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8 Giugno 1979

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SUMMARY.

We report experimental results on the cross section for the reaction $e^+e^- \longrightarrow$ hadrons as a function of the total c. m. energy in the range W=1. 42 - 3. 09 GeV. The results, combined with those already existing below the charm threshold, clearly indicate a structure for $R(W) = \sigma(e^+e^- \longrightarrow \text{hadrons})/\sigma(e^+e^- \longrightarrow \mu^+\mu^-)$ in that energy region.

We present experimental results on the cross section for the reaction

$$e^+e^- \longrightarrow \text{hadrons} \tag{1}$$

measured at Adone storage ring ($\gamma\gamma2$ experiment), in the total c. m. energy range W=1. 42- 3. 09 GeV. A preliminary analysis of the data at energies W ≥ 1. 92 GeV has already been published(1).

In the present paper we refer to the data taken at energies below 1. 972 GeV, and we present definitive results in the whole energy range (1. 42 - 3. 09 GeV) explored at Adone.

The experimental set-up has been described in detail elsewhere(1-3). It consists of two large semicylindrical telescopes placed above and below the interaction region with their axis orthogonal to the beam line. These telescopes, designed for both photons and tracks detection, are sandwiches of scintillation counters, optical spark chambers and lead converters for a total thickness of 5. 5. r.l. The solid angle covered by the triggering counters is 0. 41 x 4π sr and that covered by the optical spark chambers is 0. 66 x 4π sr.

During the data taking at lower energy (W ≤ 1. 58 GeV), the set-up has been implemented with a central core of limited streamer tubes(4) with bidimensional read-out, placed close to the doughtnut, all around the interaction region. This core, which does not enter in the trigger logic, covers a solid angle of ~ 0. 9 x 4π sr and allows to detect charged particles with an energy as low as 20 (30) MeV for pions (kaons).

The trigger logic requires a coincidence between the upper and lower telescopes of the shower detector. In order to fire a telescope a pion (kaon) must have a kinetic energy of at least 120 (190) MeV. If photons convert in the telescope, this limit can be as low as 35 (60) MeV. The photon detection efficiency of the trigger logic has been calculated by Monte-Carlo method; the optical efficiency of the spark chambers has been taken into account. In Fig. 1 we report the overall photon detection efficiency vs. photon energy.

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The present results are relative to 3505 events, corresponding to a total integrated luminosity L=346 nb^{-1}, measured by wide angle Bhabha scattering in the present apparatus. The events were selected by requiring one charged prong in each telescope, plus at least another particle (track or photon) in the apparatus. Background due to beam-gas interaction has been measured by running the machine with a single beam. These events consist mostly of only two tracks in the apparatus, and therefore are not accepted by our selection criteria. Higher multiplicity background events are a negligible fraction of genuine beam-beam events.

In order to analyse the data, the selected events have been classified into different categories, according to the number of observed tracks and photons. The number n_k of events collected in the k-th category is given by

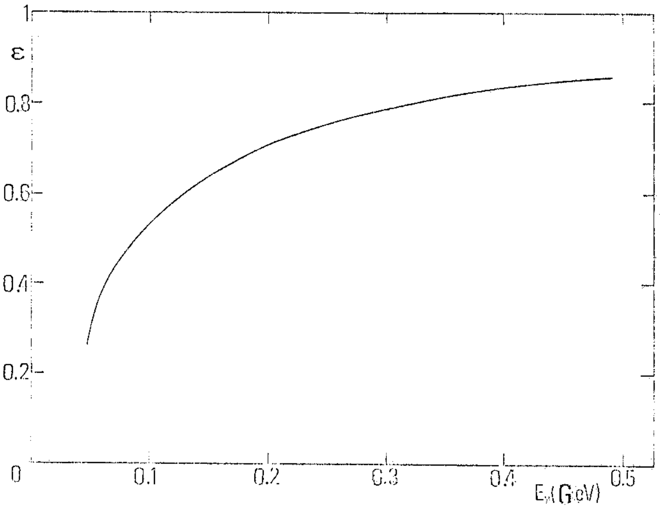

FIG. 1 - Photon detection efficiency vs. photon energy.

