# OTHER STRUCTURE IN e<sup>+</sup>e<sup>-</sup> ANNIHILATION\*

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# ABSTRACT

The total cross section for the production of hadrons in  $e^+e^-$  annihilation exhibits complex structure in the region of center-of-mass energy-about 4 GeV, where R, the ratio of the hadron to  $\mu$ -pair cross sections, changes from a plateau value of about 2.5 to a new flat region of about 5.2. Corresponding structure is not seen in exclusive  $2(\pi^+\pi^-)$  and  $3(\pi^+\pi^-)$  cross sections, nor is structure seen in identified K<sup>-</sup> spectra. Anomalous  $e_{-\mu}$  events are observed above an  $E_{e.m.}$  of about 4 GeV, which are not explainable as arising solely from K<sup>0</sup> semileptonic decays of charmed mesons, or from two body decays of a new meson.

#### INTRODUCTION

The total cross section for the annihilation of  $e^{-}e^{-}$  into hadrons has yielded a rich structure even excluding the peaks of the  $\psi(3095)$  and the  $\psi'(3684)$ . In particular there appears to be complex structure around  $E_{c.m.}$ =4 GeV, the region separating the domain where R, the ratio of hadronic to  $\mu$ -pair cross sections, changes from a plateau value of around 2.5 to a new plateau around 5.2.

I will describe the newer results of the SLAC-LBL Magnetic Detector Collaboration<sup>1</sup> in the areas of total cross section measurements and in several areas where we have searched for other structure that might be associated with the transition from the "old"  $R \approx 2$  physics to the "new"  $R \approx 5$ physics. I will go over the status of the charm search, our K<sup>-</sup> and  $\bar{p}$  spectra, the information on exclusive multipion final states, and finally the status of the anomalous  $e^{-\mu}$  events. The apparatus has been described before, so I will only mention a few details as we go along.

We define a hadronic event as one with a vertex in the luminous region of the beams, having  $\geq 3$  prongs or two prongs acoplanar by  $\geq 20^{\circ}$ , and having momenta  $\geq 300$  MeV/c. The hadronic yields are corrected for backgrounds originating from beam gas or beam wall interactions, which are typically a few percent. The yields are normalized by measurements of Bhabha scattering in the detector, or, for the "fine scans", by measurements of small angle Bhabha scattering by small counters set into notches in the beam pipe. This is done, of course, to avoid the large statistical errors associated with the wide angle Bhabha scattering of these relatively short runs. The small angle luminosity measurements are calibrated and checked for consistency with the wide angle measurements.

The efficiency of the detector is determined from a set of Monte Carlo programs that estimate the probability of detecting p charged particles given that q were produced. Several models, varying from pure pion phase space to limited transverse momentum jets, were tried, with approximately 5% variations in the overall efficiency of the detector. The Monte Carlo generated probabilities were then used with observed charged particle distributions

\*Work supported by the Energy Research and Development Administration.

(Presented at the 2nd Internat'l. Conference at Vanderbilt University on New Results in High Energy Physics; New Particles: Searches and Discoveries, Nashville, Tennessee, March 1-3, 1976) to unfold the overall detector efficiency, which is shown in Fig. 1. The efficiency varies from about 30% at  $E_{c,m} = 2.5$ GeV to about 65% at  $E_{c.m.}^{m} = 8$ GeV. The indicated errors in = 8 the total cross section plots, excluding the fine scans, are statistical with a 10% systematic error added in quadrature. We believe there may be an overall systematic error of 10% due to uncertainties in the normalization procedure, plus a possible  $E_{c,m}$  dependent error of about 15% varying smoothly with  $E_{c.m.}$ , due to errors in the determination of the detector efficiency.

The total cross section versus  $E_{c.m.}$  of about a year ago is shown in Figure 2. The cross section due to the  $\psi$  and  $\psi'$  and their radiative tails has been removed, as has been done for the subsequent plots of  $\sigma_T$  and R. The cross section drops smoothly until encountering a broad peak around 4.1 GeV, and then resumes a smooth drop. Fig. 3 shows the total cross section at the time of the leptonphoton conference.<sup>2</sup> While the



Fig. 1--Average detection efficiency vs E<sub>c.m.</sub>.





general falling behavior of  $\sigma_{T}$  is unchanged, the area around 4.1 GeV seems more complex, indicating structure around 3.9 GeV and 4.4 GeV. A plot of R versus  $E_{c.m.}$  corresponding to the data of Figure 3 is shown in Figure 4. R is flat at a value of about 2.5 up to  $E_{c.m.} \approx 3.5$  GeV, roughly consistent with the value expected from colored u, d, and s quarks. R then goes through a complicated transition region and plateaus at a value of about 5.2. This contribution of the "new physics" seems high for only a charmed quark, and might indicate thresholds for heavy leptons or other new processes have been reached. (Note that most hadronic and semileptonic decay modes of a heavy lepton would satisfy the "hadron definition" of an event.)

