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INITIAL RESULTS ON e^+e^- INTERACTIONS
AT $E_{CM} = 4$ GeV, AT THE CEA

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September 1972

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
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CAMBRIDGE ELECTRON ACCELERATOR

CAMBRIDGE, MASSACHUSETTS 02138

MASTER

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INITIAL RESULTS ON e^+e^- INTERACTIONS
AT $E_{cm} = 4$ GeV, AT THE CEA

The e^+e^- colliding beam system at the CEA has been used to perform an experiment with beam energies of $\sqrt{s} = 4$ GeV. Figure 1 shows the general layout of the relevant section of the machine. Table 1 gives the beam parameters.

Figure 2 shows some details of the interaction region beam pipe. The pressure in this pipe was less than 5×10^{-10} Torr during the experiment. Shown in this figure is the "fibre mover" which flicks a thin carbon fibre (5×10^{-4} cm diameter) through the beams to measure the vertical beam sizes and determine that the beams intersect at the correct position in space to maximize the luminosity.

1. Apparatus

The detector surrounding the interaction region was designed to detect and identify electrons, photons, and hadrons. The inner core consists of four identical quadrants, each composed of spark chambers, scintillators and radiators. The inner core covers 2π sr: the polar angular range is $45^\circ < \theta < 135^\circ$ and 70% of the azimuthal angle ϕ is covered. Simple scintillators cover the remaining 30% of the range in ϕ .

Two vertical sections, each consisting of 9" of iron with four spark chamber gaps, are placed outside the inner core. Covering a total of π sr, they serve to separate muons from hadrons through nuclear absorption.

The ϕ and θ views of the detector are shown in Fig. 3. Figure 4 is an end view of one quadrant, showing some details. The first six gaps of spark chamber are used to define the trajectories of charged particles. The radiator thicknesses are optimized for detection of high-energy γ 's and e 's; the shower spark chambers are

used to determine shower vertices, and the shower scintillators to measure energy deposited.

All the spark chambers have magnetostrictive readout with 4 or 8 spark capability, dependent on their position in the system. All counters have latches, and some have pulse height information.

Before installation around the interaction region, each quadrant was calibrated with cosmic-ray muons, electron beams varying in energy from 0.3 to 3 GeV, and tagged photon beams covering the region from 0.5 to 3 GeV. The 4 quadrants had very similar performance.

"Tagging counters" were installed in wells in the beam pipe, as shown in Fig. 5, so as to detect some of the recoil electrons and positrons from two-photon processes $e^+e^- \rightarrow e^+e^-X$.

The on-line program had extensive equipment-checking facilities, 2-body physics analysis, and an event-by-event raw data display system.

2. Triggers

Several independent triggers were used to fire the spark chambers. These are listed in Table 2. Cosmic rays are a severe background (rate = $0.33 \text{ cm}^{-2}\text{min}^{-1}$ in the upper and lower quadrants) and the majority are rejected by their time-of-flight, measured between any two pairs of #5 counters. The rejection efficiency was set to approximately 95% for tracks through opposing quadrants.

3. Luminosity Monitor

Double bremsstrahlung ($e^+e^- \rightarrow e^+e^-\gamma\gamma$) was used to measure the luminosity by detecting the two γ -rays which are emitted along the beam direction. Two similar 10X₀ shower counters were used, each being 7 m from the interaction point. Accidental background was

subtracted by time-of-flight, the signal-to-noise ratio being about 7.

The theoretical spectrum shape was fitted to the experimental one - preliminary results are shown in Fig. 6. Table 3 lists the corrections applied to the data in making an absolute measurement of luminosity. The integrated luminosity for the experiment is $(1.12 \pm 0.09) \times 10^{34} \text{ cm}^{-2}$.

