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THE NEW PARTICLES PRODUCED IN ELECTRON-POSITRON ANNIHILATION*†

Martin L. Perl
Stanford Linear Accelerator Center
Stanford University
Stanford, California

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1. INTRODUCTION

In this talk I will review the main properties of the new particles produced in $e^+ - e^-$ annihilation, but I will not attempt to present a full list of properties or references. A complete list as of May 1, 1975 is given by Feldman and Perl[1]; and more recent results were described in a series of talks[2-7] at the 1975 International Symposium on Lepton and Photon Interactions at High Energy. Hence I must apologize to the many experimenters and institutions whose work is summarized here without specific references. I will usually limit the references to review or summary papers.

The paper begins with a general description of the continuum region of hadron production in $e^+ - e^-$ annihilation. Section 2 describes the 4.1 GeV enhancement. The ψ and ψ' are discussed in Sec. 4, and the newly discovered

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particles -- the P_c, η_c, $\chi(3410)$, $\chi(3530)$ -- produced by γ transition from the ψ and ψ' are discussed in Sec. 5. Singly charmed particle searches in $e^+ - e^-$ annihilation are summarized in Sec. 6. Finally the properties of the $e\mu$ events produced in $e^+ - e^-$ annihilation are presented in Sec. 7.

This is a talk on experimental results, very little theory is presented. An adequate presentation of the theory would make the talk much too long. Occasionally I will refer to the relevent theory or I will point out theoretical problems.

2. THE CONTINUUM REGION

The total cross section, $\sigma_{had}(s)$, including the resonances, for

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

is shown in Fig. 1. (The total center-of-mass energy is designated by W, E_{cm} or $\sqrt{s}$). A more detailed picture of the higher energy region, excluding the ψ and ψ', is given in Fig. 2. To eliminate a basic 1/s behavior and set a scale for σ_{had} it is conventional[1,8] to define.

$$R = \sigma_{had}(s)/\sigma_{e^+e^- \rightarrow \mu^+\mu^-}(s) \tag{2}$$

Here

$$\sigma_{e^+e^- \rightarrow \mu^+\mu^-} = \frac{4\pi\alpha^2}{3s} = \frac{86.8}{s} \text{ nb} \tag{3}$$

where s is in GeV^2 and $\sqrt{s} \gg$ muon mass. As shown in Fig. 3, R increases from about 2 in the $2 < E_{cm} < 3$ region to about 5 in the $E_{cm} > 5$ GeV region. Part or all of this increase is usually attributed[1] to the existence of heavier quarks such as the charm quark c. Since the existence of new particles with masses in the 3 to 5 GeV region is also thought to be due to the existence of heavier quarks, the rise in R and the new particles are thought to be closely connected.[9,10] However as noted in Secs. 3 and 6 some skepticism should be maintained about the completeness of this connection.

To give a general picture of the final hadronic states in the continuum region, I show in Fig. 4 the mean charged multiplicity[1,2], $\langle n_{ch} \rangle$; and in Fig. 5 the averaged observed energy per charged track, $\langle E_{tr} \rangle$. $\langle n_{ch} \rangle$ increases logarithmically with E_{cm} ; a useful relation is

$$\langle n_{ch} \rangle = 1.93 + 1.50 \ln E_{cm} \; ; \tag{4}$$

correspondingly, $\langle E_{tr} \rangle$ increases slowly with E_{cm}. Finally as shown in Fig. 6 most hadrons have low energy. Here the rough superposition of the $s\, d\sigma/dx$ curves for $x \gtrsim 0.4$ indicates at least crude Bjorken scaling[1]. With this sketch of the continuum hadronic states in hand, we turn to the new particles.

3. THE 4.1 GeV ENHANCEMENT

Returning to Figs. 2 and 3 we observe a 10 to 15 nb enhancement above the continuum at about E_{cm} = 4.1 GeV. The full width of the enhancement at half maximum height is about 200 MeV. At this time we don't know with certainty the nature of the enhancement; it is usually assumed to be an hadronic resonance. Some physicists go further and assign the 4.1 GeV enhancement to the ψ, ψ' family, calling it the ψ'', although the width of the 4.1 GeV enhancement is 1000 times greater than the ψ or ψ' widths. The width difference is explained by assuming that the 4.1 GeV enhancement can decay into pairs of singly charmed mesons (Sec. 6), while the ψ and ψ' cannot so decay.

Experiments have not as yet provided any clear evidence as to the nature of the 4.1 GeV enhancement. The average charged multiplicity, Fig. 4, and average charged track energy are quite similar to the neighborhood continuum regions. The $d\sigma/dx$ curve[2] may be slightly different, but this may be a property of the entire 4 to 4.5 GeV region.

There is clearly much more to be learned in the 4.1 GeV region. For example, preliminary data (Fig. 3) shows that there may be a second enhancement at 4.4 GeV. However this data was taken on the very last day of Spring, 1975 running of SPEAR and must be repeated in detail.

4. THE ψ AND ψ'

It was the discovery of the ψ (also called $\psi(3095)$) and ψ' (also called $\psi(3684)$) with their astonishingly long lives, relative to their masses, which began the new particle era. The ψ and ψ' are of course copiously produced in $e^+ - e^-$ annihilation[11-13];

$$e^+ + e^- \to \psi \quad , \quad e^+ + e^- \to \psi' \tag{5}$$

The ψ is also produced[14,15,16], but not copiously, in hadron-hadron collisions. Indeed the ψ was independently discovered[14] using the reaction

$$p + Be \to \psi + \text{anything} \tag{6}$$

Finally, the ψ is easily produced by photoproduction[17,18,19], both diffractively

$$\gamma + \text{nucleon} \to \psi + \text{nucleon} \tag{7a}$$

and non-diffractively

$$\gamma + \text{nucleon} \to \psi + \text{2-or-more hadrons} \tag{7b}$$

The masses, widths, and quantum numbers of the ψ and ψ' as measured through $e^+ - e^-$ production[1,3] are listed in Table I.

TABLE I

Properties of the ψ and ψ'

	ψ	ψ'
Mass	3095 ± 4 MeV	3684 ± 5 MeV
J^{PC}	1^{--}	1^{--}
I^G	0^-	0^-
$\Gamma_e = \Gamma_\mu$	4.8 ± 0.6 KeV	2.2 ± 0.3 KeV
Γ_{had}	59 ± 14 KeV	220 ± 56 KeV
Γ	69 ± 15 KeV	225 ± 56 KeV
Γ_e/Γ	0.069 ± 0.009	0.0097 ± 0.0016
Γ_{had}/Γ	0.86 ± 0.02	0.981 ± 0.003
Γ_μ/Γ_e	1.00 ± 0.05	0.89 ± 0.16

The branching ratios to the most copious identified decay modes of the ψ are listed[1,3] in Table II. These decay modes are found using four-constraint or one-constraint fits, hence modes which have 2 or more π^0 mesons are not included. The branching ratios to the latter states can be estimated using exact or statistical isotopic spin considerations. It is then found

TABLE II

Decay Modes of the $\psi(3095)$

Mode	Branching Ratio (%)
e^+e^-	6.9 ± 0.9
$\mu^+\mu^-$	6.9 ± 0.9
$\rho\pi$	1.3 ± 0.3
$2\pi^+ 2\pi^-$	0.4 ± 0.1
$2\pi^+ 2\pi^- \pi^0$	4.0 ± 1.0
$3\pi^+ 3\pi^-$	0.4 ± 0.2
$3\pi^+ 3\pi^- \pi^0$	2.9 ± 0.7
$4\pi^+ 4\pi^- \pi^0$	0.9 ± 0.3
$\pi^+\pi^- K^+K^-$	0.4 ± 0.2

Table II continued

Mode	Branching Ratio (%)
$2\pi^+ 2\pi^- K^+K^-$	0.3 ± 0.1
$K^oK^{o*}(892)$	0.24 ± 0.05
$K^{\pm}K^{\mp *}(892)$	0.31 ± 0.07
$K^{*o}(892)K^{*o}(1420)$	0.37 ± 0.10
$p\bar{p}$	0.21 ± 0.04
$\Lambda\bar{\Lambda}$	0.16 ± 0.08
$p\bar{p}\ \pi^o$ $n\bar{p}\ \pi^-$ $\bar{p}n\ \pi^+$	0.37 ± 0.19

that at least 70% or 80% of the decay width of the $\psi(3095)$ can be accounted for. Therefore in decay the $\psi(3095)$ behaves as a normal meson, <u>except</u> that its decay width is at least 1000 times too narrow and its leptonic decay modes (ee and $\mu\mu$) are correspondingly large. This is a large exception however. And combined with the very small hadronic production cross sections, this observation means that we can only call the ψ a hadron if we introduce some principle or recipe to inhibit both hadronic decay and hadronic production.

There are two classes of theories[20,21] which can do this. One possibility is that the ψ's strong decay is exactly forbidden by its possession of a new non-additive quantum number. Various color models are examples of this[21]. The other possibility is that the ψ's strong decay is inhibited by a dynamical principle based on the existence of new additive quantum numbers. Charm is an example of this case in which the ψ's have zero charm quantum number but are composed of charmed quarks[22,23]. In the charm model the ψ's are narrow because of a dynamical principle known as Zweig's rule. This phenomenological rule states that processes in which initial quark pairs cannot appear on different final state particles are suppressed.

