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RECENT RESULTS FROM SPEAR*

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I will discuss primarily new e^+e^- colliding beam results from the SPEAR Magnetic Detector[1,2] since the Lepton-Photon Symposium last August.[3,4,5] Due to time limitations, I will not cover certain areas where there are essentially no new results, such as the anomalous μ-e events.[6] The topics I will discuss are:

I. Total cross section in the 4 GeV region

II. Exclusive multipion channels

III. ψ' decays

IV. Upper limits on high mass resonances

This talk is not meant to be a complete review of the experimental situation. For such a review, see References 3, 4, and 5.

(Invited paper presented at the 1976 Coral Gables (Florida) Conference, 19-22 January 1976)

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I. TOTAL CROSS SECTION IN THE 4 GeV REGION

Figure 1 shows the ratio $R = \sigma_{e^+e^- \to \text{hadrons}} / \sigma_{e^+e^- \to \mu^+\mu^-}$ vs $E_{c.m.}$, as was presented last August. The data have been corrected to remove the radiative tails of the narrow ψ and ψ' resonances and final states arising from two-photon processes. The error bars include statistical errors and ± 10% point-to-point systematics. There is also an overall ± 10% normalization uncertainty.

We see a rich structure in the 4 GeV region. We have recently taken more data. Figure 2 shows the ratio R in the 4 GeV region. The errors shown are statistical only. The open points represent new data. We see a complex and as yet unexplained structure in the region between 3.9 and 4.1 GeV. The data in this region are well fitted by several different assumptions about the masses and widths of resonances present. All that can be said at this point is that more data are needed to unambiguously resolve the structure in this region.

In the region around 4.4 GeV, the existence of a resonance, first reported at the Symposium, has been confirmed by new data. Figure 3 shows the ratio R from 4.3 through 4.5 GeV.

The data points have been corrected for radiative effects except those involving the 4.4 resonance itself. Radiative corrections involving the resonance itself are not used in correcting the data points; rather they are included by correcting the expected Breit-Wigner distribution. The solid curve in Fig. 3 indicates the expected shape of a single radiatively corrected Breit-Wigner fitted to the data. The data are well accounted for by a single resonance. The parameters of the resonance are shown in Table I. For comparison purposes, the corresponding parameters of the ψ and ψ' resonances are also shown.

TABLE I

Resonance Parameters

	4.4	ψ	ψ'
Mass	4414 ± 7 MeV	3095 ± 4 MeV	3684 ± 5 MeV
Γ	33 ± 10 MeV	69 ± 15 keV	225 ± 56 keV
Γ_{ee}	440 ± 140 eV	4.8 ± 0.6 keV	2.2 ± 0.3 keV
$\int\sigma_H(E)dE$	≈ 500 nb · MeV	10400 nb · MeV	3700 nb · MeV

II. EXCLUSIVE MULTIPION CHANNELS

In Fig. 1 we see not only the structure in the 4 GeV region but also that the ratio R has a relatively constant value of 5 above the 4 GeV region, while below the 4 GeV region R has a value of about 2.5. This step rise in R suggests that new hadronic degrees of freedom are opening in the 4 GeV region. It is of extreme importance to discover what, if anything, distinguishes the "new physics" from the "old physics".

I will review briefly a little of what we already know about this question. All of this has been covered previously by R. Schwitters in Ref. 3. The mean charged multiplicity versus energy is plotted in Fig. 4. The values shown have been corrected for loss of charged particles due to geometric acceptance and trigger biases. The data are consistent with a logarithmic rise with c.m. energy. There is no evidence for a change in this behavior at 4 GeV although the level of uncertainty is large. Figure 5 shows the mean energy of the observed tracks. Only tracks with 3 or more prongs were considered and all tracks were assumed to be pions. The mean charged track energy increases with c.m. energy except right near a beam energy of 4 GeV, where there is evidence for a leveling off. This may indicate a small but sudden increase in the total

(charged + neutral) multiplicity. The mean fraction of total energy appearing as charged particles is plotted in Fig. 6. Three or more prong events were used, and pion masses were assigned to all tracks. Again, the data have been corrected for loss of charged particles. The fraction of charged energy falls with increasing c.m. energy. There is no strong evidence for a discontinuity in the 4 GeV region. In short, there seems to be a hint that the neutral multiplicity increases suddenly in the 4 GeV region, but the evidence is not conclusive. I do not have sufficient time to talk about the inclusive momentum spectra or inclusive particle production.

We can attempt to learn more by studying exclusive final state production as a function of c.m. energy. We thus hope to learn whether the "new physics" favors different final states from the old physics. Unfortunately, apart from the ψ and ψ' resonances, cross sections are low. The only final states that we can study with meaningful accuracy over a broad range of energies are multipion final states with all charged pions, specifically $2(\pi^+\pi^-)$ and $3(\pi^+\pi^-)$. States with one missing π^0 can also be reconstructed, but there are experimental difficulties in separating them from background. We have previously shown that the ψ and ψ' resonances do not decay directly to an even number of pions. Thus, data taken at the resonances can be included in our analysis below.

