	4T	⩾ 5T	$(4T)_{rec.}$
2.6	166	73	54	24	5	7
2.8	160	64	55	22	5	6
3.0	338.5	109	81	27	4	9

fore neglected. In the table the numbers N_c of events recorded in each configuration are reported together with the values of the integrated luminosity.

In table 2 we give the efficiencies $\epsilon_c^{(rs)}$ with which processes involving r charged and s neutral pions are recorded in the configuration c. The efficiencies have been obtained by a Monte Carlo method assuming an invariant phase space production mechanism [1]. We have also explicitely assumed [1] that processes involving K mesons can be disregarded. This allowed us to reduce the number of unknown partial cross sections, σ_{rs}, in the system of equations

$$N_c = \{\int L\,dt\} \sum_{r,s} \epsilon_c^{(rs)}\,\sigma_{rs} \quad (4)$$

which relate the numbers of events N_c recorded in the configurations c to the σ_{rs}'s.

We have 14 events with more than 4 tracks (see table 1). With the extreme assumption that they are all due to final states with at least 8 charged pions, we get an upper limit of 0.5 nb (90% c.l.) for the cross section of channels involving at least 8 charged pions. Disregarding these channels therefore, does not affect appreciably the final results on the total multihadron cross section.

Disregarding channels with K mesons and with at least 8 charged pions is not sufficient, however, to make the number of unknowns smaller or equal than the number of eqs. (4). There are in fact essentially only three independent equations‡2; those corresponding to the numbers N_2, $N_3 + N_4$ and $N_{\geqslant 5}$.

In order to overcome this difficulty we introduce the assumption that the relationships valid for proton-antiproton annihilation at rest among the partial cross

‡2 Footnote: see next page.

Table 2
Percent efficiencies $\epsilon_c^{(r,s)}$ with which events involving r charged and s neutral pions are detected in the configuration of n tracks.

$n \backslash (r,s)$	(2,1)	(2,2)	(2,3)	(4,0)	(4,1)	(4,2)	(6,0)	(6,1)	$2E$
2	1.49 ± 0.14	2.58 ± 0.14	1.92 ± 0.13	5.31 ± 0.38	4.99 ± 0.28	2.59 ± 0.20	2.59 ± 0.27	1.96 ± 0.17	
3				5.95 ± 0.44	4.42 ± 0.25	3.68 ± 0.24	5.84 ± 0.45	4.72 ± 0.28	
4				2.25 ± 0.23	1.31 ± 0.12	1.47 ± 0.14	5.26 ± 0.38	4.02 ± 0.25	2.6
5							2.48 ± 0.18	1.74 ± 0.17	GeV
6							0.41 ± 0.08	0.28 ± 0.06	
2	1.54 ± 0.15	2.48 ± 0.13	1.59 ± 0.15	4.98 ± 0.36	4.16 ± 0.24	3.07 ± 0.22	2.72 ± 0.24	2.57 ± 0.21	
3				6.21 ± 0.47	4.23 ± 0.24	3.93 ± 0.24	5.80 ± 0.46	4.68 ± 0.28	
4				1.92 ± 0.19	1.47 ± 0.13	1.20 ± 0.13	5.30 ± 0.38	4.43 ± 0.91	2.8
5							2.63 ± 0.19	1.94 ± 0.18	GeV
6							0.44 ± 0.08	0.24 ± 0.06	
2	1.60 ± 0.17	2.41 ± 0.14	1.87 ± 0.17	5.20 ± 0.37	4.06 ± 0.25	3.04 ± 0.21	2.95 ± 0.27	2.44 ± 0.21	
3				5.34 ± 0.39	4.29 ± 0.26	3.49 ± 0.23	5.63 ± 0.43	4.62 ± 0.27	
4				2.01 ± 0.20	1.31 ± 0.13	1.54 ± 0.16	5.47 ± 0.39	4.48 ± 0.27	3.0
5							2.18 ± 0.16	1.88 ± 0.17	GeV
6							0.38 ± 0.07	0.36 ± 0.08	

sections with the same number r of charged pions but different numbers s of neutral pions, are also valid in our case. This assumption is somewhat justified by the fact that our energy region is not too far from that of the $p\bar{p}$ annihilation at rest. On the other hand the following relationships are established with rather good accuracy‡3 for $p\bar{p}$ annihilation at rest [9]:

$$\sigma_{60} \approx \sigma_{61} \approx \tfrac{1}{2}\sigma_6 \; ; \qquad \sigma_{62} = \sigma_{63} = \dots \text{ negligible}$$

$$\sigma_{41} \approx \sigma_{42} \approx 3\sigma_{40} \approx \tfrac{3}{7}\sigma_4 \; ; \quad \sigma_{43} = \sigma_{44} = \dots \text{ negligible}$$

$$3\sigma_{21} \approx \sigma_{22} \approx \tfrac{3}{4}(\sigma_2 - \sigma_{23}) \; ; \; \sigma_{24} = \sigma_{25} = \dots \text{ negligible}$$

where we have introduced the notation $\sigma_r = \Sigma_s\, \sigma_{rs}$.