Whatever the nature of the ψ, the ψ' is the same type of particle. Their production cross sections in $e^+ - e^-$ annihilation are the same order of magnitude; and they both have relatively narrow decay widths (Table I). Moreover the ψ' decays to the ψ more than half the time (Table III). However, as shown in Table III[3] we know much less about the decay modes of the ψ'.

TABLE III

Decay Modes of the $\psi(3684)$

Modes	Branching Ratio (%)	Comments
e^+e^-	0.97 ± 0.16	μ-e universality assumed
$\mu^+\mu^-$	0.97 ± 0.16	
$\psi(3100)$ anything	57 ± 8	
$\psi(3100)\ \pi^+\pi^-$	32 ± 4	these decay are included in the fraction for ψ + anything
$\psi(3100)\ \pi^0$	4 ± 2	
$2\pi^+\ 2\pi^-\pi^0$	0.35 ± 0.15	
$p\bar{p}$	0.04 ± 0.02	
$\pi^+\pi^-K^+K^-$	~ 0.05	

Our ignorance of the 31% of the ψ' decay modes which do are not to the ψ or leptonic is not due to a shortage of data. Indeed there are more $e^+ + e^- \rightarrow \psi'$ than $e^+ + e^- \rightarrow \psi$ events on tape. The reason is that the ψ', unlike the ψ (Table II) eschews four-constraint and one-constraint decay modes when it does not decay to the ψ. The ψ' preferes decay modes with at least two neutral particles -- two π^0's or a π^0 and a γ for example. We do not understand the significance of this observation. Perhaps it is related to the radiative decays of the ψ' which are described next.

5. RADIATIVE DECAYS OF THE ψ AND ψ'

In the last few months several radiative decays of the ψ' have been discovered. The study of these radiative decays is just beginning, therefore, the data I will now describe is certainly incomplete.

At both DORIS[24] and SPEAR[4,25] the decay

$$\psi' \rightarrow \gamma + \gamma + \psi \tag{8a}$$

has been detected with a branching ratio of $3.6 \pm 0.7\%$. Furthermore the energies of the γ's fall into two bands. In the DORIS data the bands are centered at about 160 MeV and about 420 MeV; the sum, of course, being the mass difference between the ψ' and the ψ. The SPEAR data is shown in Fig. 7. The explanation is that there is a new particle or intermediate state, called P_c[26] in Ref. 24; such that

$$\psi' \rightarrow \gamma + P_c \quad , \quad P_c \rightarrow \gamma + \psi \ ; \tag{8b}$$

with

$$P_c \text{ mass} \approx 3300 \text{ or } 3500 \text{ MeV}/c^2 \tag{8c}$$

The mass of the P_c cannot be settled using just the reactions in Eq. 8 unless one detects the Doppler broadening of the γ line emitted in the P_c decay. This has not yet been done.

However the SLAC-LBL magnetic detector collaboration at SPEAR has also seen ψ' radiative decays of the form[4,27]

$$\psi' \rightarrow \gamma + \text{hadrons} \tag{9}$$

where the hadrons have invariant mass distributions indicating the existence of new particles. As shown in Fig. 8 hadron combinations of $2\pi^+ 2\pi^-$, $3\pi^+ 3\pi^-$, $\pi^+\pi^- K^+K^-$. $\pi^+\pi^-$, and K^+K^- have been studied. At least two new particles, called χ's, are seen:

$$\chi(3410) \text{ with mass } 3410 \pm 10 \text{ MeV}/c^2 \tag{10a}$$

$$\chi(3530) \text{ with mass } 3530 \pm 20 \text{ MeV}/c^2 \tag{10b}$$

The $\chi(3530)$ appears to be wider than the $\chi(3410)$ and wider than the apparatus resolution. Hence the $\chi(3530)$ may contain 2 or more states.

The branching ratios for the radiative decays into the states shown in Fig. 8 are each of the order of magnitude of one or two tenths of a per cent. These are of course lower limits to the full branching ratios for

$$\psi' \to \gamma + \chi(3410) \;,\; \psi' \to \gamma + \chi(3530) \qquad (11)$$

because only some of the decay modes of the χ's are seen. It seems reasonable that these full branching ratios could each be several per cent as is the decay to the P_c state, Eq. 8b. Incidently an upper limit of the order of 5 to 10% for any single radiative decay mode of the ψ' has been set.[28]

The relation of the P_c to the χ's is not yet known. If the P_c mass is 3300 MeV/c^2 they are clearly different. If the P_c mass is 3500 MeV/c^2 the P_c and at least part of the $\chi(3530)$ are probably related. Data to be taken at DORIS and SPEAR in the Winter of 1975 and Spring of 1976 should resolve this question.

Finally two groups[5,6] at DORIS have seen radiative decays of the ψ to a new particle of mass about 2750 or 2800 MeV/c^2. The decays observed are

$$\psi \to \gamma + \text{new particle}$$

$$\text{new particle} \to \gamma + \gamma$$

a few events of the form

$$\text{new particle} \to p + \bar{p}$$

are also seen. This new particle is sometimes called η_c assuming the charm theory of the ψ particle and assuming that this new particle consists of a charmed quark-antiquark pair in a pseudoscalar state.

6. SINGLY CHARMED PARTICLE SEARCHES IN $e^+ - e^-$ ANNIHILATION

The current charm theories of the ψ particle assume that mesons exist in which only one of the partners in the quark-antiquark pair (which comprise the meson) is a charm quark. The other quark is one of the conventional u, d, or s quarks. The region $4 \lesssim E_{cm} \lesssim 5$ GeV in $e^+ - e^-$ annihilation would seem to be an excellent place to search for such singly charmed mesons. This is based on the assumptions that the ψ' does not decay into these mesons but the 4.1 GeV enhancement does so decay. Furthermore the singly charmed mesons have relatively long lifetimes since their decay into ordinary mesons would be inhibited as are the ψ and ψ' decays. Hence all that would seem to be required would be to find narrow peaks in the invariant mass distributions of some of the particles in the final state. A search[29] at $E_{cm} = 4.8$ GeV found no such peaks in particle combinations such as $\pi^+\pi^-$, $K^{\mp}\pi^{\pm}$, $K_S^0\pi^{\pm}$, $K_S^0\pi^+\pi^-$ and $\pi^{\pm}\pi^+\pi^-$. Even more disquieting is the failure of a search[30] in the $4.0 \lesssim E_{cm} \lesssim 4.4$ GeV. This region includes the 4.1 enhancement which is supposed to decay primarily to charmed mesons.

There are three ways out of this problems. The singly charmed mesons may have very small branching ratios for decay into 2 or 3 particle final states. Another possibility is that the decay modes of the singly charmed mesons always contain a π^0 or γ. And there is of course the possibility that singly charmed quarks do not exist.

7. THE eμ EVENTS

Events of the form

$$e^+ + e^- \rightarrow e^{\pm} + \mu^{\mp} + \text{2-or-more undetected particles} \qquad (12)$$

have been found at SPEAR using the SLAC-LBL magnetic detector. The undetected particles are charged particles or photons which escape the 2.6π sr solid angle of the detector, or particles very difficult to detect such as neutrons, K_L^0 mesons, or neutrinos. The evidence that these events do not have a conventional explanation is fully presented in Refs. 31 and 32; and the reader is invited to critically examine that evidence. In describing the events here I shall abstract from these references.

The $e\mu$ events described in Eq. 12 are possible signatures for several types of new particles:

1. Heavy Leptons: Suppose the electron ($e^{\pm}$) and muon ($\mu^{\pm}$) are the lowest mass members of a sequence of leptons[33-35], each lepton ($\ell^{\pm}$) having a unique quantum number n_{ℓ} and a unique associated neutrino (ν_{ℓ}). Such sequential[33] heavy leptons have the purely leptonic decay modes:

$$\ell^- \to \nu_{\ell} + e^- + \bar{\nu}_e \ , \quad \ell^- \to \nu_{\ell} + \mu^- + \bar{\nu}_{\mu} \ ; \tag{13}$$

assuming the quantum number n_{ℓ} must be conserved as are n_{μ} and n_e. (The ℓ^+ has corresponding decay modes.) If the ℓ has a sufficiently large mass it will also have semileptonic decay modes.

$$\ell^- \to \nu_{\ell} + \pi^- \ , \quad \ell^- \to \nu_{\ell} + K^- \ , \quad \ell^- \to \nu_{\ell} + \rho^- \ , \quad \ell^- \to \nu_{\ell} + 2 \text{ or more hadrons} \tag{14}$$

The reaction in Eq. 12 would then come from the lepton pair production process

$$e^+ + e^- \to \ell^+ + \ell^-$$

2. Heavy Mesons: If new charged mesons, $M^{\pm}$, exist which have relatively large leptonic decay modes (due to the inhibition of purely hadronic decay modes) then the purely leptonic decay modes.

$$M^- \to e^- + \bar{\nu}_e \ , \quad M^- \to \mu^- + \bar{\nu}_{\mu} \ ; \tag{15}$$

can lead to the reaction in Eq. 12, thru

$$e^+ + e^- \to M^+ + M^- \tag{16}$$

Such charged mesons are predicted by theories which introduce the charmed quark[20-23]. The meson spin would have to be at least 1 to allow a substantial e decay mode[31].