Fig. 7a shows the exclusive cross section for $e^+e^- \to 2(\pi^+\pi^-)$ as a function of $E_{c.m.}$. The data are consistent with a smooth exponential falloff ($\sigma \propto S^{-2.8\pm0.5}$). There is no evidence for a discontinuity or kink in the 4 GeV region. Fig. 7b shows the exclusive cross section for $e^+e^- \to 3(\pi^+\pi^-)$. Again the data are consistent with a smooth exponential falloff ($\sigma \propto S^{-2.3\pm0.8}$). If "new physics" liked to decay into $2(\pi^+\pi^-)$ or $3(\pi^+\pi^-)$ as much as old physics, we might expect a factor of two rise in the exclusive cross sections around 4 GeV where the ratio R rises by a factor of two. Although not conclusive, the data tend to show the "new physics" does not like to yield all pion final states with an even number of pions.

Figure 8 shows the mass spectrum of $\pi^+\pi^-$ pairs in $2(\pi^+\pi^-)$ and $3(\pi^+\pi^-)$ final states for a sample of the data. The raw events are histogrammed directly without any corrections. In the $2(\pi^+\pi^-)$ data, there is a strong ρ signal and a strong f signal. Indeed, the mass spectrum is fitted by assuming the final states are entirely $\rho\pi\pi$ or $f\pi\pi$, with a crude ratio $\rho\pi\pi/f\pi\pi \approx 1.9 \pm 0.5$, ignoring interference and correlations between ρ and f. The mass spectrum for the $3(\pi^+\pi^-)$ data fits well the assumption that all final states are $\rho\pi\pi\pi\pi$. No f signal is observed.

Figure 9 is a scatterplot of the mass of one $\pi^+\pi^-$ pair versus that of the other $\pi^+\pi^-$ pair in $2(\pi^+\pi^-)$ final states, plotted such that $M_1 > M_2$. We see a definite clustering at $M_1 \approx M_f$, $M_2 \approx M_\rho$, indicating the presence of the exclusive channel $e^+e^- \rightarrow \rho f$.

III. ψ' DECAYS

We have a smattering of new results to report on ψ' decays. We list the known decay modes of the ψ' and their branching ratios in Table II. We see that almost 40% of the ψ' decays are not directly accounted for. We can partially account for them indirectly as follows.

1. A few direct decays of the ψ' into "ordinary" hadrons have been observed. Typically the partial widths have a ratio

$$\frac{\Gamma(\psi' \rightarrow f)}{\Gamma(\psi \rightarrow f)} \approx 1/3 \qquad \left(\frac{BR(\psi' \rightarrow f)}{BR(\psi \rightarrow f)} \approx 1/10\right)$$

compared to the corresponding partial widths in ψ decay. Here f represents a specific final state of ordinary hadrons. This makes it exceedingly

TABLE II

Decay Modes of the ψ'

Mode	Branching Ratio (%)	Comments
e^+e^-	0.97 ± 0.16	μ-e universality assumed
$\mu^+\mu^-$	0.97 ± 0.16	
$\psi\pi^+\pi^-$	32 ± 4	
$\psi\eta$	4.3 ± 0.8	
$\psi\gamma\gamma$	3.6 ± 0.7	via an intermediate state
$\psi\pi^o\pi^o$	17 ± 3	includes all $\psi' \rightarrow \psi$ + neutrals not otherwise identified
ψ anything	57 ± 8	includes all ψ channels above
$p\bar{p}$	0.032 ± 0.014	
$2\pi^+2\pi^-\pi^o$	0.35 ± 0.15	
$\pi^+\pi^-K^+K^-$	~0.05	

difficult to observe individual exclusive states in ψ' decay. However, if we assume that the above ratio holds for all decays into ordinary hadrons, we can estimate

$$\frac{\Gamma\psi' \rightarrow \text{ordinary hadrons}}{\Gamma\psi' \rightarrow \text{all}} \approx 10\% .$$

2. Radiative decays of the ψ' to high mass C even states (χ) have been observed. Events where $\chi \rightarrow \psi\gamma$ have already been included in $\psi' \rightarrow \psi$ decays. We have also observed events where $\chi \rightarrow 2(\pi^+\pi^-)$, $3(\pi^+\pi^-)$, $\pi^+\pi^-K^+K^-$, $\pi^+\pi^-$, and K^+K^-. Making reasonable assumptions about the branching ratios of the χ states into these states, we can estimate very roughly

$$\sum_{\chi\ \text{states}} \frac{\Gamma(\psi' \rightarrow \chi)}{\Gamma(\psi' \rightarrow \text{all})} \cdot \frac{\Gamma(\chi \rightarrow \text{hadrons})}{\Gamma(\chi \rightarrow \text{all})} = 5\% .$$

Even so, $\sim 25\%$ of ψ' decays remain unaccounted for.

