RECENT RESULTS ON e^+e^- ANNIHILATION FROM PLUTO AT DORIS

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ABSTRACT: Recent results on inclusive production of the K^o_S, of the $J/\psi(3.1)$ and on anomalous muon production in e^+e^- annihilation at c.m. energies between 3.6 and 5 GeV are presented. In addition preliminary results on the cascade decays of the $\psi'(3.7)$ are discussed.

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I. Introduction

In this contribution recent results on e^+e^- annihilation are presented obtained with the PLUTO detector at the e^+e^- storage ring by the PLUTO collaboration (DESY, Universities of Hamburg, Siegen and Wuppertal). During 1976 data have been taken between the 3.1 resonance and 5.0 GeV c.m. energy W. Integrated luminosities collected at the various energies are given in Table 1. Only a small part of the data are taken at the resonances at 3.1 and 3.7 GeV. Some data are taken at 3.6 GeV, as a reference point below charm threshold. Most of the data are taken between 4 and 5 GeV, and the results presented here are from this high energy region with one exception.

A cross section of the magnetic detector PLUTO, viewed along the beam direction, is shown in Fig. 1. There are 14 cylindrical proportional chambers for triggering and track reconstruction, inside the superconducting coil with a uniform solenoidal field of 2 Tesla in a usable volume of 1.4 m diameter and 1.05 m length.

c.m.energy W (GeV)	$\int Ldt$ (nb^{-1})	month
3.1	50	Febr.
3.7	162	July, Sept.
3.6	604	July, Sept.
4.03	742	Sept.
4.1	716	May, June
4.2	247	Aug.
4.4	1169	March, Aug., Nov.
4.5	362	Nov.
4.6	434	Aug., Nov.
5.0	1375	Nov., Dec.

Table 1. Integrated Luminosities for the 1976 runs of PLUTO at the e^+e^- storage ring DORIS. The 5 GeV-data were not fully analysed at the time of the conference.

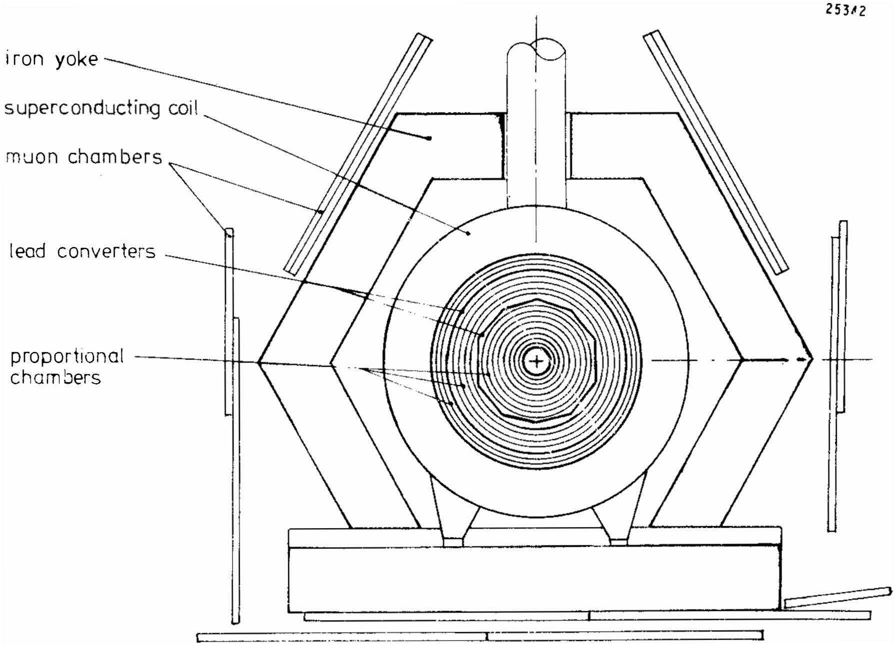

Fig. 1. Cross section of the detector PLUTO.

The chambers, covering ~90 % of 4π, have wires parallel to the beam and cathode strips oriented at 45^{o} and 90^{o} with respect to the wire direction. The detector is triggered by a logical combination of prop. wire signals. Basic criteria are at least two track elements within the first four chambers, with momenta $p > 240$ MeV/c and $|\cos\vartheta| < 0.87$, where ϑ is the angle between track and beam axis. Luminosity is monitored by small angle (~130 mrad) Bhabha scattering observed by a symmetrical arrangment of four counter telescopes. More details on the detector and the trigger are given elsewhere.[1,2)]

Muons, electrons and photons can be identified with the detector. Outside the flux return yoke, there are 25 prop. tube chambers covering ~0.43 of 4π, to allow identification of particles penetrating the iron, which has an average thickness of 68 cm. Muons with momentum above 1 GeV/c are identified. Two lead cylinders at radii of 37.5 cm (0.4 X_o) and 59.4 cm (1.7 X_o) allow identification of electrons. In addition, photons can be identified by a shower or an e^+e^--pair, converted in the lead cylinders or the material of the beam pipe or the chambers.

In the following results are presented on the total cross section (Ch.II), on inclusive production of K^o_S (Ch.III), of the J/ψ (Ch.IV) and on anomalous muon production (Ch.V), and finally some preliminary results on cascade decays of the ψ'(3.7) (Ch.VI).