3. Elementary Bosons: Although the mass of the intermediate boson ($W^{\pm}$), which is supposed to mediate the weak interaction, if it exists, is probably too high to allow pair production at the energies discussed in this paper; the decay mode

$$W^- \to e^- + \bar{\nu}_e \; , \quad W^- \leftarrow \mu^- + \bar{\nu}_\mu \; ; \tag{17}$$

can lead to the reaction of Eq. 12. We may also consider other types of elementary bosons -- not necessarily the intermediate boson W. The difference between an elementary boson and a heavy meson is that we suppose the former to be a point particle with a form factor always equal to unity.

4. Other Interpretations: The eμ events need not come from the production of a pair of particles and their subsequent leptonic decay. One can consider a resonance (R) with the weak decay mode

$$R \to e^+ + \nu_e + \mu^- + \bar{\nu}_\mu \tag{18}$$

Or one can think about the higher order weak interaction process

$$e^+ + e^- \to e^+ + \nu_e + \mu^- + \bar{\nu}_\mu \tag{19}$$

However the observed cross sections -- of the order of .01 to .02 nb -- appears to be much too large for this conjecture.

We are not yet prepared to prove that the eμ events can only be explained by the production of a pair of new particles. However this turns out to be the most natural hypothesis. Hence as I describe the events I shall assume they are due to the production and decay of a pair of new particle called U particles:

$$e^+ + e^- \to U^+ + U^- \tag{20}$$

U designates unknown and avoids any commitment to the nature of the new particle, be it a lepton, meson or elementary boson.

The eμ events meet the following criteria.

1. Two and only two charged tracks in the detecter. (These are called two-prong events.)
2. No photons detected.
3. One track is identified as an electron and the other is identified as a muon.
4. The total charge is zero.
5. Calling the e momentum $\underset{\sim}{p}_e$ and the μ momentum $\underset{\sim}{p}_\mu$ we require $|\underset{\sim}{p}_e| > 0.65$ GeV/c and $|\underset{\sim}{p}_\mu| > 0.65$ GeV/c. This is necessary[31,32] for e and μ identification.
6. We define a coplanarity angle

$$\cos \theta_{copl} = -(\underset{\sim}{n}_e \times \underset{\sim}{n}_+) \cdot (\underset{\sim}{n}_\mu \times \underset{\sim}{n}_+)/(|\underset{\sim}{n}_e \times \underset{\sim}{n}_+| \; |\underset{\sim}{n}_\mu \times \underset{\sim}{n}_+|) \qquad (21)$$

where $\underset{\sim}{n}_e$, $\underset{\sim}{n}_\mu$, $\underset{\sim}{n}_+$ are unit vectors along the directions of particles e, μ, and e^+ beam. The contamination of events from the reactions $e^+e^- \to e^+e^-$ and $e^+e^- \to \mu^+\mu^-$ is greatly reduced if we require $\theta_{copl} > 20^\circ$; and we do just this.

These criteria lead to <u>86 eμ events</u> being found in the data taken in the energy range $3.8 \leqslant E_{cm} \leqslant 7.8$ GeV.

The background[31,32] in the eμ events comes primarily from hadronic events in which the hadrons decay to an e or a μ or are misidentified by the detector as an e or a μ. Some background also comes from $e^+e^- \to e^+e^-\gamma$ or $e^+e^-\gamma\gamma$ in which the γ's are not detected and one e is misidentified as a μ. We can determine the background from hadron misidentification or decay by using three-or-more-prong events assuming every particle called an e or a μ by the detector was either a misidentified hadron or came from the decay of a hadron. This leads to calculated background, including the eeγ background, of 22 ± 5 events.

This yields a net signal of 64 eμ events. A less reliable background calculation method[32] using only two-prong events leads to a total background of 30 $\pm$ 6 events.

I shall now summarize the properties of the eμ events. A much fuller discussion appears in Ref. 36.

1. Observed Production Cross Section: Figure 9 shows the observed cross section in the detector acceptance for signature eμ events versus center-of-mass energy, with the background subtracted at each energy. The corrections to obtain the true cross section for the angle and momentum cuts used here depend on the hypothesis as to the origin of these eμ events, and the corrected cross section can be many times larger than the observed cross section. While Fig. 9 shows an apparent threshold at around 4 GeV, the statistics are small and the corrections factors are largest for low E_{cm}. Thus, the apparent threshold may not be real.

2. Number of Missing Particles: As shown in Refs. 31 and 32 the distribution of the missing mass recoiling against the e and μ in the reaction in Eq. 12 proves that at least 2 particles are missing.

3. Coplanarity Angle Distribution: We define the collinearity angle by

$$\cos \theta_{coll} = -\underset{\sim}{p}_e \cdot \underset{\sim}{p}_\mu / (|\underset{\sim}{p}_e| \; |\underset{\sim}{p}_\mu|) \tag{22}$$

When the e and μ are moving in exactly opposite directions $\theta_{coll} = 0$. The $\cos \theta_{coll}$ distribution is shown in Fig. 10. The small angle behavior of the θ_{coll} distribution is due to the θ_{copl} cut. All $\theta_{coll} < 20^o$ are eliminated and larger θ_{coll} are partially lost. At the higher E_{cm} energies the $\cos \theta_{coll}$ distribution is naturally fit by the hypothesis

$$e^+ + e^- \rightarrow U^+ + U^-$$

$$U \rightarrow e + X \text{ , } U + X \tag{23}$$

X represents one or more neutral particles

Mass of U $\lesssim$ 2 GeV

when $|\underset{\sim}{p}_e| > 0.65$ GeV/c, $|\underset{\sim}{p}_\mu| > 0.65$ GeV/c are taken into account.

At the lower energies the nature of X becomes important. We consider two possibilities for the decay of the U

$$\text{2-body decay : } \quad U^- \to e^- + \bar{\nu}_e \quad \text{and} \qquad (24a)$$
$$U^- \to \mu^- + \bar{\nu}_\mu$$

$$\text{3-body decay : } \quad U^- \to \nu_U + e^- + \bar{\nu}_e \quad \text{and} \qquad (24b)$$
$$U^- \to \nu_U + \mu^- + \bar{\nu}_\mu$$

The 2-body decay would be from a meson or elementary boson. The 3-body decay would be from a heavy lepton. For convenience I shall assume the mass of the ν_U is zero and the U-ν_U current is V-A. (I will not consider the effect of a V + A current or of the mass of the ν_U being non-zero. Also I will not discuss semi-leptonic decays of the meson or boson.)

In Fig. 10, I show fits to the data using $M_U = 1.9$ GeV/c for the 2-body decay and $M_U = 1.8$ GeV/c^2 for the 3-body decay. These masses are examples of the kind of masses which seem to fit the angle and momentum distributions. But masses in the range of 1.6 to 2.0 GeV/c^2 are acceptable. All spin-spin correlations are ignored. Particularly in the 4.8 GeV data the 2-body hypothesis has difficulty in explaining the small number of large θ_{coll} events. Reduction of M_U can cure this, but then problems arise[36] with the momentum distribution of the e and μ. An alternative cure requires strong spin-spin correlation between the mesons[31]. A 3-body decay mode obviously fits the cos θ_{coll} distributions in a more natural manner.

4. Momentum Distribution: The same observation holds for the momentum distributions as shown in Figs. 11 and 12. To combine the data from different E_{cm} runs we define

$$\rho = \frac{p - 0.65}{p_{max} - 0.65} \tag{25}$$

where p_{max} is calculated for $M_U = 1.8$ GeV (the use of $M_U = 1.9$ GeV makes very little difference) and p is $|\underset{\sim}{p}_e|$ or $|\underset{\sim}{p}_\mu|$. Each event thus appears twice. Note that $0 \leq \rho \leq 1$. Figures 11 and 12 are corrected for background[36]. We see that the 2-body decay mode usually predicts too many large ρ, that is large p, points. Only at 4.8 GeV are the 2-body and 3-body hypotheses equally applicable.

To summarize our knowledge of the eμ events I will paraphrase Gary Feldman's summary of these events at the 1975 Lepton-Photon Conference[4].

1. We know the following:
    a. Anomalous eμ events exist.
    b. The data are not consistent with all the events coming from 2-body decays.
    c. It is very unlikely that semi-leptonic decays account for all the events.
    d. We know of nothing which is inconsistent with the hypothesis that the events come from the 3-body decay of a U particle. In particular the 3-body decay could be the purely leptonic decay of a sequential heavy lepton.
2. We still have to answer the following questions.
    a. Is a heavy lepton completely consistent with the data?
    b. Is any other hypothesis consistent with the data?
    c. Is more than one thing going on? That is, are there several mechanisms producing eμ events?