It has been suggested that the ψ' could decay often into channels such as $\omega\eta$, $\omega\eta'$, or $\omega\chi(2.8)$,[7] channels in which there are two or more neutrals in the final state. These decay modes can be detected due to the electromagnetic decay $\omega \rightarrow \pi^+\pi^-$, which occurs with a branching ratio of 1.3%. Since the decays $\psi' \rightarrow \rho\eta$, $\rho\eta'$, or $\rho\chi(2.8)$ are forbidden by isospin conservation, the $\omega \rightarrow \pi^+\pi^-$ signal should be free of ρ interference. We look for peaks in the $\pi^+\pi^-$ mass spectrum at the ω mass. To increase the sensitivity of the search we first make cuts on the total momentum of the pion pair, since for each channel the ω momentum is unique. We see no evidence for $\omega\eta$, $\omega\eta'$, or $\omega\chi(2.8)$. The 90% c.l. upper limits on branching ratios are

$$\psi' \rightarrow \omega\eta \; < 2.2\%$$

$$\psi' \rightarrow \omega\eta' < 4.3\%$$

$$\psi' \rightarrow \omega\chi(2.8) < 8.6\%$$

The upper limits are crude, but rule out some models.

The analysis of the decay $\psi' \rightarrow \psi\eta$ has now been completed. The following results have been obtained

$$\frac{\Gamma\psi' \rightarrow \psi\eta}{\Gamma\psi' \rightarrow \text{all}} = 4.3 \pm 0.8\%$$

$$\frac{\Gamma\psi' \rightarrow \psi\pi^0 + \Gamma\psi' \rightarrow \psi\gamma}{\Gamma\psi' \rightarrow \text{all}} < 0.15\% \text{ at } 90\% \text{ c.l.}$$

If we assume all decays of the type $\psi' \rightarrow \psi$ + neutrals other than $\psi' \rightarrow \psi\eta$ or $\psi' \rightarrow \psi\gamma\gamma$ are $\psi' \rightarrow \psi\pi^0\pi^0$, we obtain

$$\frac{\Gamma\psi' \rightarrow \psi\pi^0\pi^0}{\Gamma\psi' \rightarrow \psi\pi^+\pi^-} = 0.53 \pm 0.06$$

consistent with the assignment of $I = 0$ to the $\pi\pi$ system. We thus conclude that the ψ' has I = 0 and G = -1, and that all $\psi' \rightarrow \psi$ decays have now been accounted

TABLE III

Properties of χ States Seen by SPEAR

Mass	Decay Modes Seen	Comments
χ (3410)	$\pi^+\pi^-$, K^+K^-, $2(\pi^+\pi^-)$, $3(\pi^+\pi^-)$, $\pi^+\pi^-K^+K^-$	$J^{PC} = 0^{++}, 2^{++}$, etc.
χ (3530)	$2(\pi^+\pi^-)$, $3(\pi^+\pi^-)$, $\pi^+\pi^-K^+K^-$	Broad state - probably two or more narrow states χ (3510) and χ (3550)
P_c (3500 or 3270)	$\gamma\psi$	Probably identical with χ (3510)

for to the level of one or two percent. The properties of the χ states observed in $\psi' \rightarrow \chi\gamma$ are detailed in Table III.

IV. UPPER LIMITS ON HIGH MASS RESONANCES

The results presented here are not new, but take on new importance with the possible resonance at 6 GeV seen by Lederman.[8] Thus, they bear repeating here. Table IV indicates the experimental upper limits on narrow resonances as a function of c.m. energy. The limits are expressed in terms of the integrated cross section $\int\sigma(E)\,dE$ expressed in nb · MeV. Narrow here means having a width less than about 1 MeV, which is the apparent width of a narrow resonance due to the energy spread in the beam. The limits on wider resonances have not been worked out in detail, but at worst our upper limits on integrated cross section increase linearly with the width of the state.

REFERENCES

1. J.-E. Augustin et al., Phys. Rev. Lett. 34, 233 (1975).
2. The collaborators in this experiment are G. S. Abrams, A. M. Boyarski, M. Breidenbach, F. Bulos, W. Chinowsky, G. J. Feldman,

TABLE IV

Results of the search for narrow resonances. Upper limits (90% confidence level) for the radiatively corrected integrated cross section of a possible narrow resonance. The width of this resonance is assumed to be small compared to the mass resolution.

Mass Range (GeV)	Limit on $\int \sigma_H \, dE_{c.m.}$ (nb MeV)
$3.20 \rightarrow 3.50$	970
$3.50 \rightarrow 3.68$	780
$3.71 \rightarrow 4.00$	850
$4.00 \rightarrow 4.40$	620
$4.40 \rightarrow 4.90$	580
$4.90 \rightarrow 5.40$	780
$5.40 \rightarrow 5.90$	800
$5.90 \rightarrow 7.60$	450

C. E. Friedberg, D. Fryberger, G. Goldhaber, G. Hanson, D. L. Hartill, J. Jaros, B. Jean-Marie, J. A. Kadyk, R. R. Larsen, D. Lüke, V. Lüth, H. L. Lynch, R. Madaras, C. C. Morehouse, K. Nguyen, J. M. Paterson, M. L. Perl, F. M. Pierre, T. P. Pun, P. Rapidis, B. Richter, B. Sadoulet, R. F. Schwitters, J. Siegrist, W. Tanenbaum, G. H. Trilling, F. Vannucci, J. S. Whitaker, F. C. Winkelmann, J. E. Wiss.