$$n_k = L \sum_i \varepsilon_{ki} \sigma_i \qquad (2)$$

where: L is the integrated luminosity; ε_{ki} is the efficiency for detecting the i-th reaction in the k-th category; σ_i is the corresponding cross section. In evaluating ε_{ki} by Monte-Carlo method, we have assumed that only pions are produced with an invariant phase space distribution. Furthermore we assumed a minimum and maximum multiplicity of three and six pions respectively. In solving the system of equations (2) by a standard maximum likelihood method, we have imposed the relation $\sigma(e^+e^- \longrightarrow \pi^+\pi^-\pi^+\pi^-\pi^0) = 2\sigma(e^+e^- \longrightarrow \pi^+\pi^-\pi^0\pi^0\pi^0)$ which derives from isospin considerations.

It should be noted that two-body final states (e. g. $e^+e^- \longrightarrow \pi^+\pi^-$; K^+K^-) have not been considered neither in the events selection criteria, nor in the equations (2). Therefore our results are given in terms of $R_{\geq 3} = \Sigma\, \sigma_i(\geq 3\pi) / (e^+e^- \longrightarrow \mu^+\mu^-)$.

In Fig. 2 we report as a function of W, the values of $R_{\geq 3}$ obtained with (open circle and without

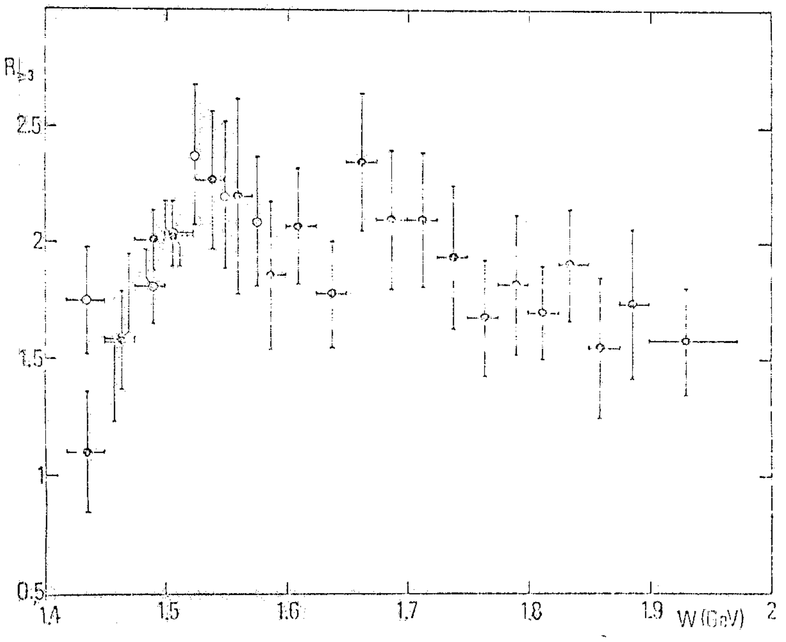

FIG. 2 - Present results on $R_{\geq 3}$ vs. total c. m. energy W; full (open) circle are obtained without (with) the central core in the set-up (see text). The quoted errors are statistical only.

(full circle) the central core in the apparatus. The agreement between the two sets of measurement is quite good, giving confidence in our data analysis method.

In Table I we report our definitive values of $R_{\geqslant 3}$ vs. W, including present results and previous ones$^{(1)}$.

As far as present results are concerned, the two sets of data reported in Fig. 2 have been averaged whenever referring to the same energy interval. Radiative corrections$^{(5)}$ have been applied to the whole data.

The quoted errors are statistical only. Systematic errors are estimated to be ~10% on monitoring and ~ 15% on efficiency calculation, and are practically energy independent. A systematic energy dependent error is present, if the hypothesis that only pions are produced is not correct, in particular, if two charged kaons replace two charged pions in all the considered final states, the detection efficiency would be practically unaffected at W=3GeV, but will be lowered by a factor ranging from ~ 7 at 1. 5 GeV to ~ 2 at 2 GeV. This effect must of course be weighted by the fraction of kaons present at the various energies. An estimation of kaon production below 1. 55 GeV has been obtained using either the central core previously described or a softer trigger which has a higher detection efficiency for kaons. Assuming a kaon production mainly due to the reaction $e^+e^- \longrightarrow KK^*$ (892), we obtained, by the same maximum likelyhood method previously described, $\sigma(e^+e^- \longrightarrow KK^*) \lesssim 8$ nb (90% c. l.); this limit leads to a systematic error of ~ 10% on $R_{\geqslant 3}$ due to kaon production.