II. Total cross section

We have measured the total cross section for e^+e^- annihilation into hadrons. Applying various cuts on the data, known QED processes like $e^+e^- \rightarrow e^+e^-$, $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \gamma\gamma$ are excluded. The event efficiency is about 80 % on the average multiplicity, as obtained from a Monte Carlo study using an all pion phase space model. Details on the experimental procedure are published[2)]; since this publication new data are obtained above W = 4.3 GeV up to 5 GeV.

The total cross section divided by the muon pair cross section ($R = \sigma_{tot}/\sigma_{\mu\mu}$) is shown in Fig.2; the dotted curve follows the measured points. Radiative corrections are applied to the data assuming a flat behaviour of the total cross section above 4 GeV. The main structures first observed by the SLAC-LBL collaboration[3)] are reproduced by the PLUTO data. At W = 3.6 GeV the ratio R is at a level of about 2.6; at W = 4 GeV there is a sharp increase with peak structure up to 4.4 GeV and at higher energies the ratio R is at a level of 4.6. The step at 4 GeV is attributed to the threshold for production of charmed particles; an increase of 1.33 is expected from the colour charm quark model. An additional increase is expected from the contribution of a heavy lepton. The higher level of 4.6 is consistent with this expectation.

In detail our data differ from the SLAC-LBL data, especially at the positions of the peaks between 4 and 4.4 GeV. Both experiments quote possible systematic errors of ~12 %, and taking into account in addition slightly different methods for radiative corrections the observed differences are not unexpected large.

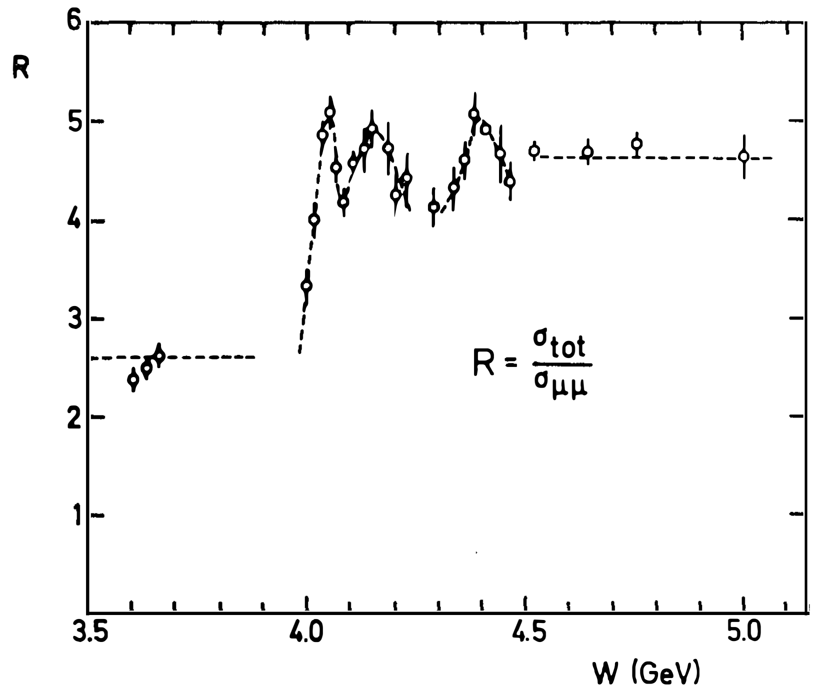

Fig. 2. The total cross section for e^+e^- annihilation into hadrons σ_{tot} divided by the muon pair cross section $\sigma_{\mu\mu}$. The dotted corve is to guide the eye.

III. Inclusive K^o_S production

If the rise of $R = \sigma_{tot}/\sigma_{\mu\mu}$ at ~4 GeV by about two units of R is taken to be an indication of the charm threshold, then an increase of kaon production is expected from the decay of charmed mesons. In this experiment the inclusive production of K^o_S is investigated[4)].

The K^o_S are identified by their decay into a $\pi^+\pi^-$ pair. The following method is used: a fit is tried to all pairs of oppositely charged particles, with geometrical constraints and constraints for momentum conservation at the fitted decay point. Cuts are applied in the χ^2 of the fit and in the decay length at 15 mm. The efficiency, obtained from a Monte Carlo study, is about 20 percent at a K^o_S-momentum of 1 GeV/c and decreases with decreasing momenta to a few percent below

200 MeV/c. Therefore also a cut at a K_S^o momentum of 200 MeV/c is applied. The invariant mass of the two-pion system obtained by the method is shown in Fig. 3. A clear peak at the mass of the K_S^o is seen with little background.