Our most recent data for R between 3.8 and 4.6 GeV are shown in Figure 5. There is a broad peak between 3.9 and 4.3 GeV with indications of substructure. A small peak is seen at 3.95 GeV with a width of about 60 MeV, and a dip is seen near 4.08 GeV. Finally, another somewhat narrower peak is seen at 4.4 GeV. It is difficult to quantitatively obtain the parameters of these peaks. The resonances are occurring in the transition between the two plateau values of R. The threshold effects of the new channels that are opening up may distort Breit-Wigner line shapes. The shape of the



Fig. 4--R vs  $E_{c.m.}$  corresponding to cross sections of Figure 3.

background is unknown so separation is problematical and the resonances may be interfering with the background and each other. We have fitted only the relatively separate peak at 4.4 GeV. Fig. 6 shows the mean charged



Fig. 5--R vs E<sub>c.m.</sub> - current results of SLAC/LBL collaboration.

multiplicity and mean observed momenta for the data in this en-

ergy region. There is no structure, thus justifying the smoothed efficiency that was used. It is interesting that in a region where  $\sigma_T$  changes by almost



Fig. 7--R vs  $E_{c.m.}$  for data used to fit  $\psi(4414)$ .

a factor of two, no significant change can be seen in these two features of the data.

Figure 7 shows a fit of a Breit-Wigner with its radiative tail to the data. The  $\chi^2$  is 17.9 for 20 degrees of freedom. If we assume J=1, then  $\Gamma_{ee} = 440 \pm 140$ eV. The resonance parameters, along with those of the  $\psi$  and  $\psi'$ for comparison, are shown in Table I. The  $\psi(4414)$  has a full width more than a hundred times that of the  $\psi'$ ; nevertheless its decay width into e pairs is around 1/5 that of the  $\psi'$ .

Shortly after the discovery of the  $\psi$ , SPEAR and the Magnetic Detector were set up to run

- 4 -

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<u> </u>	ψ(3095)	ψ'(3684)	ψ(4414)
Mass $(MeV/c^2)$	$3095 \pm 4$	$3684 \pm 5$	$4414 \pm 7$
Γ (MeV)	$0.069 \pm 0.015$	$0.228 \pm 0.056$	$33 \pm 10$
Γ <sub>ee</sub> (keV)	$4.8 \pm 0.6$	$2.1 \pm 0.3$	$0.44 \pm 0.14$
B <sub>ee</sub>	$0.069 \pm 0.009$	$0.0093 \pm 0.0016$	$(1.3 \pm 0.3) \times 10^{-5}$

in a scanning mode to search for other narrow resonances. The system's first (and only) success was the discovery of the  $\psi$ '. This scan and a subsequent scan up to  $E_{c.m.} = 7.7$  GeV are shown in Fig. 8. The first scan, excluding the  $\psi$ ', sets upper 90% confidence limits on a narrow resonance of about 900 nb-MeV, while the high energy scan sets upper limits of about 450 nb-MeV. The errors shown are only statistical.

Due to the discovery in P-B<sub>e</sub> scattering of the  $\Upsilon$ ,<sup>3</sup> a peak at 5.97 GeV decaying into e<sup>+</sup>e<sup>-</sup> pairs, there has been considerable interest in searching for it in e<sup>+</sup>e<sup>-</sup> annihilation. Consequently, we conducted a search between 5.68 and 6.08 GeV with considerably greater sensitivity than the older fine scans. The preliminary online results are shown in Fig. 9. The integrated luminosity at each point corresponds to the production of about 20  $\mu$  pairs. The data are consistent with a constant value of R  $\simeq$  5.2. If the  $\Upsilon$  is narrow compared to the SPEAR energy resolution of ~ 9 MeV FWHM (at E<sub>c.m.</sub>  $\approx$  6 GeV), then one can set an upper limit on  $\Gamma_{ee}$  of ~ 100 eV. If the  $\Upsilon$  is wide enough to be resolved at SPEAR, then we set an upper limit on the branching ratio into e pairs, B<sub>ee</sub>, of ~ 1 × 10<sup>-5</sup>.