In Fig. 3 all our results are reported together with those already measured at lower and higher energies by other experiments. The results of ACO-M3N$^{(6)}$ and of VEPP-2M$^{(7)}$ reported in Fig. 3, include only the raction $e^+e^- \longrightarrow \pi^+\pi^-\pi^0, \pi^+\pi^-\pi^+\pi^-, \pi^+\pi^-\pi^0\pi^0$ and $e^+e^- \longrightarrow \pi^+\pi^-\pi^+\pi^-, \pi^+\pi^-\pi^0\pi^0$ respectively and therefore are a lower limit to $R_{\geqslant 3}$.

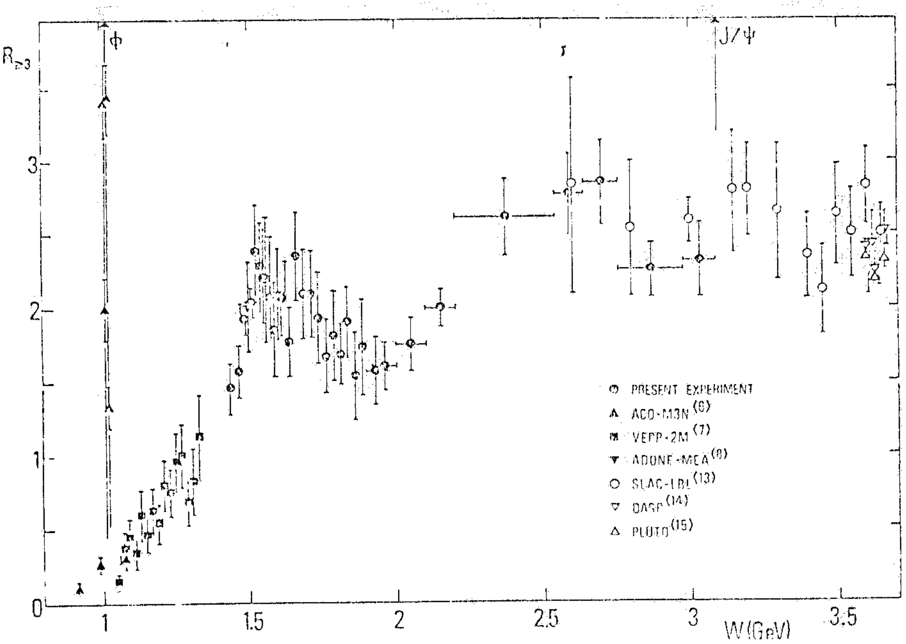

FIG. 3 - Present results and previous ones on $R_{\geqslant 3}$ vs. total c. m. energy.

In the energy range 1. 45 - 2. 15 GeV the present results are good agreement with those of ADONE-MEA$^{(8-9)}$ and DCI-M3N experiments$^{(10)}$.

In the whole energy range W=1. 0 - 3. 1 GeV the behaviour of $R_{\geqslant 3}$ now appears more clearly. After a sharp rise between 1 GeV and 1. 5 GeV, $R_{\geqslant 3}$ reaches a maximum value of ~ 2. 3 around 1.6 GeV, followed by a minimum of ~1. 6 around 1.95 GeV. An analysis$^{(9)}$ of the single processes contributing to the reaction (1) indicates that this maximum in $R_{\geqslant 3}$ is essentially due to the reactions