3. R. F. Schwitters, Proc. 1975 Int. Symposium on Lepton and Photon Interactions at High Energies, Stanford University, Stanford, California, 21-27 August 1975 (Stanford Linear Accelerator Center, Stanford University, Stanford, California, 1975), p. 5.

4. G. S. Abrams, above Proceedings, p. 25.

5. G. J. Feldman, above Proceedings, p. 39.

6. For further information on these events, see M. L. Perl, Proc. Canadian Inst. Particle Physics Int. Summer School, McGill University, Montreal, 16-21 June 1975.

7. The χ (2.8) has been seen by the DASP collaboration. See B. Wiik, Proceedings of 1975 Lepton-Photon Symposium (Ref. 3), p. 69.

8. D. C. Hom et al., submitted to Phys. Rev. Lett.

FIGURE CAPTIONS

1. R versus $E_{c.m.}$ in coarse steps.
2. R versus $E_{c.m.}$ in the 4 GeV region. The open circles are new data.
3. R versus $E_{c.m.}$ near 4.4 GeV. The solid curve is a Breit-Wigner fitted to the data.
4. Mean charged multiplicity $\langle n_{ch} \rangle$ vs $E_{c.m.}$.
5. Mean energy per track for ≥ 3 prong events vs $E_{c.m.}$.
6. Average fraction of total c.m. energy appearing in charged particles vs $E_{c.m.}$.
7. Total cross section for a) $e^+e^- \rightarrow 2(\pi^+\pi^-)$ and b) $e^+e^- \rightarrow 3(\pi^+\pi^-)$ vs $E_{c.m.}$.
8. Effective mass of $\pi^+\pi^-$ pairs in a) $e^+e^- \rightarrow 2(\pi^+\pi^-)$ and b) $e^+e^- \rightarrow 3(\pi^+\pi^-)$.
9. Scatterplot of two $\pi^+\pi^-$ effective masses in $e^+e^- \rightarrow 2(\pi^+\pi^-)$.