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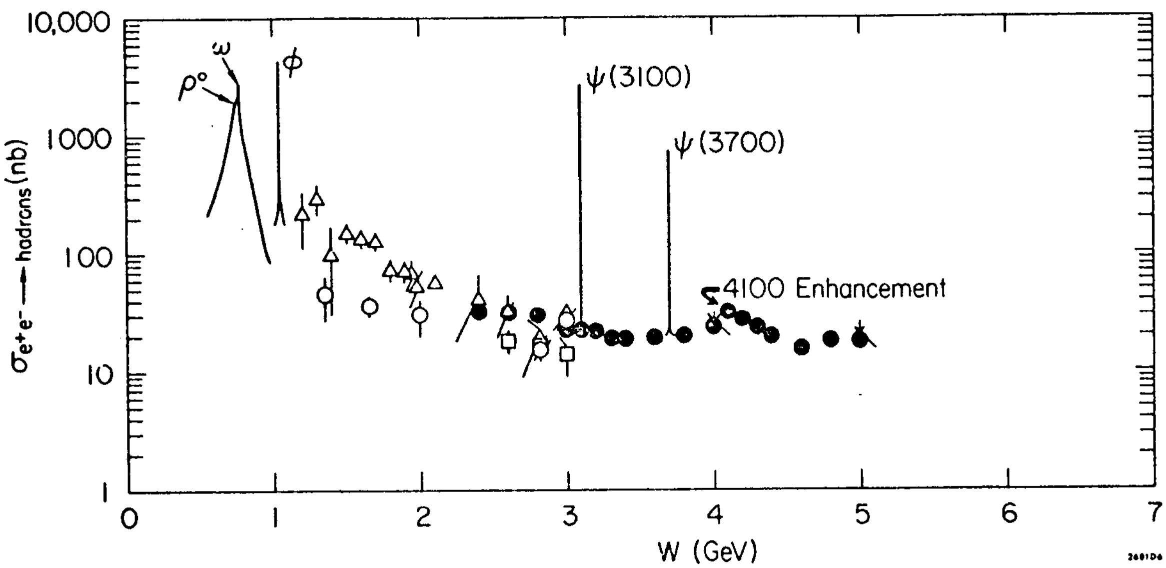
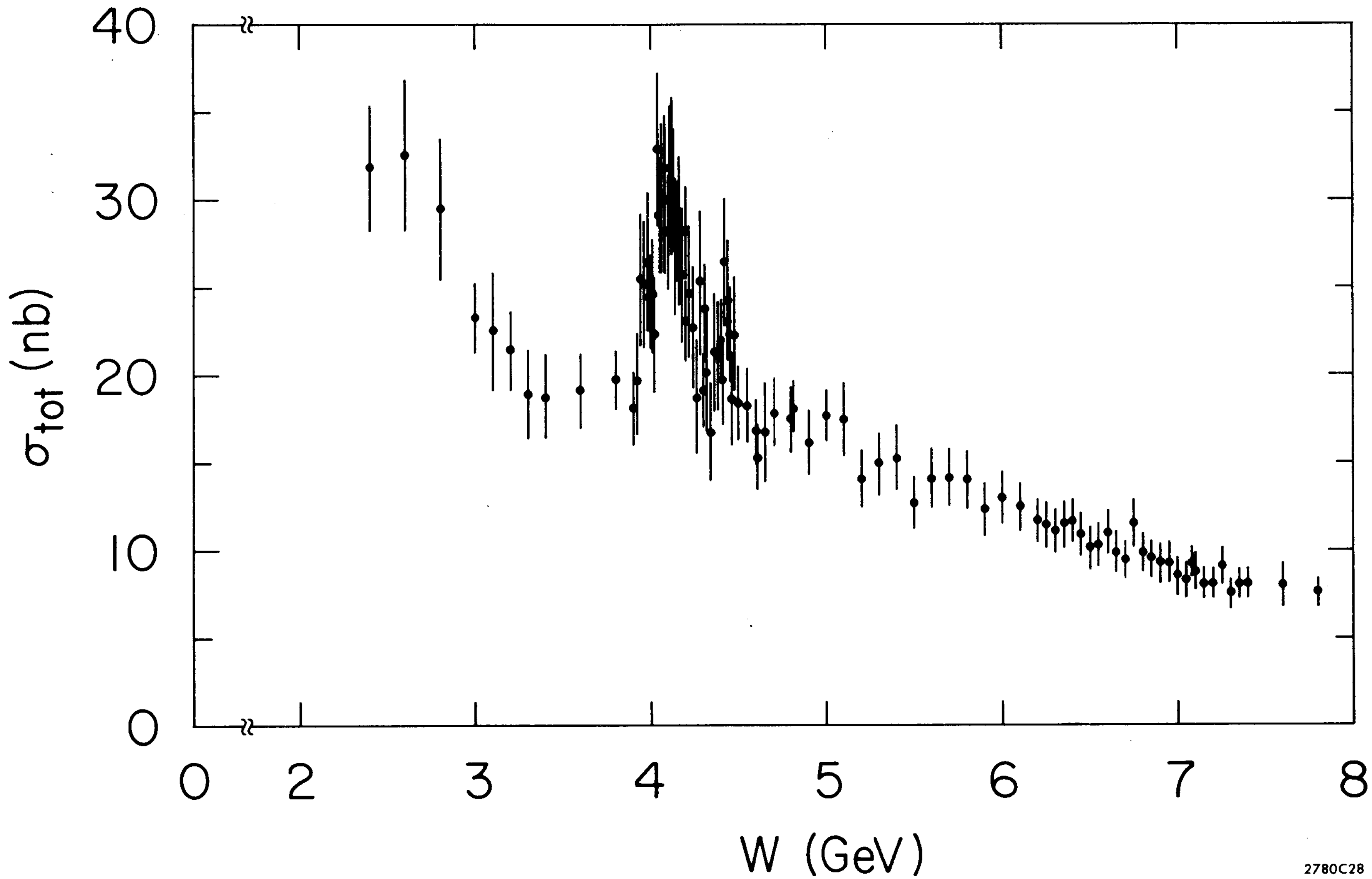


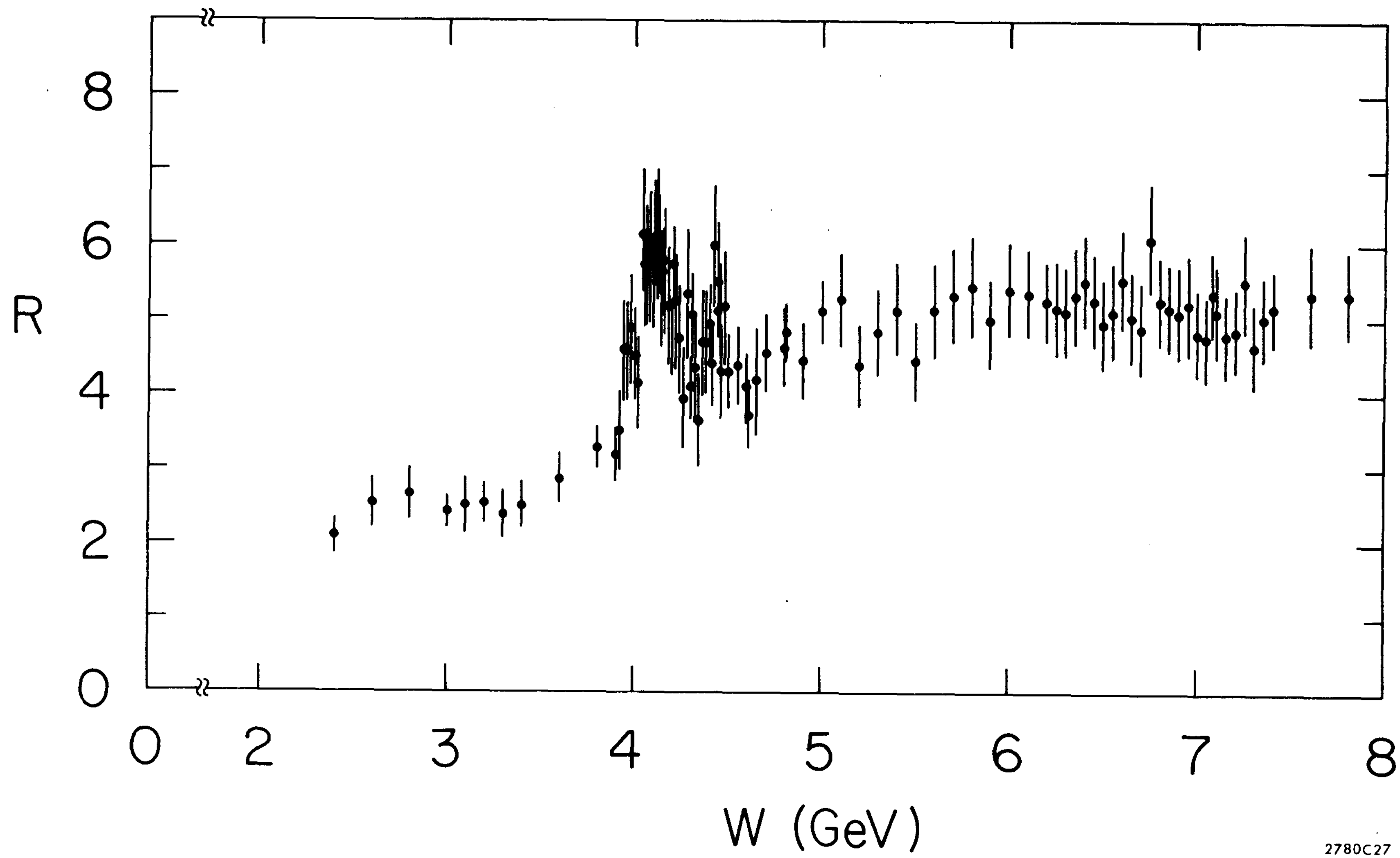
An overall view of the behavior of $\sigma_{e^+e^- \to \text{hadrons}}$ as a function of the total energy $W = E_{cm}$. Taken from Ref. 1