4. Data Taking and Gas Backgrounds

Data was collected over a two-month period (June and July 1972). The average trigger rate was approximately 1 per second, 2/3 being due to cosmic rays through adjacent quadrants, and most of the rest was caused by beam spray. Counter singles rates were in the kHz range. A small amount of time (~5%) was spent with either only one beam, or two beams with zero luminosity. The major running to determine the background from gas interactions was done by increasing the pressure in the interaction region by a factor of approximately 50 and then using one beam. This pressure increase had no appreciable effect on the large angle rates in the detector, so it was possible to condense the equivalent of two months of background running into one day. The normalization was made using the total beam current, pressure increase, and time, and is uncertain within a factor of 2. The most conservative estimate yields a running time equivalent to 50% of the luminosity time. There were no acceptable events in the background data.

5. Data Analysis and Results

The raw data was first analyzed by computer in order to reject most of the uninteresting events, as shown in Table 4. The remaining

2% of the data was visually scanned on an event-by-event basis so that the computer analysis could be checked, and events were categorized into possible reaction classes, on the basis of "qualitative" appearance and some well-defined criteria. Then the remaining events were checked visually again, this time with an interactive graphics system connected to the analysis program, so that analysis ambiguities could be resolved, zero-range tracks (δ -rays) could be removed, and the analysis redone immediately. Following this stage the events were put through a SUMX program to present the relevant histograms.

5a. $e^+e^- \rightarrow e^+e^-$

One two-dimensional projection of the interaction region for e^+e^- events (before any cuts were made) is shown in Fig. 7. Cuts were made as shown in Fig. 7 for the x, y, z coordinates. Figure 8 is a distribution in θ after this IR cut was made. Cuts were made very conservatively in θ in this preliminary analysis, so that edge effects in spark chambers, source displacement and length, and rectangular aperture corrections, need not be considered. The cut in ϕ (ϕ range $\pm 28^\circ$ for each quadrant) was conservative for similar reasons. A collinearity cut was made in $\Delta\theta$ as shown in Fig. 9 ($\Delta\theta$ is the space angle between tracks). Figure 10 is a $\Delta\phi$ plot before the $\Delta\theta$ cut was made. Figure 11 is a typical scatter plot showing shower pulse height versus number of shower sparks in one quadrant. This latter data was taken from a 2-body SUMX output which contained all "2-body" events (e.g. cosmic rays) which survived the above-mentioned IR, θ and ϕ cuts. The separation between showering and non-showering events is obvious.

After all these cuts were made 111 horizontal "ee" events and 95 vertical "ee" events remained. Additional considerations involving cuts on the number of sparks in the shower spark chambers, cuts on the shower counter pulse height, and radiative corrections add an uncertainty of about 4% to the number of events. Thus the final number of events is 206 ± 16.7 .

Using the measured value of integrated luminosity ($1.12 \pm .09 \times 10^{34} \text{ cm}^{-2}$) and the total number of ee events, the value of the experimental ee cross section is:

$$\sigma_{\text{exp}} = (1.84 \pm .21) \times 10^{-32} \text{ cm}^2 \quad [4 < q^2 < 16 (\text{GeV}/c)^2]$$

The value of the theoretical ee cross section as predicted by Q.E.D. is

$$\sigma_{\text{th}} = 2.06 \times 10^{-32} \text{ cm}^2$$

5b. $e^+e^- \rightarrow \gamma\gamma$

The expected number of $\gamma\gamma$ events is small, and computer recognition of γ -ray directions is difficult, so the observed events were hand-analyzed after the output was produced as shown in Table 4. Temporarily a very limited range in θ was used ($65^\circ < \theta < 115^\circ$) since detailed considerations of edge effects for γ -ray showers and scanning efficiency have not been made. The same ϕ range ($\pm 28^\circ$ per quadrant), was used as for the e^+e^- data. A collinearity criterion of $\Delta\theta \leq 12^\circ$ was applied. Twenty three events survived and after a 6% radiative correction and 6% correction for γ -ray non-conversion in the spark chambers the measured cross section is $(2.05 \pm 0.45) \times 10^{-33} \text{ cm}^2$ and the Q.E.D. cross section is $2.13 \times 10^{-33} \text{ cm}^2$. In the measured cross section the scanning efficiency was assumed to be 100%. The range in q^2 is from 4.6 to 11.4 GeV^2 .