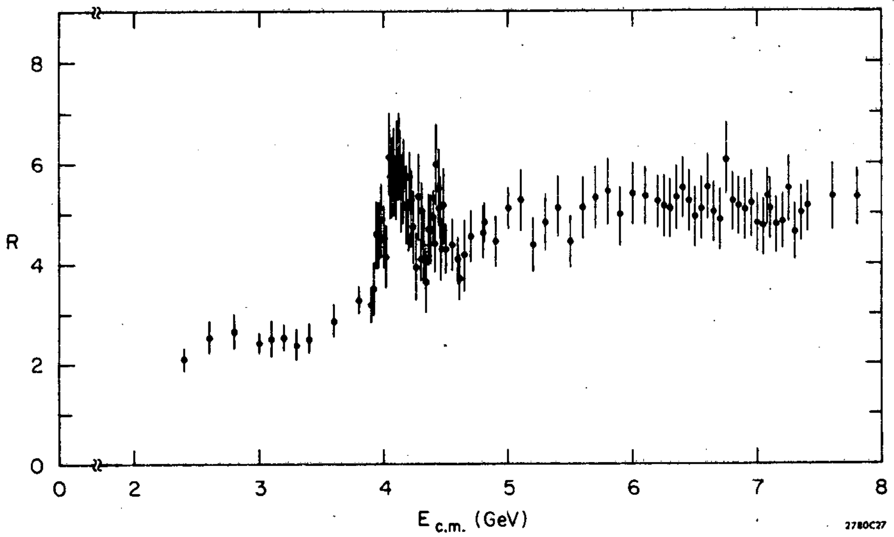

R
8
6
4
2
0
0
2
3
4
5
6
7
8
E c.m. (GeV)
2780C27

Fig. 1

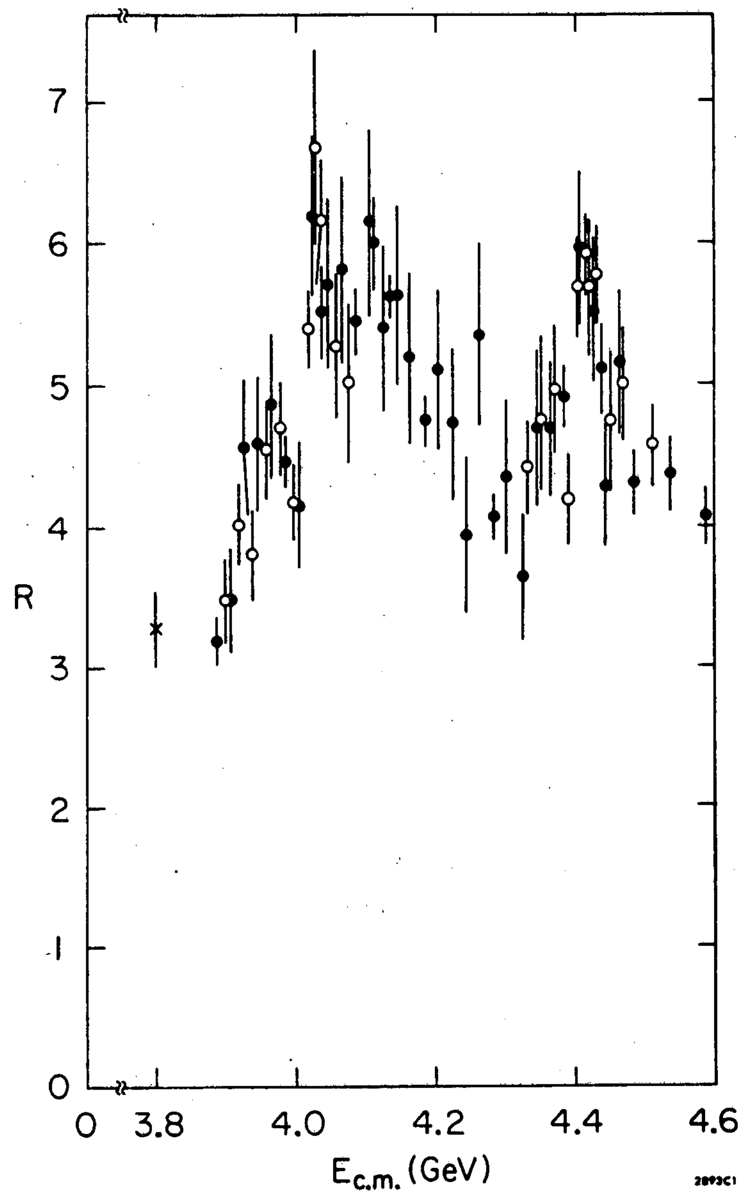

R
7
6
5
4
3
2
1
0
0
3.8
4.0
4.2
4.4
4.6
E c.m. (GeV)

Fig. 2

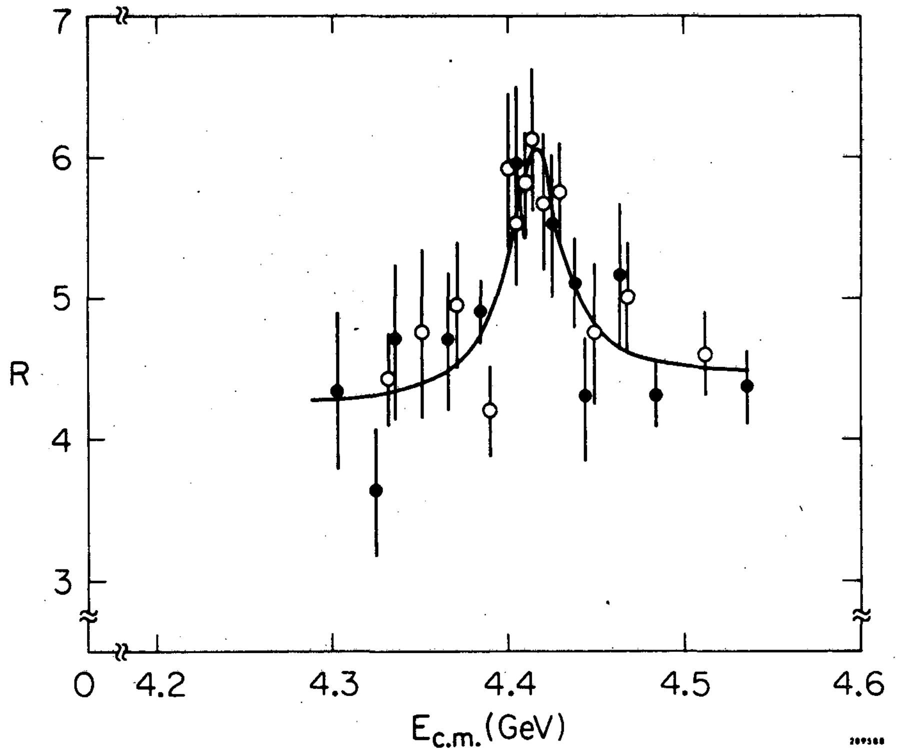

R
7
6
5
4
3
0
4.2
4.3
4.4
4.5
4.6
E c.m. (GeV)