TABLE 1

ΔW (MeV)	W (MeV)	$R_{\geqslant 3}$
1419 - 1450	1435	1.46 ± 0.17
1450 - 1475	1464	1.58 ± 0.18
1475 - 1500	1491	1.93 ± 0.10
1500 - 1524	1506	2.04 ± 0.10
1525	1525	2.38 ± 0.30
1526 - 1549	1539	2.28 ± 0.30
1550	1550	2.20 ± 0.32
1551 - 1574	1560	2.20 ± 0.42
1575	1575	2.09 ± 0.28
1576 - 1600	1587	1.86 ± 0.32
1600 - 1625	1610	2.07 ± 0.25
1625 - 1650	1638	1.78 ± 0.23
1650 - 1675	1663	2.35 ± 0.30
1675 - 1700	1687	2.10 ± 0.30
1700 - 1725	1713	2.10 ± 0.29
1725 - 1750	1738	1.94 ± 0.31
1750 - 1775	1764	1.68 ± 0.25
1775 - 1800	1790	1.82 ± 0.30
1800 - 1825	1812	1.70 ± 0.20
1825 - 1850	1834	1.91 ± 0.24
1850 - 1875	1859	1.55 ± 0.30
1875 - 1900	1886	1.74 ± 0.33
1900 - 1972	1930	1.58 ± 0.23
1920 - 2000	1960	1.61 ± 0.16
2000 - 2100	2050	1.76 ± 0.18
2100 - 2200	2150	2.00 ± 0.12
2200 - 2540	2370	2.61 ± 0.26
2540 - 2640	2590	2.77 ± 0.28
2640 - 2760	2700	2.85 ± 0.29
2760 - 2980	2870	2.26 ± 0.18
2980 - 3090	3035	2.32 ± 0.25

Column 1	:	Total c. m. energy interval on which data has been lumped. Between 1. 9 and 2. 0 GeV present result and previous one(1) overlap.
Column 2	:	Mean total c. m. energy value of the corresponding interval ΔW.
Column 3	:	$R_{\geqslant 3}$ values. Radiative corrections has been applied.

(1) indicates that this maximum in $R_{\gtrsim 3}$ is essentially due to the reactions $e^+e^- \longrightarrow 2\pi^+ 2\pi^-$ and $e^+e^- \longrightarrow \pi^+\pi^-\pi^0\pi^0$ which have a resonance-like behaviour around 1.6 GeV. No evidence is present for a $\rho'(1250)$, which was expected(11) in the framework of the extended vector dominance model.

At higher energy, in spite of larger statistical errors, a step of $R_{\geqslant 3}$ appears between 2 and 2.5 GeV which can be interpreted(11) as the full opening of the strange degree of freedom. Finally in the energy range between 2.5 GeV and the effective charm threshold, $R_{\geqslant 3}$ seems to reach a plateau of ~ 2.5 which is not in contrast with the quark model prediction, if QCD corrections are taken into account(12).

From the values of σ_i obtained by solving equations (2), the charged ($\langle n_c \rangle$) and neutral ($\langle n_o \rangle$) multiplicities are deduced. In Table 2 and in Fig. 4 present values are reported together with those presented earlier(1) from the same experiment. For comparison, the charged multiplicities obtained by SLAC-LBL(13) are also reported in Fig. 4; the agreement between the two experiments is good in the overlapping region. Solid line a) (Fig. 4) is a fit to the experimental values for energies higher than 2 GeV, both from present experiment as well as SLAC-LBL(13):
$\langle n_c \rangle = (1.67 \pm 0.06) \ln W(\mathrm{GeV}) + (2.08 \pm 0.08)$.

TABLE 2

ΔW (MeV)	W (MeV)	$\langle n_c \rangle$	$\langle n_o \rangle$
1419 - 1450	1435	3.05 ± 0.13	1.34 ± 0.13
1450 - 1500	1485	3.04 ± 0.05	1.17 ± 0.05
1500 - 1550	1511	3.15 ± 0.05	1.31 ± 0.05
1550 - 1600	1570	3.12 ± 0.09	1.34 ± 0.09
1600 - 1650	1624	3.25 ± 0.10	1.28 ± 0.10
1650 - 1700	1675	3.07 ± 0.11	1.34 ± 0.11
1700 - 1750	1725	3.14 ± 0.12	1.62 ± 0.12
1750 - 1800	1776	3.00 ± 0.13	1.44 ± 0.13
1800 - 1850	1822	3.24 ± 0.10	1.61 ± 0.10
1850 - 1900	1872	3.18 ± 0.15	1.42 ± 0.15
1900 - 1972	1930	3.09 ± 0.17	1.73 ± 0.17
1920 - 2000	1960	3.20 ± 0.11	1.75 ± 0.15
2000 - 2100	2050	3.35 ± 0.11	1.85 ± 0.15
2100 - 2200	2150	3.53 ± 0.07	1.90 ± 0.10
2200 - 2540	2370	3.38 ± 0.11	1.90 ± 0.15
2540 - 2640	2590	3.40 ± 0.12	2.35 ± 0.16
2640 - 2760	2700	3.63 ± 0.12	2.40 ± 0.16
2760 - 2980	2870	3.60 ± 0.11	2.25 ± 0.15