The following figures showing K_S^o data are corrected for detection efficiency and for the $\pi^o\pi^o$ decay of the K_S^o, background is subtracted. The inclusive cross

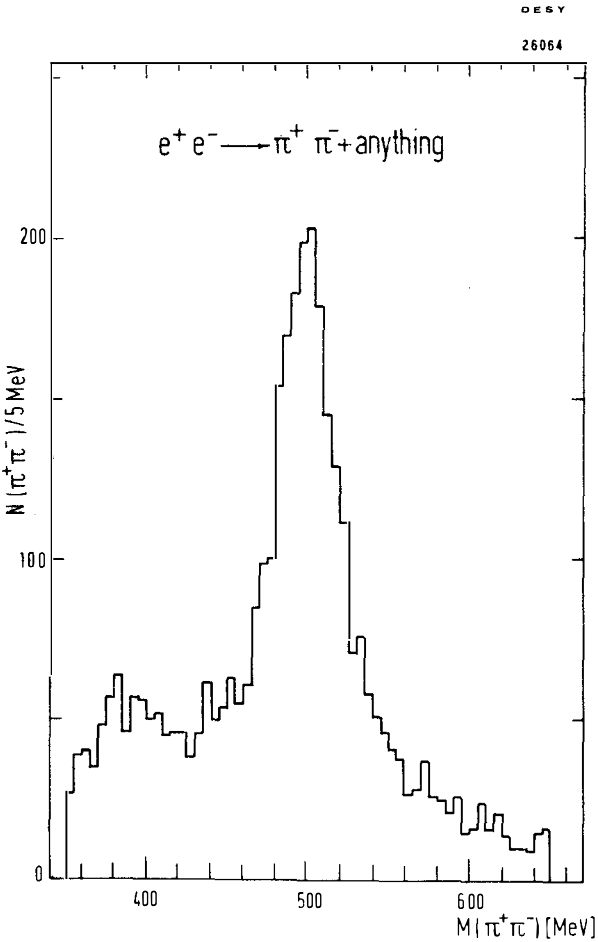

Fig. 3. The K_S^o signal in the distribution of the invariant mass of the $\pi^+\pi^-$ system.

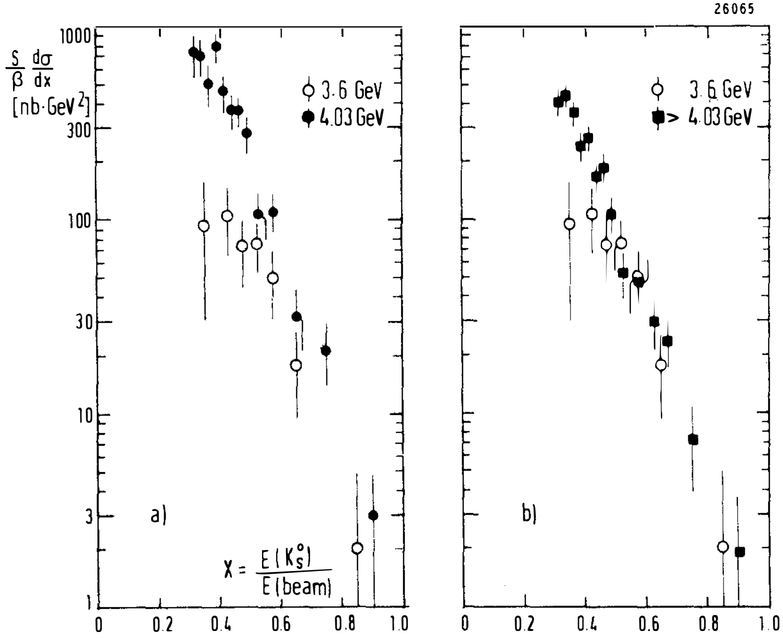

Fig. 4. The inclusive K_S^o cross section for W = 3.6, W = 4.03 GeV (a) and 4.03 < W < 4.8 GeV (b) as a function of x.

section for K_S^o production as a function of the variable x, defined by

$$x = \frac{E(K_S^o)}{E(beam)} \quad ,$$

is shown in Figs. 4a and b. The cross section is shown for W = 4.03 GeV in Fig. 4a and for 4.03 < W < 4.8 GeV in Fig. 4b; shown also in both figures is the cross section at W = 3.6 GeV for comparison. The cross section values nearly agree above x = 0.5 for the different energies, but below x = 0.5 there is a large increase at W = 4.03 GeV and above, compared to the data at 3.6 GeV. This behavior is also observed by the DASP group[5)] for inclusive $K^{\pm}$ production; it is consistent with the hypothesis, that the kaons come from the decay of intermediate pairs of charmed particles with a mass of ~2 GeV.

The total cross section for inclusive K_S^o production is shown in Fig. 5 as a function of the total c.m. energy W. The data points are not corrected for the cut at 200 MeV/c nor for trigger losses; both effects are estimated to be less than 10 percent. A sharp peak in the total K_S^o production cross section is observed at 4.03 GeV, and a higher level above compared to 3.6 GeV, but without peaks. Data on K_S^o production from SLAC-LBL[6] show a higher point at 4.4 GeV, but agree within errors for the other energies.

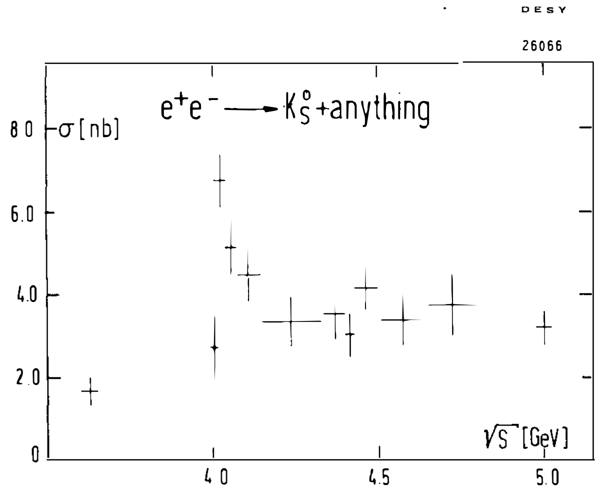

Fig. 5. The total inclusive K_S^o cross section for K_S^o momentum p > 200 MeV/c as a function of c.m. energy.

