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MULTIPARTICLE PRODUCTION FROM e^+e^- INTERACTIONS AT HIGH ENERGY

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Measurements of multiple particle production at ADONE, the Frascati e^+e^- storage ring, have been carried out at C.M. energies 1.4 GeV to 2.4 GeV. The hadronic nature of the observed particles is discussed and a lower limit of 30 nbarn set for the total multiparticle cross section.

We present the results of an experiment carried out at ADONE, the Frascati 2 × 1.5 GeV e^+e^- storage ring. This experiment was designed to perform an initial exploration of the features of e^+e^- interactions. Energies between 1.4 and 2.4 GeV in the center of mass system were explored in this experiment.

A detailed description of the experimental apparatus (see fig. 1) has been given previously [1]. The method used for analysis, and some preliminary results have already been presented elsewhere [2].

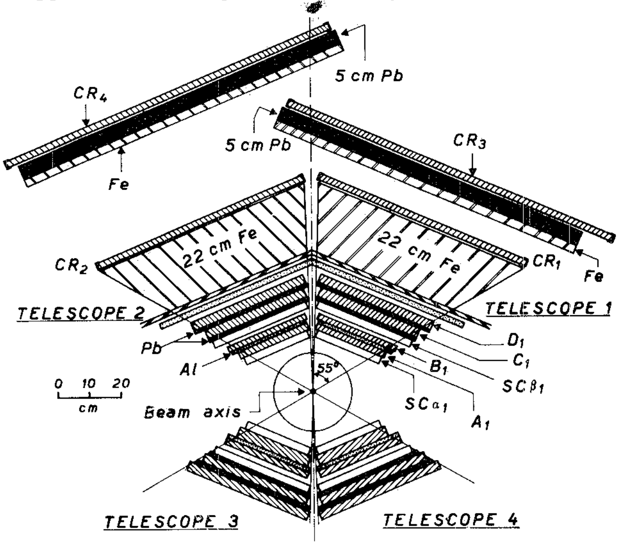

Fig. 1. Section of the experimental apparatus orthogonal to beam axis. The θ acceptance is between 60° and 120° (z-axis being along the beam direction).

Let us recall here that the apparatus consists of four identical telescopes surrounding one experimental section of ADONE and covering ~0.35 of the total solid angle as seen from the center of the apparatus*. Each telescope consists of absorbers, scintillation counters, and magnetostrictive spark chambers, which allow us to extract the following information concerning the detected particles:

a) pulse height analysis in a lead-scintillator sandwich to identify electrons by their electromagnetic showers;

b) azimuthal direction, φ, of the detected particle (z-axis along the beam direction). When more than two particles enter the same telescope only that closest to the magnetostrictive pick-up is recorded.

We also record the time of each event with respect to the beam-beam impact (Δt). 22 cm of Fe absorber cover the top two telescopes and above the absorber two large scintillation counters (CR_1, CR_2), in anticoincidence with our trigger, drastically reduce the flux of detected

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* Actually the source has a finite longitudinal length [1] which is comparable with the linear dimension of the counters. This reduces the effective solid angle of the apparatus.

cosmic rays. In a second stage of the experiment, a second absorber (1.5 cm of iron, 5 cm lead) and two additional counters CR_3 and CR_4 were placed above CR_1 and CR_2. CR_3 and CR_4 were then put in anticoincidence with our trigger, while CR_1 and CR_2 were simply recorded in association with each event. These marked events then give us information on the penetration of the detected particles*.

The reaction we wish to discuss here is

$$e^+ + e^- \to a^\pm + b^\pm + \text{anything} \qquad (1)$$

where $a^\pm$ and $b^\pm$ are charged particles.

The master coincidence which triggers the apparatus requires the presence of at least two charged particles ($a^\pm$ and $b^\pm$) detected in two different telescopes**. If, in addition to $a^\pm$ and $b^\pm$, other particles enter other telescopes, they are also recorded. If the additional particles are neutrals they will give a pulse in the scintillation sandwich (C+D) but not in the initial counter A.

The selection of evens from reaction (1) (non-coplanar events) is made with the following criteria:

a) more than two charged particles are detected;

b) two charged particles are observed *and* they have a non-coplanarity angle, $|\Delta\varphi|$, larger then 13°.