## CHARM SEARCH

A search has been made in the invariant mass spectra of  $K^{\pm}\pi^{+}$ ,  $\pi^{+}\pi^{-}$ ,  $K^{+}K^{-}$ ,  $K_{S}K^{\pm}$ ,  $K_{S}\pi^{\pm}$ ,  $K_{S}\pi^{+}\pi^{-}$ ,  $K^{+}\pi^{\pm}\pi^{\pm}$ , and  $\pi^{+}\pi^{-}\pi^{\pm}$ , looking for peaks corresponding to a new meson. The amount of data that has been examined since our last publication<sup>4</sup> has approximately tripled, but the results are still negative. Data samples of roughly 10,000 events at  $E_{c.m.} = 4.1, 4.4$ , and 4.8 GeV have been searched. If one assumes that the "new physics" is associated with the production of charmed mesons, then upper limits on various decay branching ratios can be set. These limits appear to "push" the expected values, <sup>5</sup> but do not rule out the theory. Of course, if part of the increase in R is due to phenomena other than charm, the upper limits are higher.

#### PARTICLE SPECTRA

The Magnetic Detector separates  $\pi$ 's, K's, and p's by a time-of-flight system consisting of 48 plastic scintillators in a cylindrical array at a radius of 1.5 m from the beam. The time resolution is ~ 400 ps, allowing  $\pi$ -K separation up to momenta of 600 MeV/c and K-p separation up to 1.0 GeV/c. Only negative prongs are identified to avoid problems from beamgas events which preferentially scatter protons. The particle spectra are







Fig. 9--High sensitivity fine scan of  $\sigma_{T}$  vs  $E_{c.m.}$  for 5.68 GeV  $\leq E_{c.m.} \leq 6.08$  GeV.

corrected for trigger efficiencies, decay losses, and losses due to several particles striking a single timing counter.

Figure 10 shows the particle production cross sections at  $E_{c.m.} = 4.8 \text{ GeV}$ . The spectra at other energies are similar. The  $\pi$ 's peak before the K's or p's. Figure 11 shows the fractions of K<sup>-</sup> and p versus momenta for various  $E_{c.m.}$  between 3.0 and 7.4 GeV. The fractions of K<sup>-</sup> and p increase smoothly over the identified range in momentum. Incidentally, the K<sup>-</sup> fraction must stop increasing by a momentum of 1 GeV/c in order to connect with the  $K^{\mp}\bar{p}$  fraction of  $0.21 \pm 0.06$  for particles with p > 1.1 GeV/c at  $E_{c.m.} = 4.8$ GeV measured by the Maryland-Pavia-Princeton group.<sup>6</sup> Fig. 12 shows the number of identified K<sup>-</sup> and  $\bar{p}$  per event versus  $E_{c.m.}$ . Since the identification procedure has fixed momentum cutoffs and



Fig. 10--d $\sigma$ /dp for  $\pi$ 's, K's, and p's at  $E_{c.m.} = 4.8$  GeV.









the mean momentum of all charged particles is increasing with  $E_{c.m.}$ , 7 it is difficult to interpret the general behavior of the plot. However, we have previously seen that there is no dramatic change in the mean momentum of charged particles in the

 $E_{c.m.} \approx 4 \text{ GeV region.}$  It is in this region where the transition to the "new physics" occurs, and where the 4.1 GeV bump causes a large change in  $\sigma_T$ . Nevertheless, no change is seen in the K<sup>-</sup> spectra, as might naively be expected from the decay products of charmed mesons if charm is involved with the step in R. It is also interesting to note the drop in K<sup>-</sup> per event at the  $\psi$  and  $\psi$ '. This effect, with less sensitivity, is not seen for the  $\bar{p}$ 's.