Fig. 3

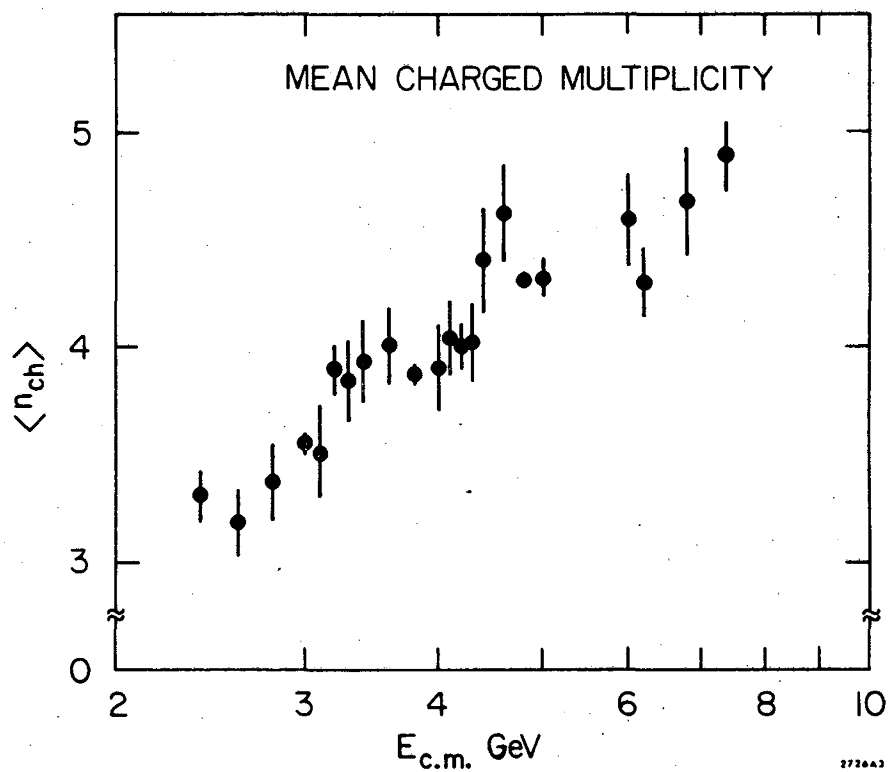
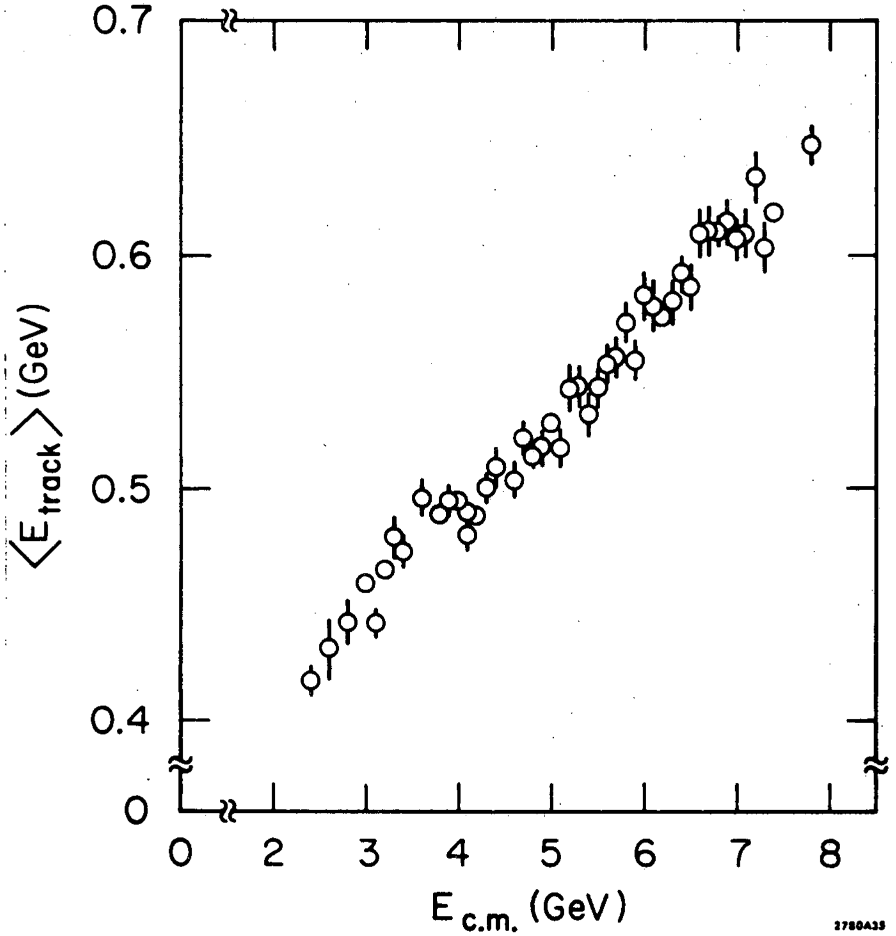
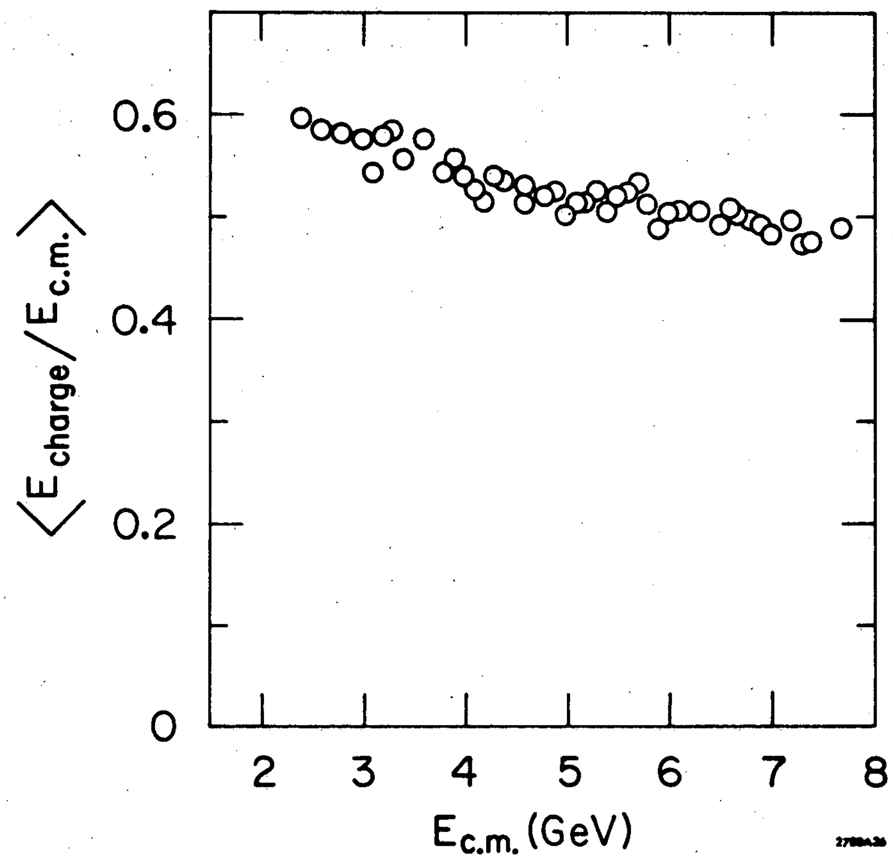