Demonstration of the existence of $e^+e^- \to a^\pm b^\pm$ + *anything*. In fig. 2(a) we show the distribution of events fulfilling the above criteria, as a function of Δt. From this distribution we can define an interval *in-time* with the beam-beam impact. In fig. 2(b) we show the distribution of non-coplanar in-time events as a function of the distance, L, between the particle trajectory and the e^+e^- beam axis. We see that the in-time, non-coplanar events, essentially come from beam interactions. If we select only those events for which $|L| \leq 30$ mm we obtain a total of 1033 events.

The cosmic ray background, CR, varies for the different energies and the different detected configurations (2 particles detected, 3 particles detected, tec.) from 0% to 30%, the average contamination being 16%.

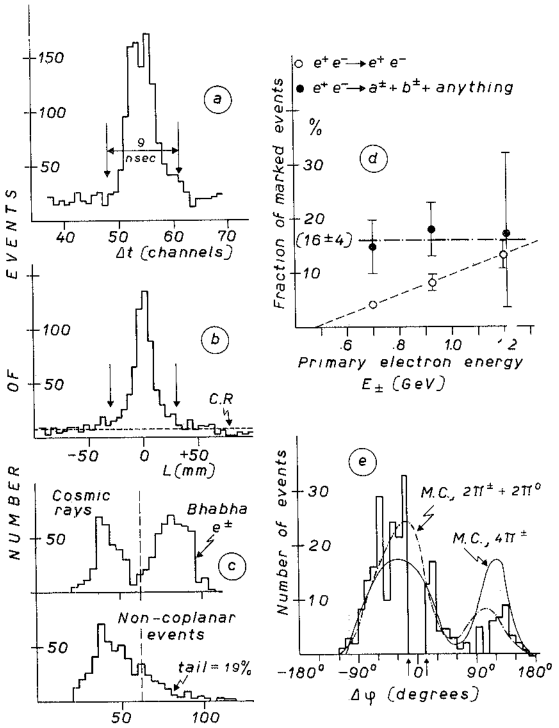

Fig. 2. Analysis of non-coplanar evens (see text). (a) Δt distribution of events from the beam region. (b) L distribution of in-time events compared with the out-of-time (C.R.) normalized distribution (arrows indicate source definition. (c) pulse height distribution compared with C.R. and Bhabha electron spectra. (d) the fraction of "marked" events compared to "marked" Bhabha events. (e) $\Delta\varphi$ distribution compared with a phase space Montecarlo calculation for two possible pion final states.

To determine the amount of e-gas background, we have collected data with one beam and with two separated beams stored in the ring***. The average contamination over the full sample was 26%, although it varies considerably with each detected configuration and increases with C.M. energy. A final correction of 18% was applied to the two charged tracks events due to the non-coplanarity cut $|\Delta\varphi| \leq 13^\circ$. This correction was determined by a smooth interpolation of the experimental $\Delta\varphi$ distribution between -13° and $+13^\circ$ which, as will be seen, is consistent with a statistical distribution determined by a Montecarlo program.

After subtraction of CR and e-gas contamination and after the $\Delta\varphi$ cut correction, a total of

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* The minimum kinetic energy of a pion to be marked was ~ 350 MeV, while pions with more than ~ 500 MeV were vetoed by CR_3 and CR_4, unless they were absorbed by nuclear interaction (actually the fraction of particles absorbed is quite large: e.g. 85% of 400 MeV pions). In order to have a homogeneous set of data the marked events have not been included in the total of events given in table 1.

** If $a^\pm$ and $b^\pm$ are pions their minimum energy to be detected is ~ 75 MeV.

*** The normalization of these e-gas background runs was obtained by monitoring single bremsstrahlung production on the residual gas [2].

Table 1
List of non-coplanar events according to their detected configurations, after all the corrections were applied. The crude number of events detected are given in parenthesis (no. 4 charged events were detected).