The comparison with the "ee" data gives

$$\frac{\sigma(\gamma\gamma)/\sigma(ee) \text{ measured}}{\sigma(\gamma\gamma)/\sigma(ee) \text{ O.E.D.}} = 1.09 \pm 0.25$$

5c. $e^+e^- \rightarrow \mu^+\mu^-$

The total number of $\mu^+\mu^-$ events expected is about 20. No attempt has been made to extract this data yet.

5d. $e^+e^- \rightarrow \text{hadrons}$

After scanning we obtained a sample of 202 events which had either 3 or more prongs or 2 prongs which satisfied $\alpha < 160^\circ$ or $|\phi_1 - \phi_2| < 170^\circ$, where α is the angle in space between the prongs and ϕ_i is the azimuthal angle. (See Table 4.)

The requirement that the event vertex lie in a volume $X \times Y \times Z = 4 \times 3 \times 9 \text{ cm}^3$ enclosing the interaction region eliminated 80 events which either originated in the fibre holder or in cosmic rays that scattered off the material in the detector (Fig. 12). From the remaining sample of 122 events, 31 2-prong events were eliminated by a non-coplanarity cut $|\phi_1 - \phi_2| < 160^\circ$.

The events were then re-scanned to eliminate electromagnetic final states. Four events in the sample of 91 events were identified as $e^+e^-\gamma$ final states. The remaining 87 events were classified according to prong count as follows:

Number of Prongs	Number of Events
2	32
3	28
4	21
5	6

Backgrounds produced by cosmic rays were evaluated by increasing the volume of the IR by a factor of 4. Only one extra event was accepted

and hence we estimate cosmic background to be $\leq 1/3$ event.

Beam-gas background was evaluated by increasing the volume of the interaction region in the beam direction only. No additional events were found. This is consistent with the previously mentioned high gas-pressure runs.

Based on the 87 events and $\int L dt = (1.0 \pm 0.09) \times 10^{34} \text{ cm}^{-2}$, the measured cross section is

$$\begin{aligned} \sigma(ee \rightarrow \text{hadrons}) &= \frac{1}{\epsilon} \times (1.6 \pm 0.2) \sigma_t(e^+e^- \rightarrow \mu^+\mu^-) \\ &= \frac{1}{\epsilon} \times (8.7 \pm 1.2) \times 10^{-33} \text{ cm}^2 \end{aligned}$$

To estimate ϵ two models have been considered in this preliminary analysis.

A Monte Carlo simulation of invariant phase-space generated pionic states and determined whether they trigger BOLD, considering solid angle limitations, nuclear absorption ($L_{\text{coll}} = 101 \text{ g cm}^{-2}$ in iron) and the cuts mentioned earlier. See Table 5a. The total efficiency for this model is $\epsilon = 0.35 \pm 0.06$.

A second model considered only the geometric acceptance of BOLD for independently and isotropically produced prongs with no nuclear absorption or scan-cuts. The total efficiency was $\epsilon = 0.6^{+0.08}_{-0.11}$ (see Table 5b).

Considering the extreme assumptions of these models we estimate

$$\epsilon = .45 \pm .15$$

Hence we estimate the range for the total hadronic cross section

$$(14.5 \pm 2.0) \times 10^{-33} \text{ cm}^2 \leq \sigma(e^+e^- \rightarrow \text{hadrons}) \leq (29.0 \pm 4.0) \times 10^{-33} \text{ cm}^2$$

or

$$(2.7 \pm 0.3) \sigma_{\mu\mu} \leq \sigma(e^+e^- \rightarrow \text{hadrons}) \leq (5.3 \pm 0.7) \sigma_{\mu\mu}$$

Average charged multiplicity = 4.5 ± 1 .

In Table 6 we show the combinatorial configurations of tracks in the four BOLD quadrants for the 4-prong events. These are compared to the geometric predictions assuming no correlations between the particles. There is no evidence for any significant back-to-back jet-like structures in these events.

The preceding results are preliminary and we expect to produce a more detailed analysis in the near future.

Acknowledgements

We wish to thank many people, in particular M. E. Law, and all the personnel of the CEA Laboratory for their dedication and hard work. Without their efforts this experiment would not have been possible.