# **EXCLUSIVE MULTIPION FINAL STATES**

It might be possible to gain some understanding of the "new physics" by examining the cross section for exclusive final states as a function of  $E_{c.m.}$ . If the processes responsible for the doubling of R produced exclusive final states similar to those of the "old physics", we might expect a substantial increase in those cross sections in the  $E_{c.m.} = 4$  GeV region. The only exclusive final states that we are able to analyze over a wide

The only exclusive final states that we are able to analyze over a wide range of  $E_{c, m}$  are the states  $2(\pi^+\pi^-)$  and  $3(\pi^+\pi^-)$ . Other states have not been studied over the full SPEAR energy range because of limitations of cross sections, acceptance, resolution, and particle identification. The actual events analyzed can be those where all the prongs were seen (4-c events), or where one charged particle was missing (1-c events). 1-c events were not used above  $E_{c, m}$  = 4 GeV to avoid contamination problems. The

- 8 -



Fig. 13--Cross sections for exclusive production of a)  $2(\pi^+\pi^-)$ and b)  $3(\pi^+\pi^-)$  vs E<sub>c.m.</sub> data sample at 3 GeV was enriched by using data from  $\psi$  running. This is legitimate since the  $\psi$  has odd Gparity, implying that the decays to states with an even number of pions are mediated by a virtual photon.

The cross sections as a function of  $E_{c.m.}$  are shown in Fig. 13. The upper plot is the  $2(\pi^+\pi^-)$  cross section and is consistent with a smooth fall,  $\sigma \sim s^{-2.8 \pm 0.5}$ . The lower plot is the  $3(\pi^+\pi^-)$  cross section and it also falls approximately like  $\sigma \sim$  $s^{-2.3 \pm 0.8}$ . Neither set of data shows any structure in the  $E_{c.m.} =$ 4 GeV region.

At the low energy point, there are sufficient data to investigate resonance production within the exclusive states. Fig. 14 shows the invariant mass distribution for pairs of  $\pi$ 's. In the  $2(\pi^+\pi^-)$  data, strong  $\rho$ and f signals are seen; the solid curve is a fit using only uncorrelated Breit-Wigner shapes for the  $\rho$  and f, with a ratio of  $\rho\pi\pi$  to  $f\pi\pi$  of 1.9 ± 0.5. The  $3(\pi^+\pi^-)$  data are fit with only a  $\rho\pi\pi\pi\pi$  assumption. No f signal is seen. The dashed curves in both plots show invariant phase space. Figure 15 is a scatter plot of the mass of one pair of  $\pi$ 's versus the mass of the other for the  $2(\pi^+\pi^-)$ data, plotted so that  $M_1 > M_2$ . A clustering of points is seen at  $M_1 \approx$  $M_f$ ,  $M_2 \approx M_\rho$ , which is evidence for the exclusive process  $e^+e^- \rightarrow \rho f$ .

#### ANOMALOUS $e - \mu$ EVENTS

Probably by now most of you have heard the arguments for the anomalous  $e_{-\mu}$  signal seen at SPEAR. Rather than review these arguments,<sup>8</sup> I will discuss a small subset of the

data from the so-called muon tower before going over the phenomenology of the  $e-\mu$  data.

During the interval when SPEAR I changed into SPEAR II, two concrete absorbers corresponding to  $\sim 30$  cm of iron were placed on top of the magnetic detector and spark chambers were installed above each absorber, as shown in Fig. 16. Candidate events for the tower analysis were required to have precisely two oppositely charged particles headed in directions so that,









if they were muons, one should get to level 2 or level 3, and the other should get to a spark chamber at level 1. It was also required that no photons be seen in the shower counters; and that the charged tracks have momenta > 650 MeV/c, be acoplanar by  $> 20^{\circ}$ , and have a missing mass squared recoiling against them greater than  $(1.5 \text{ GeV/c}^2)^2$ . The acoplanarity and missing mass requirements discriminate against radiative  $e^+e^-$  and  $\mu^+\mu^-$  events. Fiftyeight events satisfying these requirements were found. A muon is identified as a particle with small pulse height in the shower counters and a signal within the expected area of the muon spark chambers. An electron

is identified as a particle with large pulse height in the shower counter and no signal in the expected muon spark chamber area. Other prongs are called hadrons (h).

Misidentification probabilities for e's and  $\mu$ 's are determined from a sample of collinear lepton pairs. The probability that an electron simulates a  $\mu$  at levels 1 and 2 in the tower is less than  $2 \times 10^{-3}$ . The probability that a  $\mu$  gives a large shower counter signal and does not penetrate the absorber



# Fig. 16--Muon detectors in SPEAR I and SPEAR II.

is less than  $3 \times 10^{-3}$ . Hadron misidentification probabilities are estimated from data in which 3 or more prongs are detected and all are assumed to be hadrons. The probability of a hadron simulating a  $\mu$  at level 2 is about 7% and the probability of a hadron simulating an e is about 20%.