			Non coplanar events					
C.M. energy $E_+ + E_-$ (GeV) (1)	Integrated luminosity (cm^{-2}) (2)	Corrected Bhabha events (3)	Events with 2 charged particles detected (4)	Events with 2 charged +1 neutral detected (5)	Events with 2 charged +2 neutrals detected (6)	Events with 3 charged particles detected (6)	Events with 3 charged +1 neutral detected (7)	Total non-coplanar events (8)
1.4	119×10^{32}	472 ± 33	(55) 40.6 ± 9.4	(8) 6.4 ± 3.5	(0) 0.1 ± 1.1	(6) 5.4 ± 2.5	(1) 0.6 ± 1.1	(70) 53.0 ± 10.4
1.5	231	720 ± 34	(99) 90.7 ± 12.1	(15) 11.1 ± 4.8	(1) 1.0 ± 1.2	(12) 11.1 ± 3.8	(1) 0.6 ± 1.5	(128) 114.5 ± 13.7
1.6	67	166 ± 17	(32) 26.5 ± 7.0	(4) 2.8 ± 2.4	(0) 0.0 ± 1.1	(6) 5.3 ± 2.5	(0) 0.0 ± 1.1	(42) 34.6 ± 7.9
1.65	76	170 ± 17	(44) 28.2 ± 8.6	(7) 6.4 ± 3.1	(2) 2.0 ± 1.5	(2) 1.7 ± 1.5	(2) 2.0 ± 1.5	(57) 40.3 ± 9.5
1.7	130	261 ± 21	(59) 42.9 ± 9.7	(7) 4.1 ± 3.3	(1) 0.3 ± 1.1	(1) 0.0 ± 1.2	(0) 0.0 ± 1.3	(65) 47.3 ± 10.5
1.75	83	152 ± 16	(46) 33.1 ± 8.5	(4) 1.8 ± 2.8	(0) 0.0 ± 1.1	(4) 3.4 ± 2.1	(0) 0.0 ± 1.2	(54) 38.3 ± 9.3
1.8	115	189 ± 18	(68) 50.1 ± 10.5	(4) 1.0 ± 2.6	(0) -0.3 ± 1.1	(2) 2.0 ± 1.5	(0) -0.3 ± 1.3	(74) 52.5 ± 11.0
1.85	514	770 ± 36	(109) 84.9 ± 16.4	(23) 25.9 ± 6.5	(2) -2.0 ± 1.7	(10) 10.6 ± 4.2	(2) 2.7 ± 2.3	(146) 122.1 ± 18.6
1.9	122	166 ± 17	(45) 24.5 ± 8.8	(3) 2.1 ± 2.3	(2) 2.0 ± 1.5	(3) 3.3 ± 2.0	(0) 0.0 ± 1.2	(53) 31.9 ± 9.5
2.0	257	293 ± 25	(145) 90.4 ± 17.9	(7) 5.8 ± 3.7	(0) 0.0 ± 1.1	(5) 5.8 ± 2.7	(0) -0.7 ± 1.5	(157) 101.3 ± 18.5
2.4	751	453 ± 23	(140) 22.6 ± 24.6	(26) 21.9 ± 6.3	(3) 3.9 ± 2.5	(13) 12.7 ± 4.1	(2) 1.7 ± 2.0	(184) 62.8 ± 25.9
totals	2465 ± 10^{32}	3812 ± 83	(842) 534.5 ± 43.7	(108) 89.3 ± 13.6	(11) 6.9 ± 4.0	(64) 61.3 ± 9.1	(8) 6.6 ± 5.0	(1033) 698.6 ± 47.1

698 events remain. These events are listed in table 1 for each C.M. energy according to their different detected configurations. In the same table we give the corrected number of Bhabha events* collected at the same time under the same conditions. The integrated luminosities in column (2) were deduced from these Bhabha events in order to minimize problems due to uncertainties in the spark chambers efficiencies (the chamber efficiencies were measured to be between 0.85 and 0.95).

Nature of the observed particles. Fig. 2(c) shows the pulse height spectrum of particles in the shower counters (C+D). The distribution of the detected non-coplanar events is compared with the spectrum of minimum ionizing particles (C.R.) and high energy electrons from Bhabha scattering. The spectrum of non-coplanar events is similar to the C.R. spectrum, although it shows non negligible tail towards the larger pulse heights. However there is no correlation between large pulse heights in the different telescopes for each event. If the detected particles were pions, this tail is what one would expect due to the following effects: the probability to have more than one particle in the same telescope, estimated to be 12% from the fraction of events with more than two detected particles; nuclear interactions in the sandwich counters; the possibility that the detected particle is a slow pion. We conclude that the bulk of the detected particles are not high energy electrons, and that the pulse height spectrum is compatible with all of them being pions.