At W = 3.6 GeV, the ratio of the K_S^o cross section to the total cross section is $\sigma(K_S^o)/\sigma_{tot} \approx 0.1$ K_S^o per event. For the region above 4 GeV new physics comes in and the following calculation can be done for the estimation of the mean number of K_S^o per new event. Assume that above charm threshold there are three contributions to the ratio R of the total cross section to the muon pair cross section:

$$R = \frac{\sigma_{tot}}{\sigma_{\mu\mu}} = R_{q\bar{q}} + R_{c\bar{c}} + R_{L\bar{L}}$$

The old contribution of the $R_{q\bar{q}}$ (q = p, n, λ quarks) can be estimated from the measured value at 3.6 GeV to be ~2.6. The new contribution ΔR, assumed here to be $R_{c\bar{c}}$ (c = charmed quark) plus $R_{L\bar{L}}$, a contribution from production of a pair of heavy leptons, are about two units of R. A similar expression is assumed for the

K^o_S yield,

$$R(K^o_S) = \frac{\sigma(K^o_S)}{\sigma_{\mu\mu}} = R_{q\bar{q}}(K^o_S) + R_{c\bar{c}}(K^o_S) + R_{L\bar{L}}(K^o_S).$$

Again the $q\bar{q}$-contribution can be taken from the data at 3.6 GeV; the $L\bar{L}$-contribution to the K^o_S cross section can be neglected, because it should be very small. Then the number of K^o_S per new event is obtained simply by dividing $\Delta R(K^o_S) = R_{c\bar{c}}(K^o_S)$ by ΔR. This quantity is shown by open circles in Fig. 6 as a function of c.m. energy. Subtracting the $L\bar{L}$-contribution also from ΔR, i.e. calculating $R_{c\bar{c}}(K^o_S)/R_{c\bar{c}}$, the full circles shown in Fig. 6 are obtained. From the charm model roughly about 0.5 K^o_S per new event are expected, neglecting the Cabbibo angle and assuming equal yield of K^o_S, K^o_L, K^+ and K^-. This latter assumption is supported by a comparison of the PLUTO-K^o_S and the DASP-$K^\pm$ yield. Indeed the level of nearly 0.5 K^o_S per event is observed, as expected.

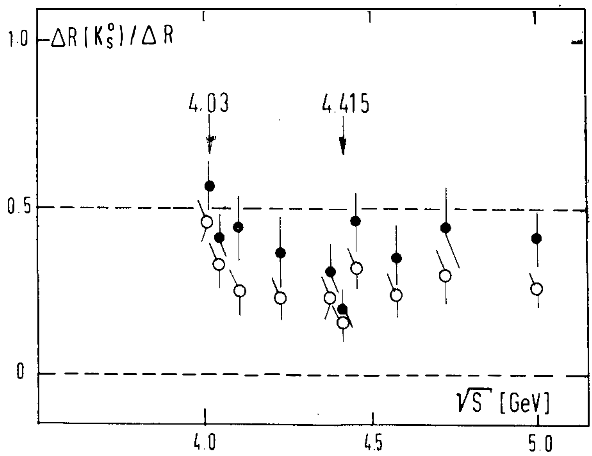

Fig. 6. The number of K^o_S ($p > 0.2$ GeV/c) per new event above W = 4 GeV. Accounting for the heavy lepton contribution to the new events results in the full points.

IV. Inclusive J/ψ production

There are different predictions for production of the J/ψ in the inclusive reaction

$$e^+e^- \rightarrow J/\psi + \text{anything} \qquad (4.1)$$

The fraction of the total cross section for inclusive J/ψ production may be comparable to the suppression of the hadronic J/ψ decays[7], of the order of 10^{-3}. A very different prediction is from the molecular charmonium hypothesis, in with new states are predicted built from four quarks[8]. A possible decay mechanism for these states is by quark rearrangement, in which a normal meson and a J/ψ is formed. There are predictions that about 10 percent of all events are of the type

$$e^+e^- \rightarrow J/\psi + (2 \text{ or } 4 \text{ pions}), \qquad (4.2)$$

especially at W = 4.4 GeV.