Column 1 and 2	:	Like in Table 1.
Column 3	:	Average charged multiplicity.
Column 4	:	Average neutral multiplicity.

The quoted errors are statistical only.

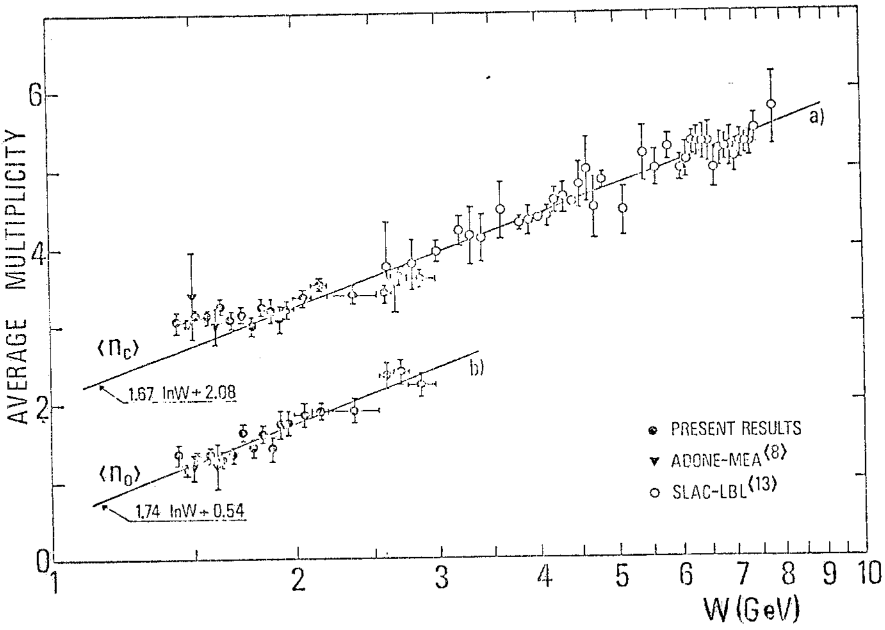

FIG. 4 - Average charged $\langle n_c \rangle$ and neutral $\langle n_0 \rangle$ multiplicity vs. total c. m. energy W. Solid line a) is a fit to all $\langle n_c \rangle$ data, for energies $W \gtrsim 2$ GeV (see text). Solid line b) is a fit to $\langle n_0 \rangle$ present results.

At energies below 2 GeV the charged multiplicity is higher than obtained through this fit, because of the resonating behaviour of the $2\pi^+ \; 2\pi^-$ channel around 1. 6 GeV.

Solid line b) (Fig. 4) is a fit to the $\langle n_0 \rangle$ values of the present experiment: $\langle n_0 \rangle = (1.74 \pm 0.13)$ ln W (GeV)+(0.54 ± 0.07). In this case the logarithmic fit is a good one for the whole explored energy range. Finally in the assumed invariant phase space model the charged energy fraction is given by

$$\langle E_c / W \rangle = \langle n_c \rangle / (\langle n_c \rangle + \langle n_0 \rangle)$$

In the energy interval $2.54 \leq W \leq 2.98$ GeV where both SLAC-LBL(13) and present results exist, we obtain from our data $\langle E_c / W \rangle = 0.60 \pm 0.02$ which is in quite good agreement with the SLAC-LBL (see ref. (16)) results.

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