In fig. 2(d) we have plotted as a function of the incident electron energy ($E_{\pm}$) the fraction of events containing a particle which crosses the 22 cm of Fe absorber and stops between CR_1, CR_2

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* See ref. [1] for the corrections applied to the Bhabha events.

and CR_3, CR_4 (marked events). While the number of marked Bhabha events decreases to zero at low energies, the number of marked non-coplanar events remains constant (within the large errors) at 16%. We can therefore exclude the possibility that these non-coplanar events are due to low energy ($\leqslant$ 500 MeV) electrons. Further, the fraction of marked non-coplanar events is consistent with a major part of the detected particles being pions. (We have calculated that 16% of $\sim$ 400 MeV pions would be marked).

Additional information on the nature of the non-coplanar events can be obtained from the $\Delta\varphi$ (non-coplanarity) distribution*. This distribution is shown in fig. 2(e). For reference it is compared with the statitical distribution expected for $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ and $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ (phase space Montecarlo calculation). We can conclude that the detected non-coplanar events have a $\Delta\varphi$ distribution compatible with some mixture of final states with a statistical angular distribution. They do not contain, for $|\Delta\varphi| \geqslant 13^o$, a significant contribution from the reaction $e^+e^- \to e^+e^-e^+e^-$ (the only plausible reaction which could give low energy non-coplanar electrons) since the distribution for this reaction would be peaked around $\Delta\varphi = 0$ [3].

Energy dependence of the yield. In fig. 3 we show the energy dependence of the ratio of non-coplanar events to the integrated luminosity $\mathcal{L} = \int \mathcal{L}(t)\mathrm{d}t$ at each C. M. energy. The data points of fig. 3 divided by the efficiency of detection, ϵ, of the apparatus directly provide the cross-sections.

Absolute values of the cross-sections. The evaluation of cross-sections involves a detailed calculation of the efficiency of detection of our apparatus which, of course, depends on the states actually produced. The yield (n_D) of events in a given detected configuration D (D could be, for example, three charged tracks (3c) + a neutral (1n) detected in our apparatus) is given by

$$n_D = \mathcal{L}\cdot\sum_A \epsilon_D^A \sigma_A$$

$\mathcal{L}$ is the integrated luminosity; σ_A is the cross-section to produce a given channel A (for example,

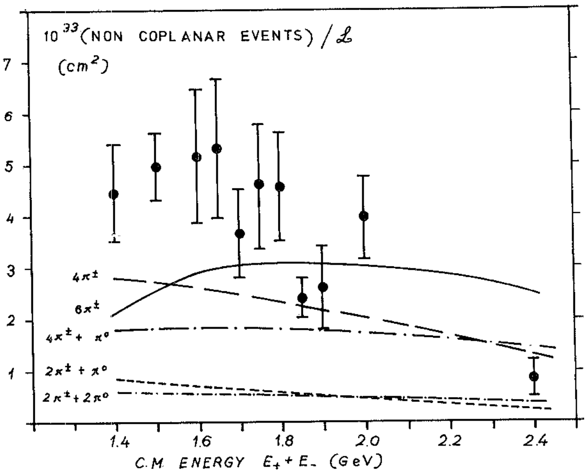

Fig. 3. Energy dependence of the ratio of the number of non-coplanar events to the integrated luminosity $\mathcal{L}$. The curves are the result of a phase space M. C. calculation of this ratio for several possible channels using a constant cross-section for each channel of 30 nbarn.

$\sigma_A = \sigma(e^+e^- \to \pi^+\pi^-\pi^+\pi^-)$); and ϵ_D^A is the efficiency of the apparatus to detect the configuration D from reaction A.

Since we have six different detected configurations of evens (2c, 2c+1n, 2c+2n, 3c, 3c+n, 4c) in principle, apart from the statistical significance of some of our experimental numbers, it would be possible to extract from the data the cross-sections for six different channels once the efficiencies have been calculated. However, a priori, there is no reason to restrict the choice of final states to 6 or less channels and moreover the actual dynamics of the processes are unknown.