Fig. 1



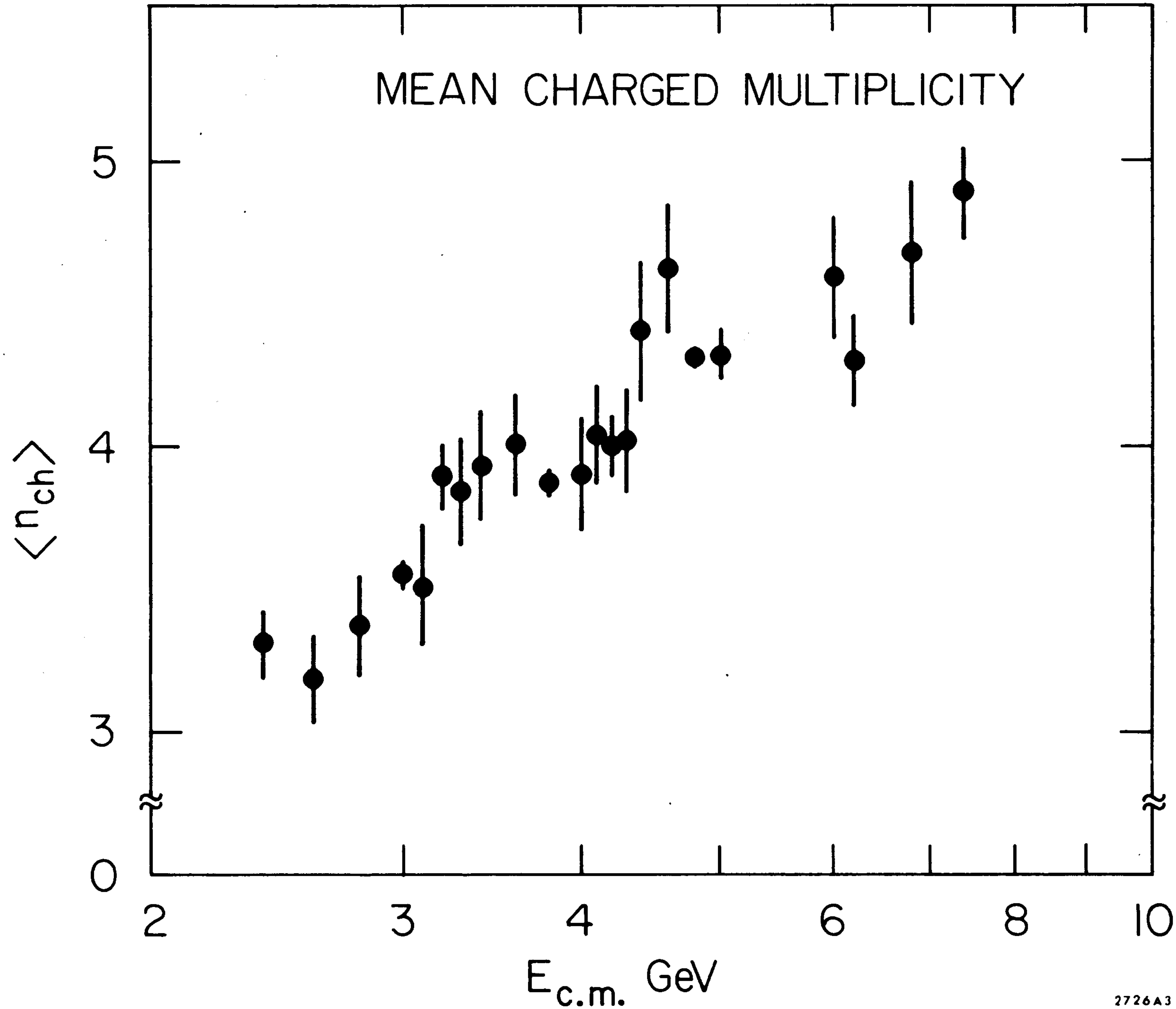
$\sigma_{e^+e^- \to \text{hadrons}}$ versus W for W > 2 GeV. Taken from Ref. 2.

Fig. 2



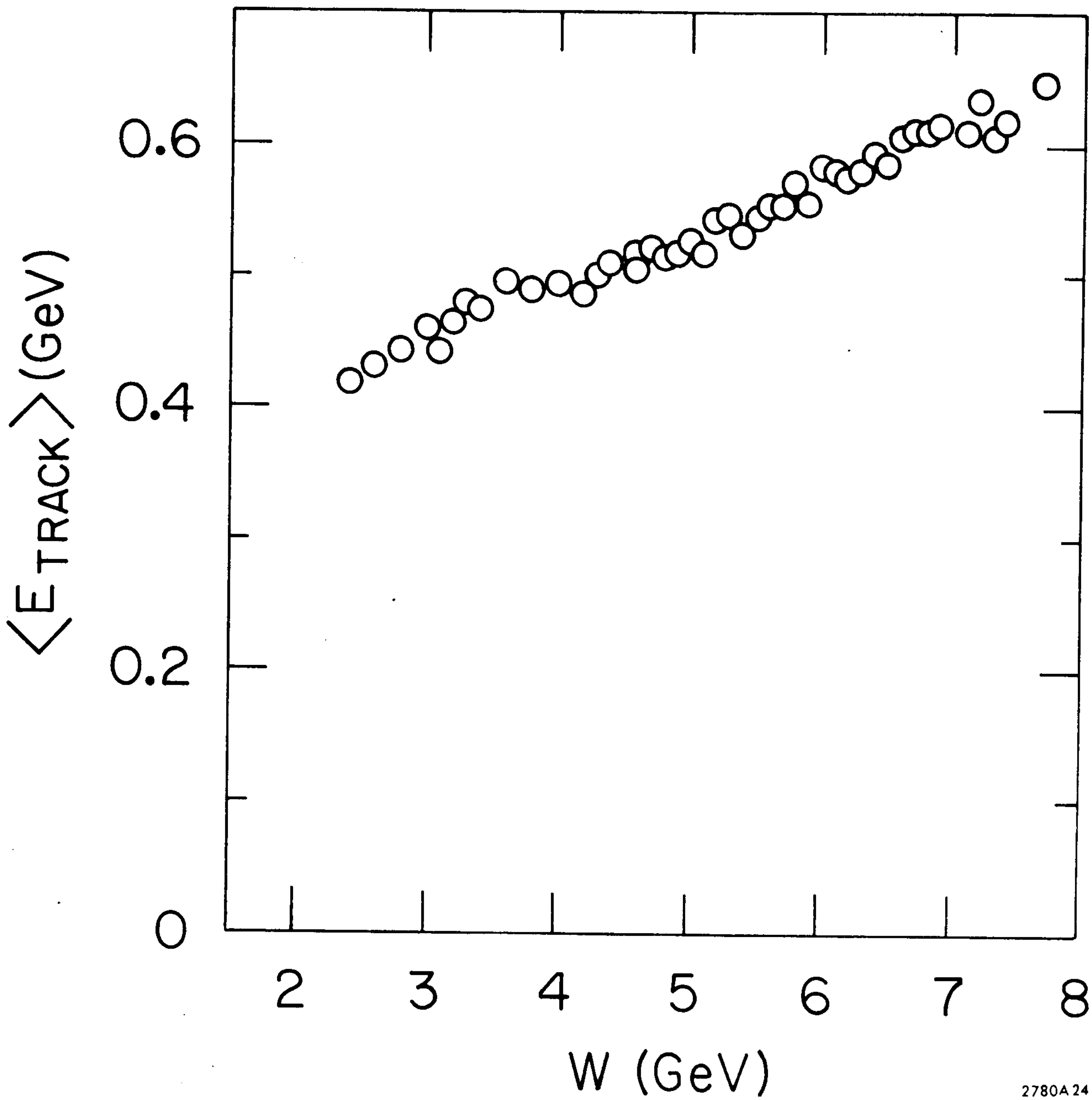
$R = \sigma_{e^+e^- \to hadrons} / \sigma_{e^+e^- \to \mu^+\mu^-}$ versus W. Taken from Ref. 2.