MEAN CHARGED MULTIPLICITY
⟨n ch⟩
5
4
3
0
2
3
4
6
8
10
E c.m. GeV

Fig. 4



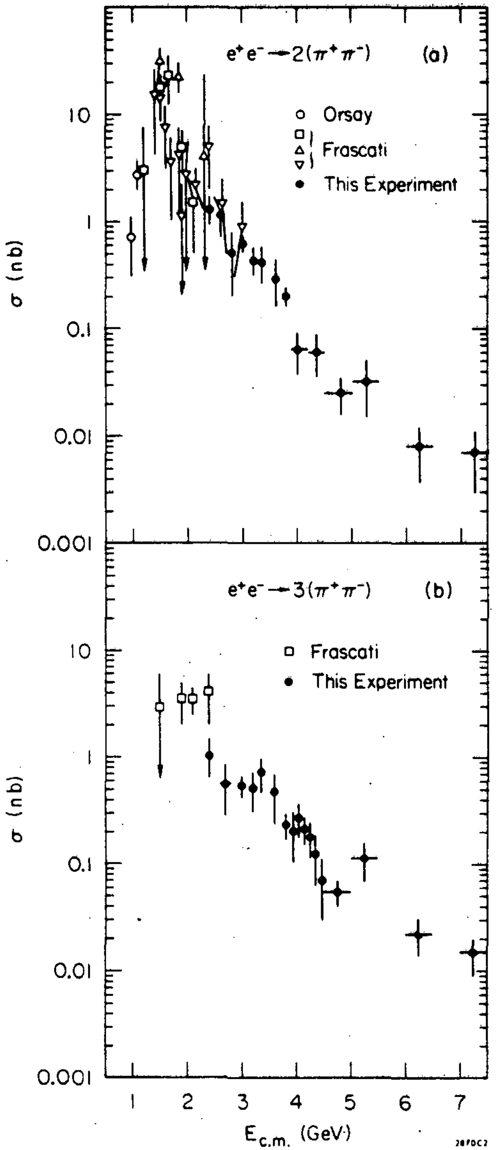
0.7
0.6
0.5
0.4
0
$\langle E_{track} \rangle$ (GeV)
0
2
3
4
5
6
7
8
$E_{c.m.}$ (GeV)
2780A35