As an example, we have calculated the ϵ_D^A's using a statistical model of pion production (invariant phase space Montecarlo calculation). We obtain efficiencies (see table 2) ranging from $\leqslant$ 1% to $\sim$10% depending on the C. M. energy, the produced channel, and the detected configuration. This means, clearly, that to obtain cross-sections we must multiply the observed numbers of events by a calculated, model dependent, number ranging from 10 to more than 100 in the different cases. The small values of these efficiencies result mainly from the small solid angle seen by the apparatus and the energy cuts on the detected particles. To increase the uncertainty, corrections for nuclear absorbtion (already included in the ϵ's of table 2, assuming the particles are pions), turn out to be of the order of 20% - 50% depending on the energy and channel. For all of

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* $\Delta\varphi$ is the difference of the angles between the azimuthal projection of the tracks and is zero when the two particles go in opposite directions. The sign of $\Delta\varphi$ is specularly defined for left and right telescopes. If one particle goes in a top telescope the event will have a positive $\Delta\varphi$ if the other particle lies in the half plane (defined by the first track) containing the other top telescope. Consistently, if both particles go in the bottom telescope $\Delta\varphi$ is positive.

Table 2
Values of the efficiencies to detect a particular configuration from several possible produced states of pions, assuming a statistical model.
(Invariant phase space Montecarlo calculation)

Produced state	$E_+ + E_-$ GeV	Efficiency for detection of 2c %	2c+1n %	2c+2n %	3c %	3c+1n %	4c %
$\pi^+\pi^-\pi^0$	1.4	2.2	0.7	0.0			
	1.8	1.4	0.5	0.0			
	2.4	0.6	0.2	0.0			
$\pi^+\pi^-2\pi^0$	1.4	1.1	0.7	0.2			
	1.8	1.0	0.7	0.1			
	2.4	0.7	0.4	0.1			
$\pi^+\pi^-3\pi^0$	1.4	0.5	0.4	0.2			
	1.8	0.6	0.5	0.2			
	2.4	0.6	0.3	0.2			
$\pi^+\pi^-4\pi^0$	1.4	0.1	0.2	0.1			
	1.8	0.2	0.4	0.2			
	2.4	0.2	0.3	0.2			
$\pi^+\pi^-\pi^+\pi^-$	1.4	8.5			0.9		0.0
	1.8	7.0			0.7		0.0
	2.4	4.0			0.4		0.0
$\pi^+\pi^-\pi^+\pi^-\pi^0$	1.4	4.0	1.5	0.0	0.4	0.1	0.0
	1.8	4.1	1.4	0.0	0.4	0.1	0.0
	2.4	3.5	1.0	0.0	0.2	0.1	0.0
$\pi^+\pi^-\pi^+\pi^-2\pi^0$	1.4	1.6	1.0	0.1	0.1	0.1	0.0
	1.8	2.4	1.7	0.4	0.3	0.1	0.0
	2.4	2.0	1.4	0.3	0.2	0.2	0.0
$3\pi^+ + 3\pi^-$	1.4	6.5			0.6		0.0
	1.8	8.8			1.3		0.1
	2.4	7.4			1.1		0.1
$4\pi^+ + 4\pi^-$	1.4	0.1			0.0		0.0
	1.8	6.3			0.7		0.0
	2.4	8.3			1.8		0.1

these reasons we feel that with the existing small solid angle apparatus it is very difficult to safely extract a reasonably model independent cross section for multiparticle production.

Keeping in mind the above considerations, we have plotted in fig. 3 for several possible channels (A) the value of $N_A/\mathcal{L}$ $(=\epsilon^A \sigma_A)$ calculated using the efficiencies obtained by the phase space MC program, and a constant cross-section (σ_A) of 30 nbarn.

Using these same efficiencies (ϵ^A), i.e. with the hypothesis that we are dealing with statistical production of pions, we can put a conservative lower limit on the value of the cross-section $\sigma(e^+e^- \rightarrow a^\pm + b^\pm + \text{anything})$ by assuming that only the channel with the largest efficiency contributes. This yields*

$$\sigma(e^+e^- \rightarrow a + b + \text{anything}) \geqslant 30 \text{ nbarn}$$

averaged over the energy range explored (1.4 - 2.4 GeV). This is in agreement with our preliminary evaluation in the energy range 1.6 to 2.0 GeV.

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* A slightly larger value for this limit could be set if one takes into consideration the separate configurations containing charged+neutrals.

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