Fig. 3



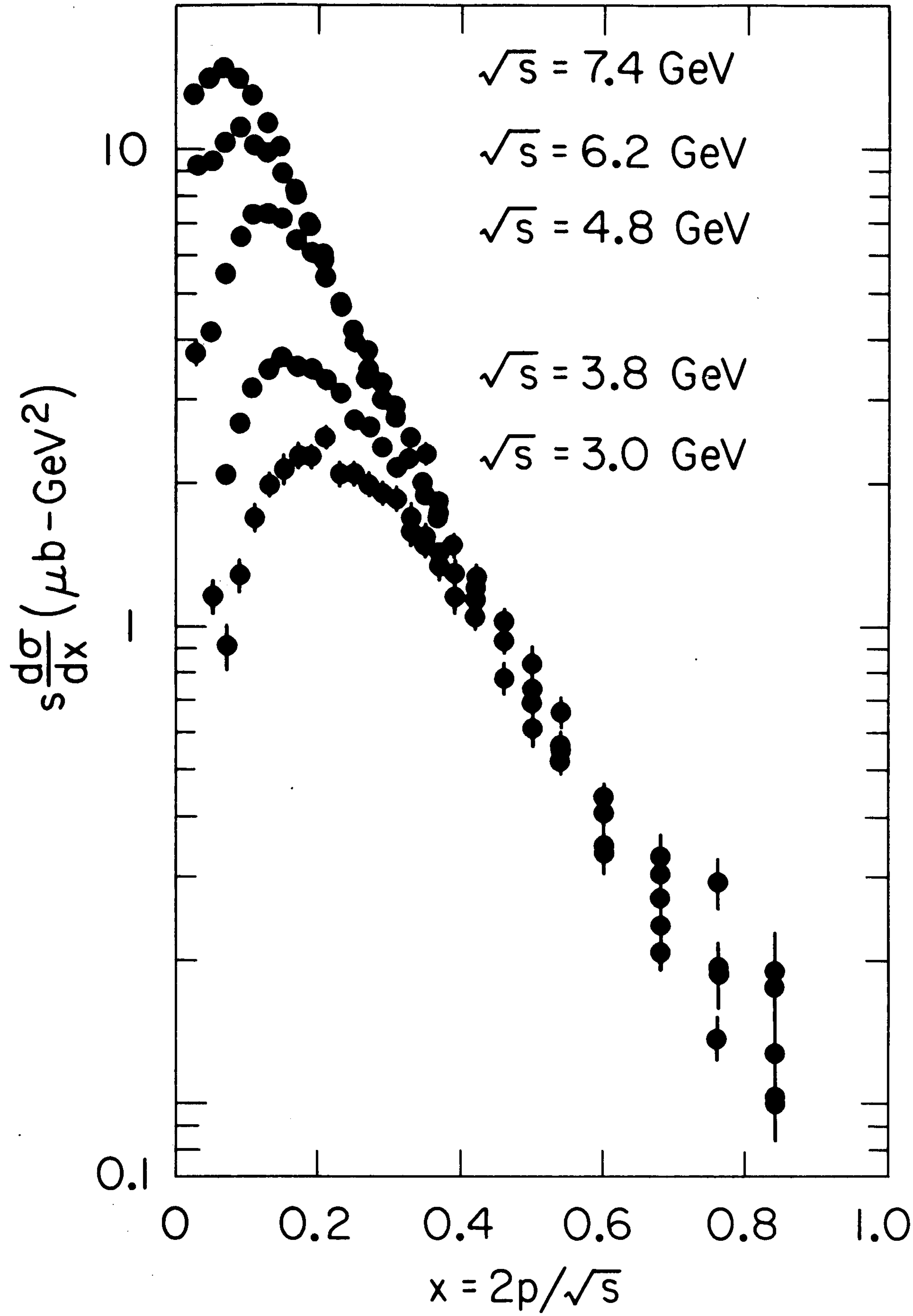
The mean charged track multiplicity versus E_{cm}. Taken from Ref. 2.

Fig. 4



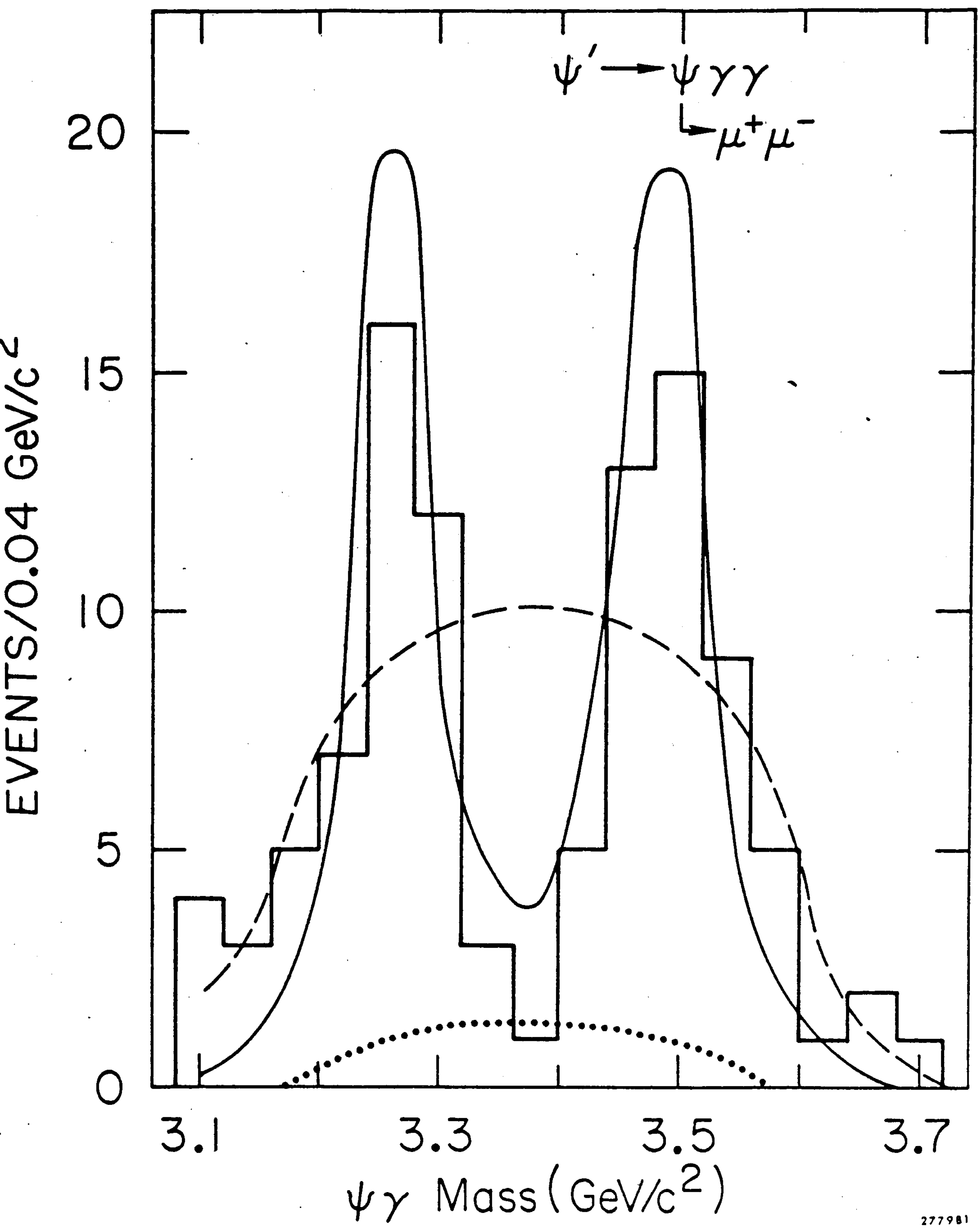
The average energy per charged track versus E_{cm}. Taken from Ref. 2.