Inclusive J/ψ production is investigated in the PLUTO experiment, with the J/ψ decaying to two muons, where one muon is required to be identified in the detector. Events of the type

$$e^+e^- \rightarrow \mu^\pm + m^\mp + \geq 1 \text{ charged particle} \qquad (4.3)$$

are selected; for both the muon and the particle m a momentum above 1 GeV/c and $|\cos\vartheta| < 0.752$ is required. Details on the muon identification are given in the next chapter. The distribution of the mass $M(\mu^\pm m^\mp)$, shown in Fig. 7, shows a clear clustering of events at the J/ψ mass. A known contribution to these events is from the radiative tail of the ψ', according to the reaction chain

$$\begin{array}{l} e^+e^- \rightarrow \gamma e^+e^- \\ \qquad\quad \hookrightarrow \psi' \rightarrow J/\psi\ \pi^+\pi^- \\ \qquad\qquad\qquad\quad \hookrightarrow \mu^+\mu^- \end{array} \qquad (4.4)$$

All events consistent with the kinematical constraints given by this reaction are excluded; only five events remain, which may be due to the direct process

$$e^+e^- \rightarrow J/\psi + \text{hadrons} \qquad (4.5)$$

The results, corrected for acceptance and for the $\mu^+\mu^-$ branching ratio of the

J/ψ, are given in Fig. 8.

The cross section for events consistent with reaction (4.4) follows the calculated contribution of the ψ' radiative tail. The result for the direct process reaction (4.5) are given for five energy regions as data points and 90 percent upper limits. The process is at the level of 10^{-3} of the total cross section, shown also in the figure. The average cross section between 4 and 5 GeV c.m. energy is ~35 pb. One concludes that inclusive J/ψ production is only a small fraction of the total cross section. It is in fact much lower than predictions from charm molecule models.

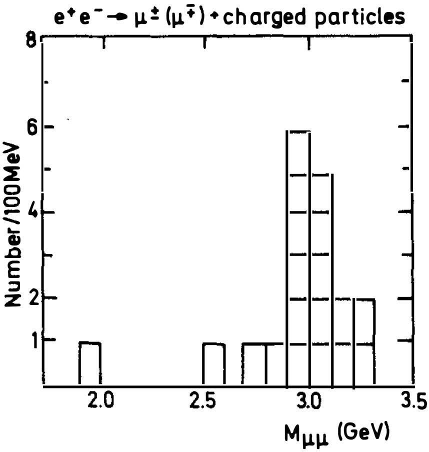

Fig. 7. Distribution of the dimuon mass.

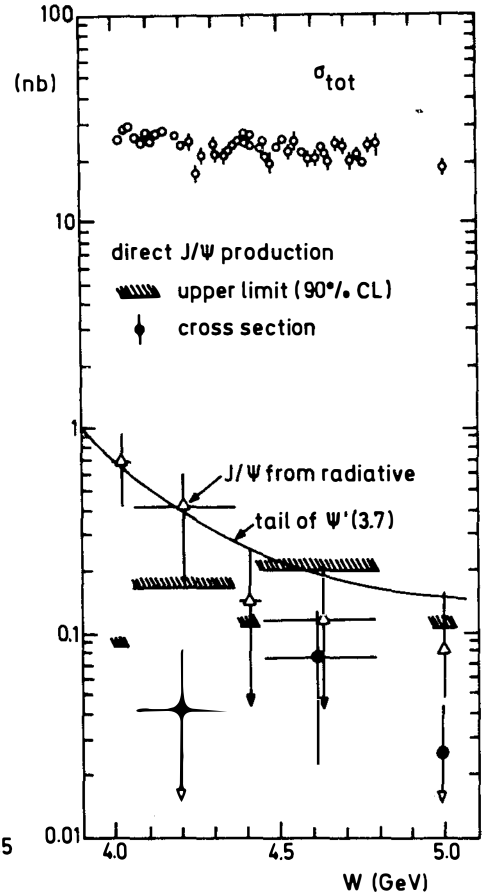

Fig. 8. Cross section for direct and radiative J/ψ production. The total annihilation cross section is shown for comparison.

V. Anomalous inclusive muon production

For the investigation of inclusive muon production two classes of events are considered, the two-prong class

$$e^+e^- \to \mu^\pm + 1 \text{ charged particle} \tag{5.1}$$

and the multi-prong class

$$e^+e^- \to \mu^\pm + \geq 2 \text{ charged particles.} \tag{5.2}$$

Events with muons from inclusive J/ψ production of reaction (4.1) are excluded in this analysis. Events with tracks satisfying the criteria:

momentum $p \geq 1$ GeV/c;

$|\cos\vartheta| < 0.752$;

pointing to a muon chamber (~0.45 of 4π)

are selected. If the particle belonging to the track defined above is not detected in the muon chamber, it is considered to be a hadron. A particle detected in the muon chamber is a muon candidate, it is either a real muon or a hadron from punch through or decay. The probability for a hadron to appear as a muon has been determined from data at the 3.1 resonance; this probability is (2.8 ± 0.7)%, nearly independent from momentum in the momentum range considered here. The number of muon candidates has to be corrected for different thickness of the iron, the corrected number corresponds to the cut-off momentum of 1 GeV/c.

Energy (GeV)	3.6	4.0 - 4.3	4.3 - 4.8
$\int Ldt$ (nb^{-1})	613	1660	2037
Hadrons	630	1684	2100
μ candidates	14	44	109
" , corrected	17.5	52.9	130.9
Hadron background	17.6	47.2	58.8
μ events	0 ± 5	6 ± 12	72 ± 27
cross section (pb)	<36	<40	79 ± 29

Table 2. Results on inclusive muon production in the multi-prong class.