Fig. 5



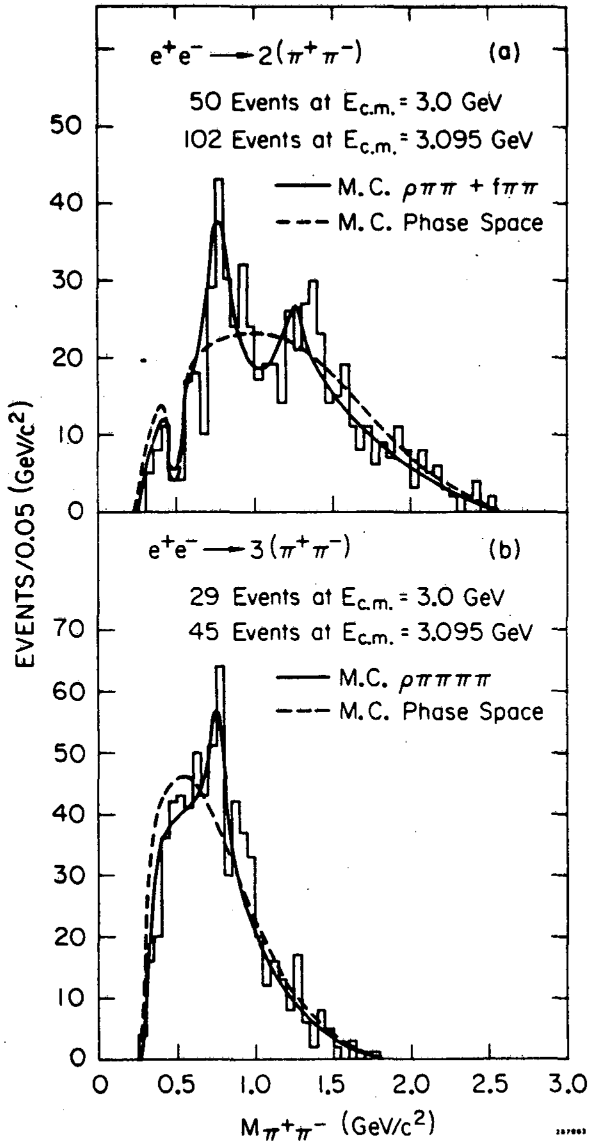
0.6
0.4
0.2
0
$\langle E_{charge}/E_{c.m.} \rangle$
2
3
4
5
6
7
8
$E_{c.m.}$ (GeV)
2780A36

Fig. 6



e+e- → 2(π+π-)
(a)
Orsay
Frascati
This Experiment
e+e- → 3(π+π-)
(b)
Frascati
This Experiment
σ (nb)
10
1
0.1
0.01
0.001
1
2
3
4
5
6
7
Ec.m. (GeV)

Fig. 7



e+e- → 2(π+π-)
(a)
50 Events at Ec.m. = 3.0 GeV
102 Events at Ec.m. = 3.095 GeV
M.C. ρππ + fππ
M.C. Phase Space
e+e- → 3(π+π-)
(b)
29 Events at Ec.m. = 3.0 GeV
45 Events at Ec.m. = 3.095 GeV
M.C. ρππππ
M.C. Phase Space
EVENTS/0.05 (GeV/c²)
0
0.5
1.0
1.5
2.0
2.5
3.0
Mπ+π- (GeV/c²)

Fig. 8

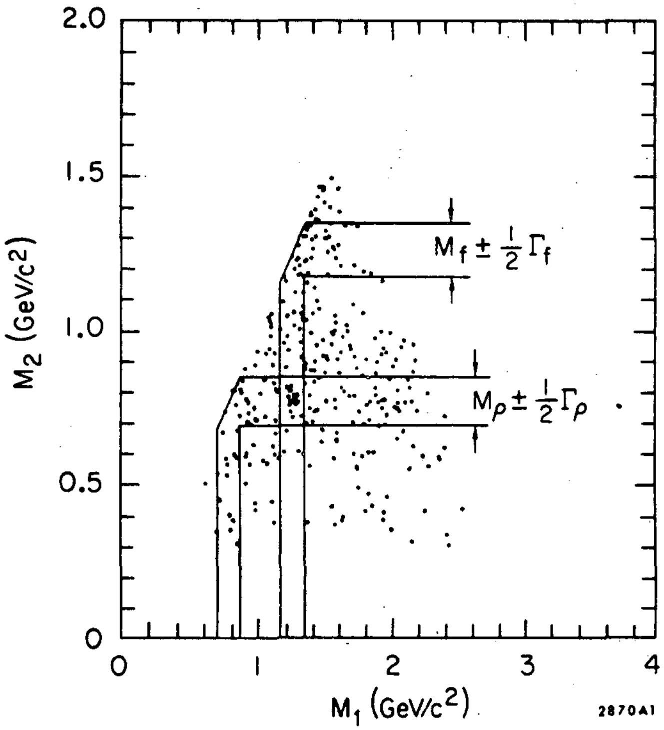

2.0
1.5
1.0
0.5
0
M_2 (GeV/c^2)
0
1
2
3
4
M_1 (GeV/c^2)
$M_f \pm \frac{1}{2}\Gamma_f$
$M_\rho \pm \frac{1}{2}\Gamma_\rho$
2870A1

Fig. 9

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