Fig. 5



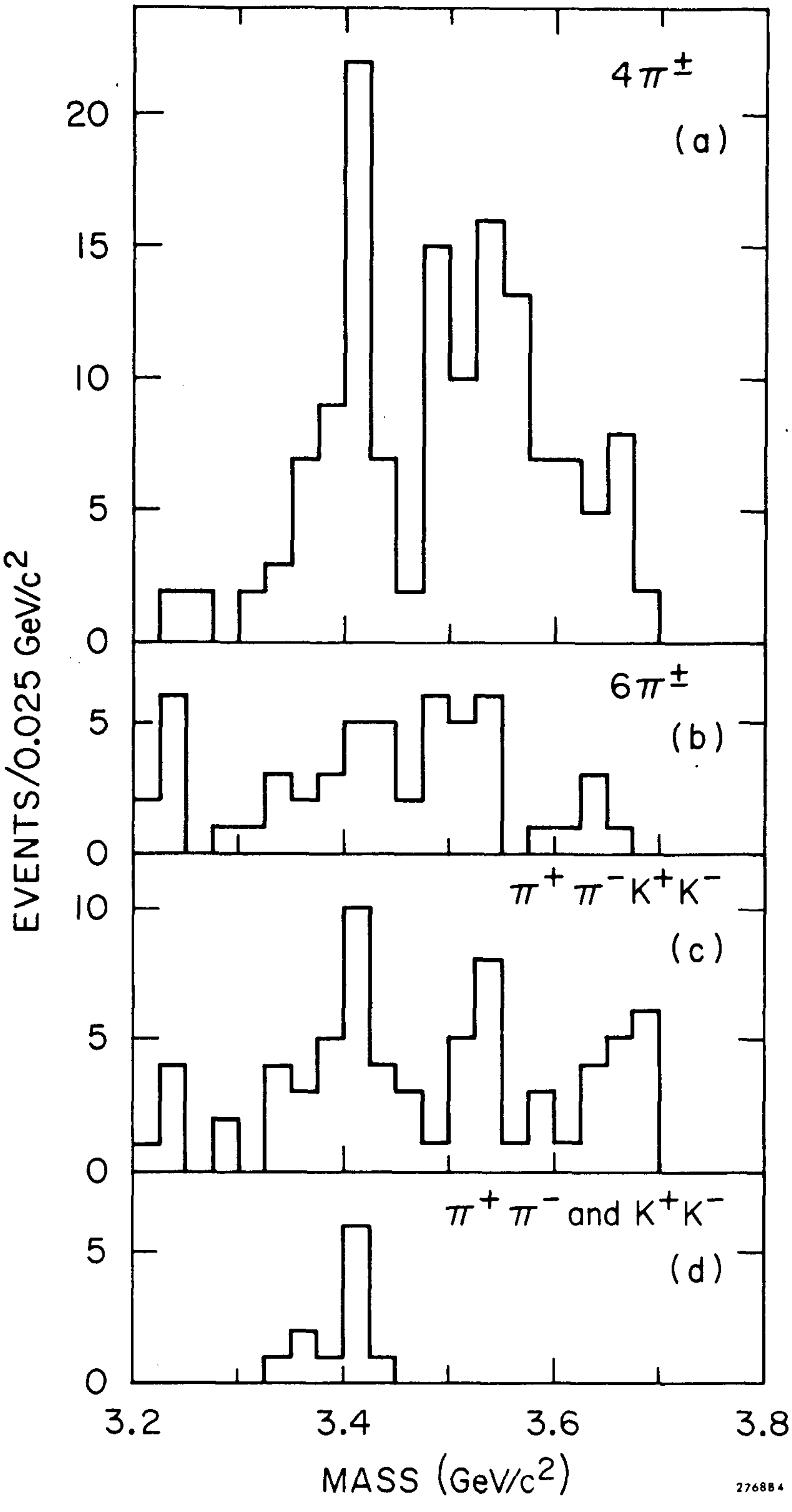
The distribution of the momentum p of the charged particles scaled by using $x = 2p/\sqrt{s}$. $\sqrt{s} = E_{cm}$. Taken from Ref. 2

Fig. 6



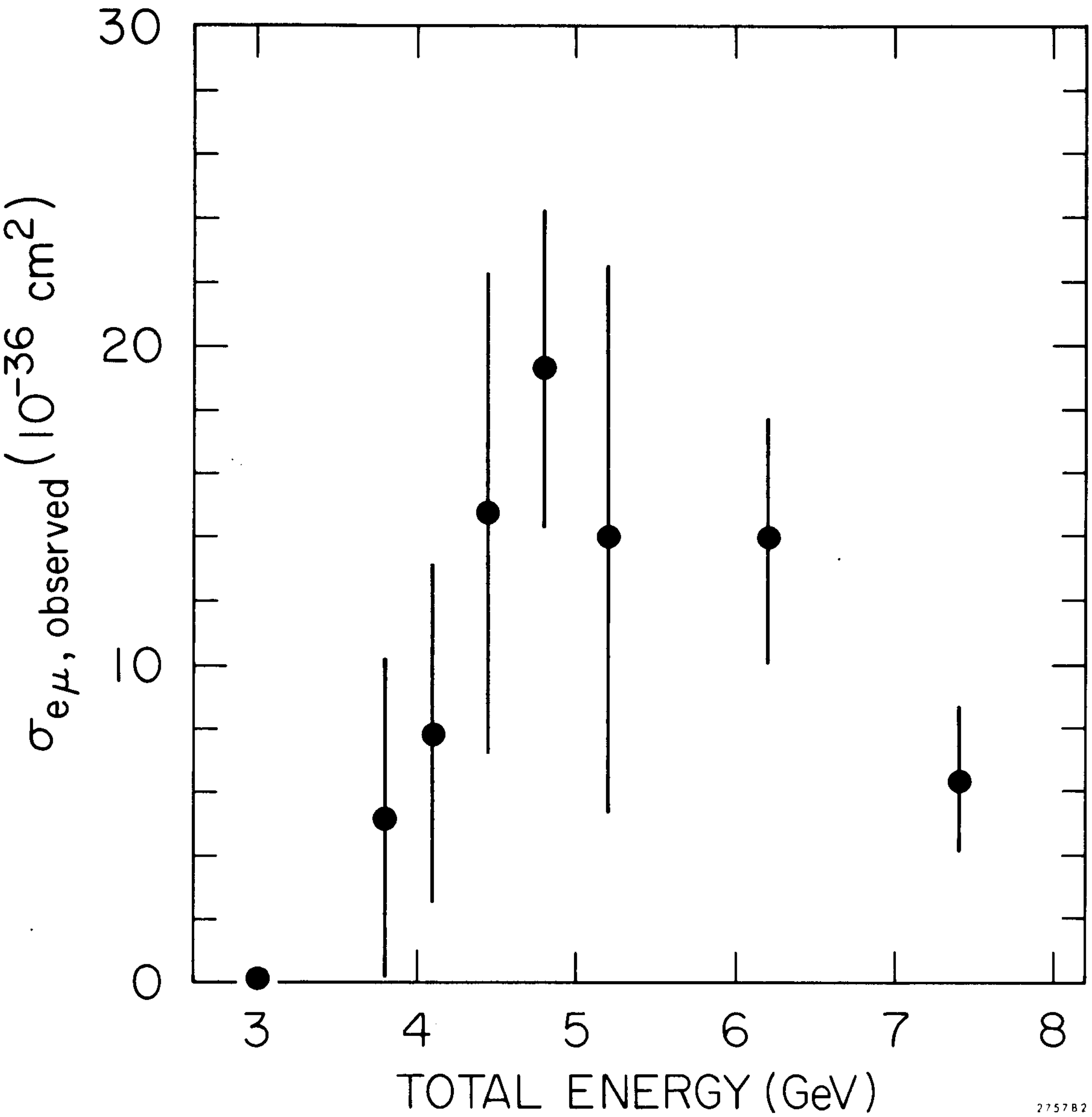
The $\psi\gamma$ mass distribution for the decay $\psi' \to \psi + \gamma + \gamma$. Taken from Ref. 25.

Fig. 7



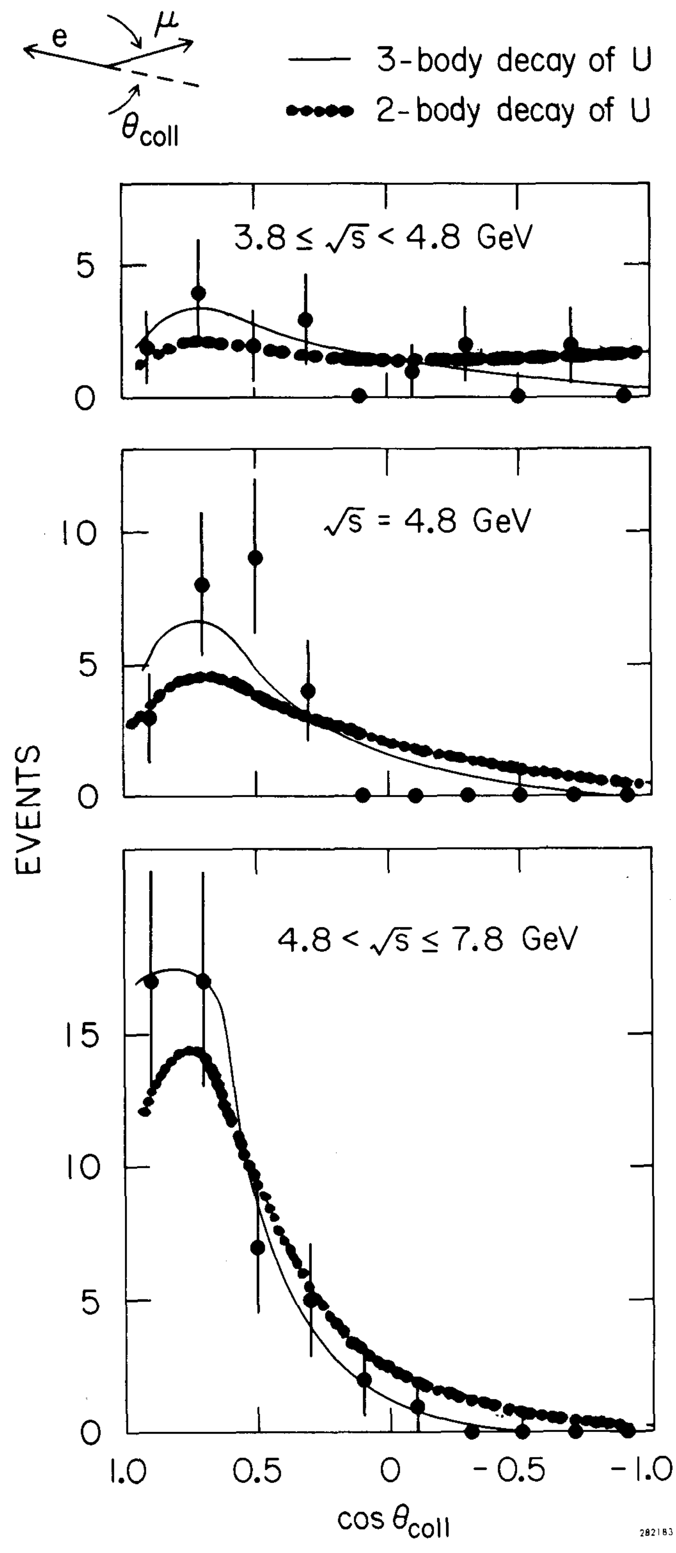
Invariant mass distributions of various particle combinations which fit the decay $\psi' \to \gamma$ + hadrons. Taken from Refs. 4 and 27.