Assuming a statistical behaviour in the isospin space [10] we obtian furhtermore $\sigma_{23} = \frac{1}{2}\sigma_{41}$ and are left just with three equations in the three unknowns σ_2, σ_4 and σ_6.

‡2 Unlike the case which has led to the observation of the $\rho'(1600)$ meson [8], the fully reconstructed events with 4 charged pions, have now little statistical significance. This is so not only because of the limited number of $(4T)_{rec}$ events, but also because in the present energy region σ_{40} is small; and smaller, in particular, than σ_{41} and σ_{42} which give a non-negligible contribution to the number of reconstructed 4T events.

‡3 It should be emphasized that variations in the relative weights of cross sections σ_{rs} having the same number r of charged pions, have little influence on the value of the total cross section $\sigma_{tot} \equiv \sigma_{mh} = \Sigma_r\, \Sigma_s\, \sigma_{rs} = \Sigma_r\, \sigma_r$.

Even though we cannot use the number of reconstructed 4T events to get an additional constraint‡2, we verified that the solution of our equations yield a number of reconstructed 4T events consistent with that observed.

The results of the present experiment are summarized in table 3 where the partial cross sections σ_2, σ_4, σ_6 and the total cross section σ_{mh}, are reported together with the ratio $\sigma_{mh}/\sigma_{\mu\mu}$. The energy dependence of σ_{mh} is shown in fig. 2 where previous results [1–3] are also reported.

The average value of the ratio $\sigma_{mh}/\sigma_{\mu\mu}$ over the energy range explored is

$$\sigma_{mb}/\sigma_{\mu\mu} = 1.58 \pm 0.25 \,.$$

We have tested that this result is not much affected by reasonable changes in the relative weights of the partial cross sections. Consequently the quoted error - which is merely the statistical one - should be somewhat enlarged, but essentially only to take into account possible deviations from the hypothesis of invariant phase space introduced in the Monte Carlo calculation of the efficiencies.

From the experimental data of table 3 we obtain for the average multiplicity, at the mean energy $2E$ = 2.85 GeV, the mean value

$$\langle n_c \rangle = 2.9 \pm 0.3 \,.$$

A maximum systematic error of +0.3 should be added

Table 3

Results on multihadron partial and total cross sections, expressed in nanobarn (1nb = 10^{-33} cm^2).

$2E$	2.6 GeV	2.8 GeV	3.0 GeV	2.85 GeV
σ_2	11.1 ± 5.4	9.6 ± 5.0	8.6 ± 4.5	9.7 ± 2.9
σ_4	6.0 ± 1.7	6.2 ± 1.7	4.8 ± 1.6	5.7 ± 1.0
σ_6	1.2 ± 0.7	1.2 ± 0.7	0.5 ± 0.5	1.0 ± 0.4
σ_{mh}	18.3 ± 4.7	17.0 ± 5.0	13.9 ± 5.0	16.4 ± 2.6
$\sigma_{mh}/\sigma_{\mu\mu}$	1.47 ± 0.38	1.58 ± 0.47	1.49 ± 0.54	1.58 ± 0.25

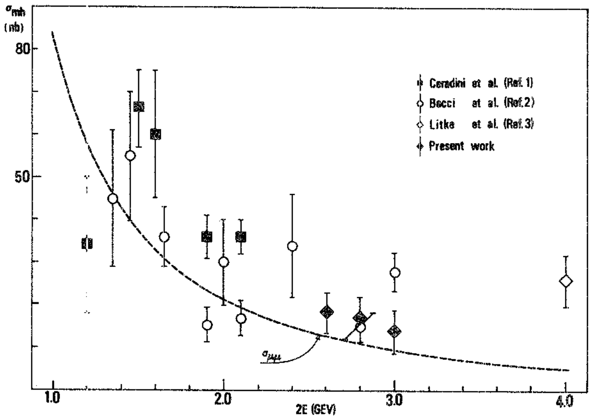

Fig. 2. Energy dependence of the total cross section for multihadron production by e$^+$ and e$^-$ colliding beams. The curve gives for comparison the "point-like" cross section for e$^+$e$^-$ annihilation into muon pairs.

here to take into account possible contributions from final states with at least 8 charged particles which have been entirely neglected.

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