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12. Multiprongs events. Two-dimensional projection of the event vertex showing the interaction region and the fibre holder.

TABLE 1

Machine Parameters

Beam energy	=	2.0 GeV
Rf frequency	=	475.74 MHz
Circumferential frequency	=	1.3 MHz
Number of e^- bunches	$\approx$	100
Number of e^+ bunches	$\approx$	100
Beam size at interaction region		
σ_z	$\sim$	1.4 cm
σ_h	$\sim$	2.5×10^{-3} cm
σ_v	$\sim$	2.5×10^{-3} cm
Typical e^- current	=	4 mA
Typical e^+ current	=	4 mA
Typical beam lifetime	=	3000 sec
Vertical crossing angle in interaction region	=	2.5 mrad
Injection time	$\approx$	7 min
Storage time	$\approx$	20 min
Peak luminosity	$\approx$	$3 \times 10^{28} \text{ cm}^{-2} \text{ sec}^{-1}$

TABLE 2
BOLD Triggers

Trigger	Description	Cosmic Ray Veto	Comments
1	2 opposite quadrants with each quadrant having any 3 counters out of the first 4.	yes	Threshold: $T_{\pi} = 95$ MeV for charged π
2	Any 2 quadrants with each quadrant having counter 1 and any 3 of (1, 2, 3, 4).	yes	Threshold: $T_{\pi} = 95$ MeV must be charged particles
3	Any 3 quadrants. Each quadrant has any 3 of (1, 2, 3, 4).	no	Threshold: $T_{\pi} = 95$ MeV for charged π
4	Any 2 quadrants with a shower in each quadrant (a shower is defined by pulse height in sum of (2, 3, 4, 5) counters.	no	4 x minimum ionizing $\equiv \sim 800$ MeV deposited by e or γ shower
5	Any 1 quadrant with a shower and any 2 of 8 inner counters.	no	1 shower and 2 charged particles with Threshold $T_{\pi} = 20$ MeV
6	Tagging - any 2 quadrants with each quadrant having counter 1 and 2 on, and (PT1 or PT2) and (ET1 or ET2).	yes	$1\% < \frac{\Delta p}{p} < 18\%$ for tagging counters. $T_{\pi} > 70$ MeV $T_e > 200$ MeV ($\epsilon \approx 75\%$) (in a quadrant).

TABLE 3

INTEGRATED LUMINOSITY
FROM DOUBLE BREMSSTRAHLUNG MONITOR

$$\int L dt = \frac{(N \text{ counts})(\text{correction factors})}{\sigma_{DB}}$$

Corrections and Errors in $\int L dt$	$\frac{k}{E_0} = 0.1$	$\frac{k}{E_0} = 0.3$
Threshold uncertainty	$1.00 \pm 6.5\%$	$1.00 \pm 6.4\%$
Counter resolution	$1.059 \pm 3.7\%$	$1.069 \pm 4.0\%$
Geometric aperture	$1.415 \pm 1.7\%$	$1.389 \pm 1.7\%$
Veto counter correction	$1.269 \pm 1.8\%$	$1.269 \pm 1.8\%$
Veto counter dead time	$1.012 \pm 0.5\%$	$1.012 \pm 0.5\%$
Total	$1.924 \pm 7.8\%$	$1.907 \pm 7.9\%$
Number of DB counts	$185,700 \pm 1\%$	$44,140 \pm 1\%$
σ_{DB} for correct $\frac{k}{E}$ but without photon correlations	$7.212 \times 10^{-29} \text{ cm}^2$	$1.340 \times 10^{-29} \text{ cm}^2$
<p><u>$\therefore$ Total integrated luminosity = $(1.12 \pm 0.09) \times 10^{34} \text{ cm}^{-2}$</u></p>		