The results on the multi-prong class is given in Table 2. The number of μ events is after subtraction of the hadron background by punch through and decay. The cross section given are calculated assuming an isotropic angular distribution and refers to the momentum cut-off at 1 GeV/c. Below W = 4.3 GeV no anomalous muon signal remains. For the energy region 4.3 to 4.8 GeV an effect at the three standard deviation level is observed. A possible explanation for the origin of these events is charm pair production with a semileptonic decay of one or both charm particles. The size of the signal is compatible with this hypothesis, according to estimates of Gronau et al.,[9], which are based on the inclusive electron spectrum observed by the DASP group[10].

For the two-prong class a large contribution to the muon events is due to the QED processes

$$e^+e^- \to \mu^+\mu^- \tag{5.3}$$

$$e^+e^- \to \mu^+\mu^-\gamma \tag{5.4}$$

$$e^+e^- \to \mu^+\mu^-\gamma\gamma. \tag{5.5}$$

Contributions from reaction (5.5) are estimated[11] and found to be less than 10 percent of the final result. Elastic and radiative muon production in reactions (5.3) and (5.4) is excluded by cuts; cuts are applied in the relative azimuthal angle $\Delta\Phi$, $\Delta\Phi < 170^o$ and in the missing mass according to

$$MM^2 > 1.4 \left(\frac{E_{beam}}{1.8\ \mathrm{GeV}}\right) \mathrm{GeV}^2 ,$$

which takes into account the degradation of resolution in missing mass with increasing beam energy. For more than half of the events of reaction (5.4) the photon converts in the detector, the additional constraints provide a check of the missing mass cut on an event-by-event basis. After removal of the QED background the subtraction of hadron background is done in the same way as for the multi-prong class. The results are given in Table 3.

Energy (GeV)	3.6	4.0 - 4.3	4.3 - 4.8
$\int$Ldt (nb^{-1})	613	1660	2037
Hadrons	209	592	743
μ candidates	6	42	93
" , corrected	7.3	53.1	108.8
Hadron background	5.9	16.6	20.8
μ events	1.4 ± 2	36.5 ± 10	88 ± 15
cross section (pb)	< 23	76 ± 21	149 ± 25

Table 3. Results on inclusive muon production in the two-prong class.

Again the cross section refers to the momentum cut-off at 1 GeV/c, but no correction is made for the cut in missing mass, since this cannot be done in a model independent way. Sizeable signals are observed above W = 4 GeV, but no indication for anomalous muons at W = 3.6 GeV. The cross section for inclusive anomalous muon production in the two-prong class is shown in Fig. 9. Similar results have been found by the SLAC-LBL group[12)]; the published values of Ref.12 are also shown in Fig. 9, scaled down to account for the different muon momentum acceptance. The data from both experiments are in good agreement.

Two-prong muon events are expected to come dominantly from production and decay of a heavy lepton L according to reaction

$$\begin{array}{l} e^+e^- \rightarrow L^+L^- \\ \qquad\qquad\quad \hookrightarrow \nu_L \mu^- \bar{\nu} \\ \qquad\quad \hookrightarrow \nu_L + (1\ \text{charged particle})^+ \end{array} \tag{5.6}$$

with large missing momentum and energy, since there are at least three neutrinos. Evidence for a heavy lepton has been reported by the SLAC-LBL group[13)]; the heavy lepton is now designated τ by M.L. Perl[14)]. If our observed muon events in the two-prong class are mainly from the heavy lepton, then a certain fraction of the two-prong class should be μe-events, with no other particles observed in the detector, from reaction

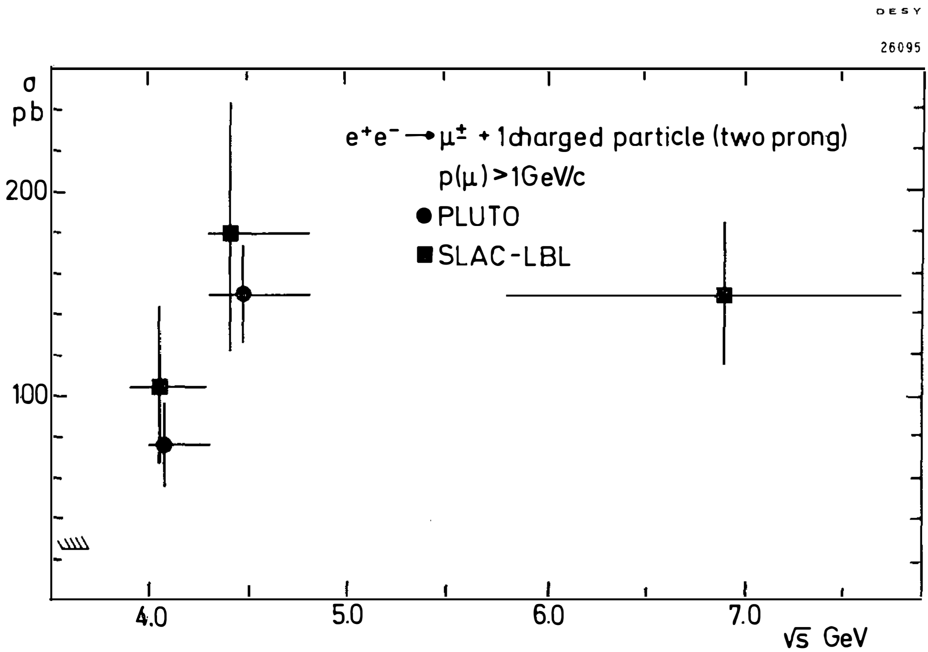

Fig. 9. The inclusive muon cross section in the two-prong class as a function of c.m. energy.