Fig. 8



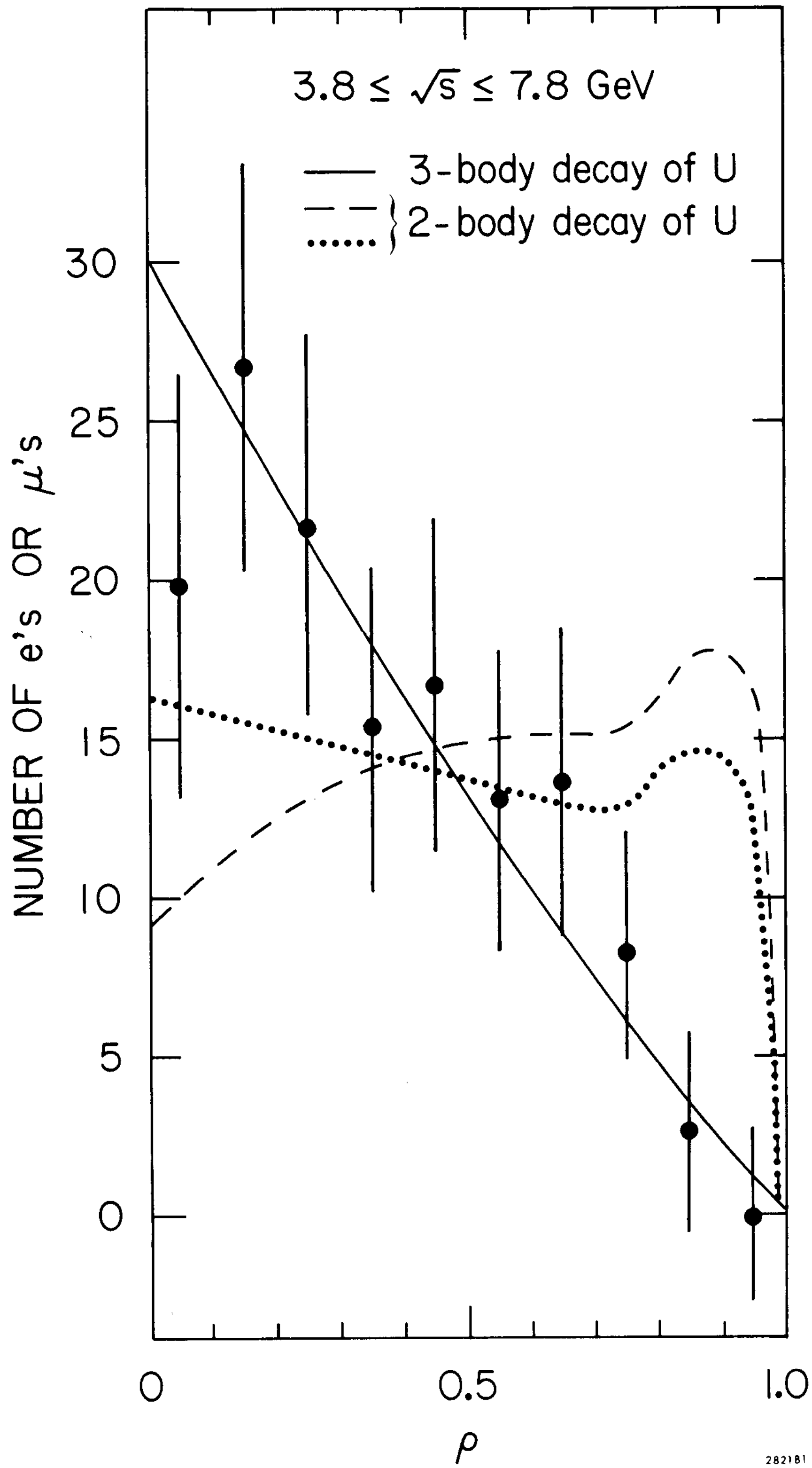
The observed cross section for the eμ events.

Fig. 9



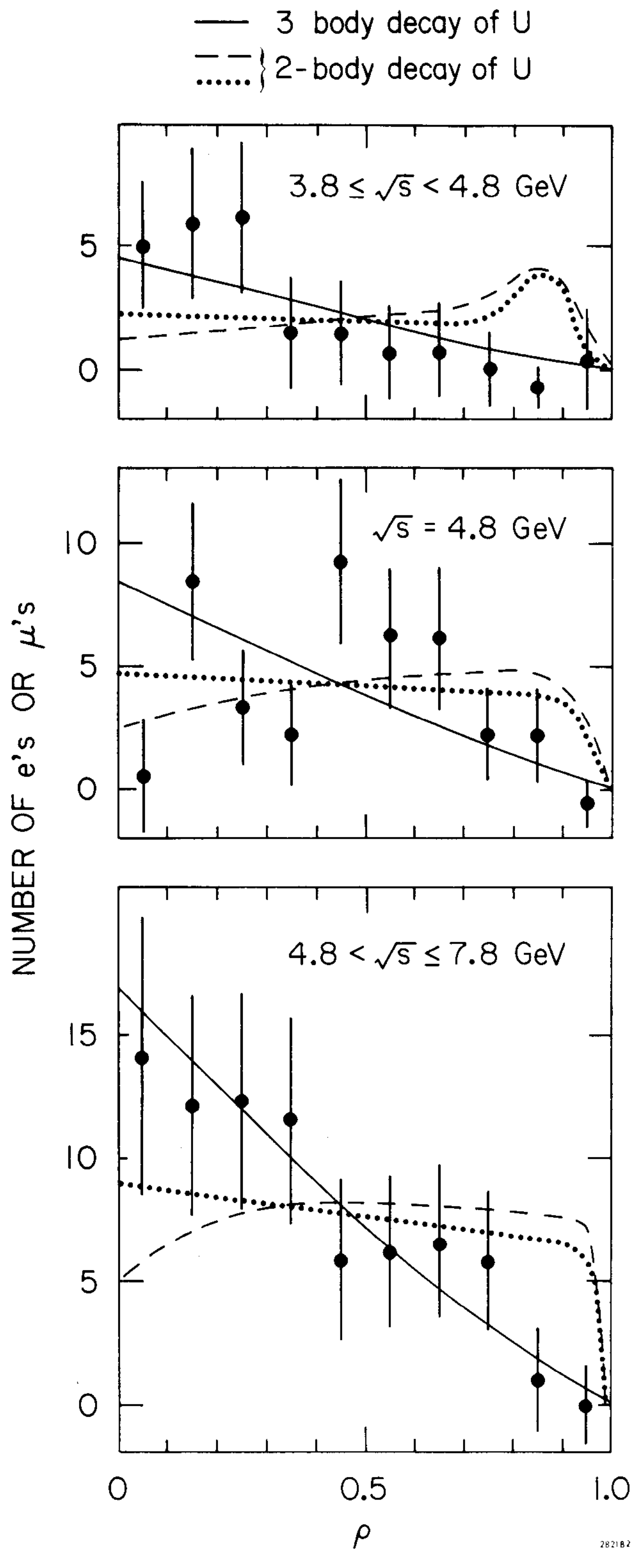
The distribution in cos θ_{coll} for three different $\sqrt{s} = E_{cm}$ intervals. The solid curve is for the production of a pair of U particles, the U taken to be a heavy lepton of 1.8 GeV/c^2 mass coupled to its massless neutrino through V-A. Hence each U undergoes the 3-body decay of Eq. 24b in the text. The dotted curve is for the production of a pair of U particles, the U taken to be a boson of 1.9 GeV/c^2 mass decaying through its purely leptonic decay mode. Hence each U undergoes the 2-body decay of Eq. 24a in the text. In the calculation of both curves all spin-spin correlations are ignored.

Fig. 10



The distribution in $\rho = (p - 0.65)/(p_{max} - 0.65)$ (see text) for all $\sqrt{s}$. The solid and dotted curves are defined in the caption to Fig. 10. The dashed curve is the same as the dotted curve except that the θ_{coll} distribution has been distorted to fit the data in Fig. 10.

Fig. 11



The distribution in ρ for three intervals in $\sqrt{s}$. See caption to Figs. 10 and 11 for meaning of curves.

Fig. 12