TABLE 4
DATA ANALYSIS

TABLE 5

ASSUMED STATES

		$2\pi_{ch}\pi^0$	$4\pi_{ch}$ $4\pi_{ch}\pi^0$	$6\pi_{ch}$ $6\pi_{ch}\pi^0$	$8\pi_{ch}$
		$2\pi_{ch}2\pi^0$	$4\pi_{ch}2\pi^0$	$6\pi_{ch}2\pi^0$	
Number of Prongs Detected	2	.09	.159	.129	.074
	3		.159	.236	.213
	4		.032	.138	.202
	5			.048	.146
	6			.008	.054
	7				.006

TABLE 5a. Detection efficiencies for assumed states N charged + N' neutral pions, averaged over N'. Monte Carlo simulation of invariant phase space with $L_{coll} = 101.2 \text{ gr/cm}^2$ in Fe. Two-prong events satisfy $\alpha < 160^\circ$ and $|\phi_1 - \phi_2| < 160^\circ$, where α is the relative angle between prongs and ϕ_i the azimuth.

ASSUMED STATES

		$2\pi_{ch}\pi^0$	$4\pi_{ch}$	$6\pi_{ch}$	$8\pi_{ch}$
Number of Prongs Detected	2	.19	.28	.18	.082
	3		.23	.29	.205
	4		.062	.23	.27
	5			.094	.220

TABLE 5b. Detection efficiencies assuming isotropic distribution of prongs with $\Delta\Omega = 2\pi \text{ sr}$ and BOLD trigger conditions without considering showers.

TABLE 6

Combinatorial Configurations of Tracks
in the Four BOLD Quadrants
for 4-Prong Events

Configuration (1 example only, permutations implied)	Experimental Result	Geometric Prediction (no correlations)
(1, 1, 1, 1)	3	2.0
(1, 1, 2, 0)	13	11.8
(3, 1, 0, 0)	1	2.6
(3, 0, 1, 0)	0	1.3
(2, 2, 0, 0)	1	2.0
(2, 0, 2, 0)	3	1.0
	<hr/> 21	

Fig. 1. Main components of the CEA Bypass. The symbols Q, BM, ABM, LM, IR stand for quadrupole magnet, bending magnet, auxiliary bending magnet, luminosity monitor and interaction region

BYPASS INTERACTION BEAM PIPE

FIGURE 2

FIGURE 3

ϕ - VIEW OF OUTER B.O.L.D. QUADRANT

FIGURE 4

FIGURE 5

FIGURE 6

TEST 0

MAXNS

 

STHE FRAME (-0) CONTAINS THE OVERSPILL 211 ENTRIES IN ALL

SCALE 1.0000

CUTS ARE SHOWN

FIGURE 8

CONTENTS ALL CHAN. 756.00

NOT INCLUDING UNDERFLDAS

•CC NOR OVERFLOW•

.00 786 ENTRIES IN ALL.

SCALE 1.0000

TEST :

PAGE 11 -11

SCALE 1.0000

FIGURE 10

CIRCLED EVENTS
ARE REMOVED BY
 $\Delta\theta < 200^\circ$ CUT

.00. 117 ENTRIES IN ALL.

ELECTRON-POSITRON TWO BODY SUMX
 BLOCK 7 DIAGRAM 5 MSPSH(2) VERSUS SHAD(2), VERTICAL 2-BODY EVENTS
 MASTER TESTS 3 15 100 105
 XLBC -70 -71
 YLBC -153 -153
 TEST 15 16

PASS 1 -1

PAGE 50 90

AFTER IR, θ , ϕ CUTS

FIGURE 11

SCAPEX
 MAXN9 +23456789ABCDEFGHIJKLMNPQRSTUW

HORIZONTAL SCALE: ARBITRARY

THE FRAME (-0) CONTAINS THE OVERSPILL 518 ENTRIES IN ALL

N-BODY SUMX AUGUST 27 1972.
 BL9CK 7 DIAGRAM 4 EVENT VERTEX. YSTAR VERSUS ZSTAR
 XL9C 136
 YL9C 135
 TEST 0

PASS 1 =1

PAGE 42 -42

SCALE 1 cm = 4 channels

2 prong

No CUTS

FIGURE 12

SCAPEX
 MAXNS +23456789ABCDE

STHE FRAME (-0) CONTAINS THE OVERSPILL 136 ENTRIES IN ALL

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