$$e^+e^- \to L^+L^- \to \mu^\pm e^\mp + \text{neutrinos}. \tag{5.7}$$

The expected number of μe-events can be estimated under the assumptions: heavy lepton mass of 1.95 GeV, point-like cross section $\sigma(L^+L^-) = \sigma(\mu^+\mu^-)\frac{3\beta - \beta^3}{2}$, e-μ universality and a μ-spectrum from V-A structure of three-body leptonic decay. Taking into account the electron detection efficiency and the geometrical acceptance, ten events of the type (5.7) are expected in our event sample.

Indeed we find 12 events of this type. From the known probability for misidentification of electrons and muons, the background is estimated to be less than 1.5 events. This clearly establishes a μe signal in our detector. The momentum spectrum of the electron shown in Fig. 10, is compatible with the curve, which is a V-A leptonic spectrum folded with the momentum dependent detection efficiency for electrons.

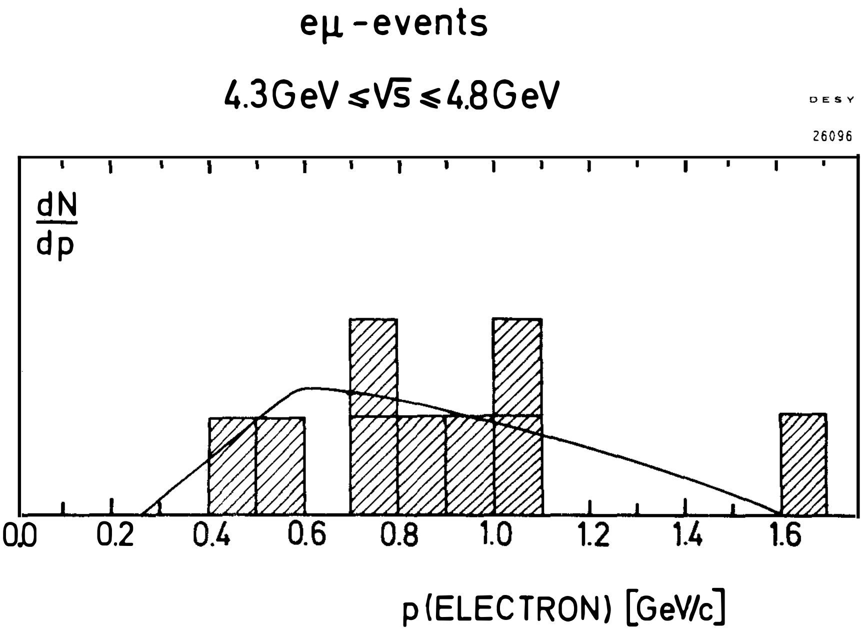

Fig. 10. The electron momentum spectrum for the 9 μe events observed in the energy region 4.3 to 4.8 GeV. The curve is a V-A decay spectrum of a 1.95 GeV heavy lepton, folded with the momentum dependent electron detection efficiency and normalized to the observed number of events.

A different explanation for the observed μe events could be the reaction

$$e^+e^- \to C^+C^-$$
$$\quad C^- \to K_L^o e^- \nu$$
$$\quad C^+ \to K_L^o \mu^+ \nu$$

in which charm particles C have a semileptonic decay with undetected long lived K^o. Assuming all events to come from this reaction, three times more events are expected with at least one K_L^o replaced by a short lived K^o, that decays into pions almost always close to the production vertex. About 30 events of this type, falling in the multi-prong class, are expected. All muon events in the multi-prong class are examined for electron candidates among the additional tracks. Expecting seven events background from the knwon misidentification probability six events are found, which are therefore consistent with background. One concludes that the observed μe events in the two-prong class are unlikely to come from semileptonic charm decays.

VI. Photons from decay of the $\psi'(3.7)$

In this final chapter preliminary results are presented obtained with photons from the decay of the $\psi'(3.7)$. With the detector PLUTO it is possible to measure the photon direction by detection of a shower or a e^+e^- pair from conversion in the material of the chambers (0.2 X_o before the first lead cylinder) or in the lead cylinders (0.4 X_o and 1.7 X_o). In a certain fraction of cases also the energy of the photon can be measured from the e^+e^- tracks. The photon energy spectrum obtained at the $\psi'(3.7)$ resonance is shown in Fig. 11.