Of the 58 events, 10 were identified as  $e^+e^-$ , 11 as  $\mu^+\mu^-$ , and 37 as combinations of e,  $\mu$ , and h, including 5 e $\mu$  with the  $\mu$  identified at level 2 or 3. A conservative estimate of the misidentification background can be made by assuming the 37 events are all hh. The arithmetic is summarized in Table II,

Event Type	Number	Misidentification Probability	Background Contribution
ee	10	0.002	0.02
μμ	11	0.003	0.03
hh	37	$0.2 \times 0.07$	0.53
TOTAL	58	· · · · · · · · · · · · · · · · · · ·	0.57

TABLE II

and the expected background is 0.57 e $\mu$  events. The statistical probability that the 5 observed e $\mu$  events are due to the background is about  $3 \times 10^{-4}$ .

- 11 -

Onto the physics! Possible sources of the  $e-\mu$  events might be the decay of a new meson:



Another possibility is the leptonic decay of a sequential heavy lepton:

Another possibility is the semileptonic decay of charmed mesons, such as:

Other possibilities such as radiative pair production and two-photon processes appear unlikely.<sup>8</sup> It is also unlikely that the semileptonic decays of charmed mesons are the sole source of the  $e_{-\mu}$  events. The  $\pi^{+}\pi^{-}$  signal of a K<sub>s</sub> decay is clearly observed in the magnetic detector. In a data set having 49 eµ events, a search was made for events of the form eµK<sub>s</sub>, eeK<sub>s</sub>, and µµK<sub>s</sub>. If all of the  $e_{-\mu}$  events were from K<sup>o</sup> semileptonic decays, then, putting in the efficiencies and acceptances, 47  $\mu$ K<sub>s</sub> events should have been seen. None were observed. Another way to state the result is that the fraction of

e $\mu$  events due to K<sub>0</sub> semileptonic decays is less than 5% at a 90% confidence level. If other semileptonic decay modes are considered, the upper limit to the semileptonic contribution is less than 19 to 32%, depending upon assumptions about the misidentification of e- $\mu$  events.

The raw cross section for the production of  $e\mu$  events versus  $E_{c.m.}$ is shown in Fig. 17. The cross sections have not been corrected for the detector acceptance or the kinematic cuts since the origin of the events is unknown. There appears to be a threshold slightly below  $E_{c.m.} = 4$  GeV. The statistical accuracy is insufficient to distinguish between the production of a heavy lepton pair, which would fall like  $\beta/s$ , or meson pairs, which would fall like ( $\beta/s$ )<sup>3</sup>. More information can be gained by combining the data at different  $E_{c.m.}$  to examine the



Fig. 17--Uncorrected cross section for observation of e and  $\mu$  and no other particles vs  $E_{c.m.}$ .





momentum spectrum by constructing a variable

$$\rho = \frac{p-0.65 \text{ GeV/c}}{p_{max}-0.65 \text{ GeV/c}}$$

The data are shown in Fig. 18. The solid line is the distribution expected from the V-A decays of heavy leptons of mass  $1.8 \text{ GeV/c}^2$ . It is a good fit with a  $\chi^2$ /DOF of about one. The dotted curve is the distribution expected from an isotropic two-body decay while the dashed curve is a two-body decay with a collinearity angle distribution adjusted to match the data. Both curves are poor fits to the data; the isotropic decay curve has a  $\chi^2$ /DOF of about four and the curve which matches the collinearity distribution is worse. This indicates that not all of the  $e-\mu$  events come from two-body decays. Figure 19 shows the collinearity angle distributions of the  $e-\mu$ 's for three ranges of Ec.m.: The heavy lepton distributions are again better fits than the two-body decay distributions. The distribution becomes much less isotropic as E<sub>c.m.</sub> increases, which is characteristic of the production of a pair of particles.

#### SUMMARY

The total hadronic cross section to  $\mu$  pair ratio R is flat above and below a transition region around 4 GeV. The transition region has at least three peaks in it. No other structure is seen in the total cross section, nor is any seen in K<sup>-</sup> spectra, or in  $4\pi$  and  $6\pi$  exclusive cross sections. There are no encouraging results from the charm search, but the present limits are not very damaging to charm theories. Anomalous  $e-\mu$  events exist, with origins that cannot be explained as coming exclusively from semileptonic decays or two-body decays.





Hopefully some of the questions implied by these data will be answered by the next conference.

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