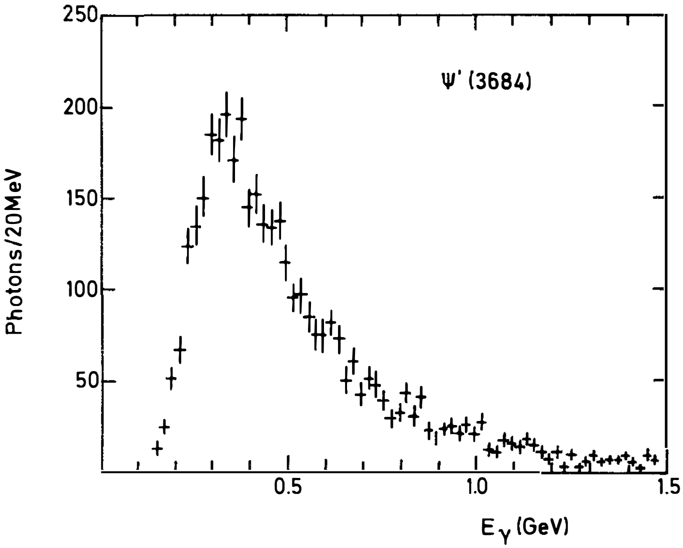

Fig. 11. Photon energy spectrum from $\psi'(3.684)$ decay, not corrected for detection efficiency.

No photon lines are observed from the decays

$$\psi' \to P_c/\chi\ \gamma \qquad (6.1)$$
$$\quad\quad \hookrightarrow \gamma\ J/\psi$$

because the photon energies fall in the region of steeply increasing efficiency for photon detection. Nevertheless, it is possible to try kinematical fits to events with two charged particles and at least one observed photon (photons observed only by a shower behind the second lead cylinder are not used in the fit) to the hypothesis

$$e^+e^- \rightarrow \mu^+\mu^- \gamma\gamma \tag{6.2}$$

which is equivalent to reaction (6.1), if the J/ψ is decaying to a $\mu^+\mu^-$ pair. In the spectrum of $M(\mu^+\mu^-)$ for all events fitting hypothsis (6.2) a small peak is observed at the position of the J/ψ. For these events the kinematical fit is repeated constraining the invariant $\mu^+\mu^-$ mass to the J/ψ mass. Events with a large χ^2 in the fit and also events consistent with $\psi' \rightarrow J/\psi\ \eta$ decay are excluded. All events are further checked for consistency with the assumed hypothesis using in addition the observation of showers behind the second lead cylinder. The remaining 17 events are shown in Fig. 12 together with data from the DASP group[15)] and the SLAC-LBL group[16)]; as usual the two $J\gamma$ masses are plotted against each other. A clustering of events is observed at four mass values. Three of the clusters are consistent with reaction

$$e^+e^- \rightarrow \psi' \rightarrow \chi/P_c + \gamma \tag{6.3}$$

at χ/P_c mass values also observed in hadronic decay modes[17)]; the position of these mass values are indicated by arrows in Fig. 12. There is an indication of an additional intermediate state with mass 3.454 GeV observed up to now only in the cascade decay mode of reaction (6.1). There are five events observed by the DASP and SLAC-LBL groups. Three more events are added by the PLUTO group increasing the evidence for the existence of this intermediate state.

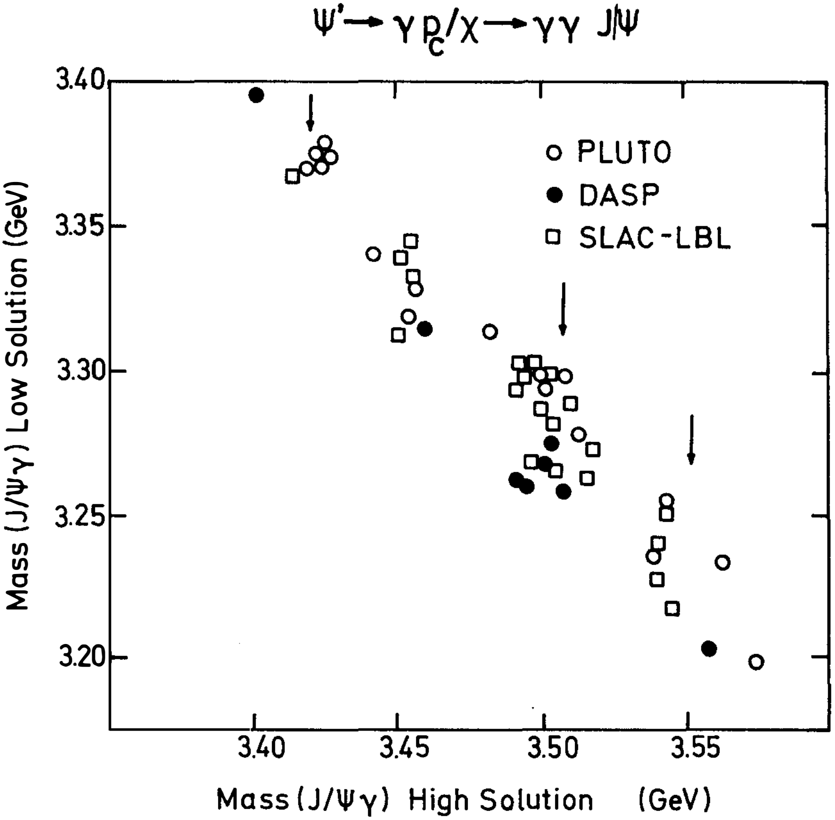

Fig. 12. Low mass solution versus high mass solution for the decay $\psi' \to \gamma P_c/\chi \to \gamma\gamma\ J/\psi$. The positions of the resonances as determined by hadronic decay modes are indicated by arrows.

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