THE TOTAL HADRONIC CROSS SECTION FOR e^+e^- ANNIHILATION BETWEEN 3.1 AND 4.8 GEV CENTER OF MASS ENERGY

PLUTO Collaboration

J. BURMESTER, L. CRIEGEE, H.C. DEHNE, K. DERIKUM, R. DEVENISH, J.D. FOX, G. FRANKE, G. FLÜGGE, Ch. GERKE, G. HORLITZ, Th. KAHL, G. KNIES, M. RÖSSLER, S. WOLFF, R. SCHMITZ, T.N. RANGA SWAMY [1], U. TIMM, H. WAHL [2], P. WALOSCHEK, G.G. WINTER, W. ZIMMERMANN

Deutsches Elektronen-Synchrotron DESY, Hamburg

V. BLOBEL, H. JENSING, B. KOPPITZ, E. LOHRMANN [3]

II Institut für Experimentalphysik der Universitat Hamburg, Germany

A. BÄCKER, J. BÜRGER, C. GRUPEN, M. ROST

Gesamthochschule Siegen, Germany

H. MEYER, K. WACKER

Gesamthochschule Wuppertal, Germany

Received 3 January 1977

Using the solenoidal magnetic detector PLUTO, we have measured the total cross section for e^+e^- annihilation into hadrons. Results are presented for center of mass energies between 3.6 and 4.8 GeV, and in the regions of the $J/\psi(3.1)$ and $\psi(3.7)$ resonances. We also present results for the 2 prong cross section in the energy range 3.6 to 4.8 GeV.

We present measurements of the total cross section for e^+e^- annihilation into hadrons at CMS energies between 3.6 and 4.8 GeV, and in the regions of the $J/\psi(3.1)$ and $\psi(3.7)$ resonances. We also present the cross section for the process $e^+e^- \to 2$ prongs + unseen neutrals at CMS energies between 3.6 and 4.8 GeV. Data were taken with the magnetic detector PLUTO at the e^+e^- storage ring DORIS.

The total cross section for hadron production through one photon annihilation (or the ratio $R = (\sigma_{e^+e^- \to \text{hadrons}})/(\sigma_{e^+e^- \to \mu^+\mu^-})$) provides fundamental information on the structure of hadrons. For example in the quark parton model the quantity R is directly related to the number of charged partons, provided that the CMS energy is large enough. In particular

$R = 2$ in the SU(3) model with colour ,

$R = 10/3$ in the SU(4) charm model with colour.

Recently data on R have been published for the CMS energy range 3.8–4.6 GeV [1]. The data show not only that R is large but also that there is at least one resonacne and most probably more in this energy region. The strong threshold effect seen in the data around 4.0 GeV is widely assumed to be due to the onset of charmed particle production [2].

With the present generation of e^+e^- experiments the accuracy with which the absolute value of R can be measured is limited by systematic errors. The authors of ref. [1] quote systematic errors of the order of 15% i.e. of the order of one unit in R at the energies in question. In view of the importance of R we consider it essential that the measurements be repeated by a detector with a different trigger system and high detection efficiency (hence a different systematic error). For the present experiment we estimate the systematic

[1] Now at Tate Institute, Bombay, India.
[2] On leave from CERN, Geneva, Switzerland.
[3] On leave at CERN, Geneva, Switzerland.

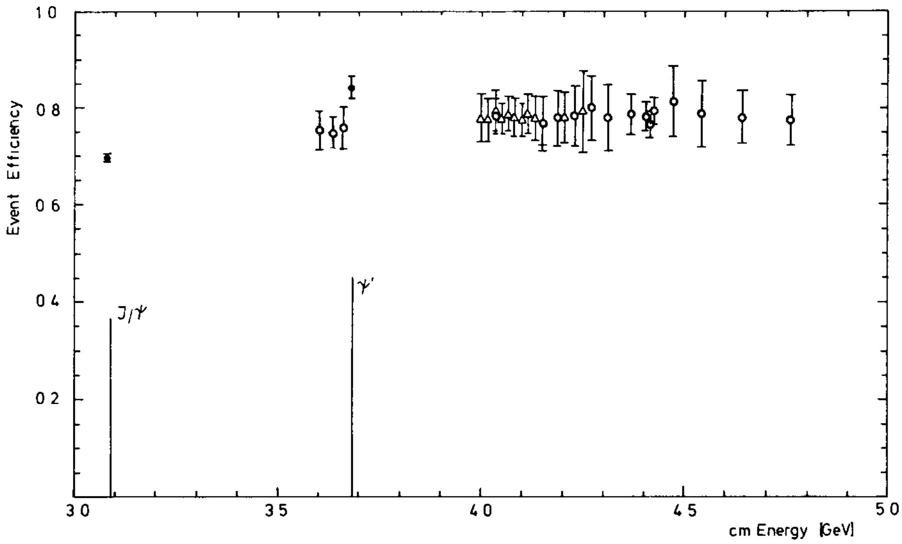

Fig. 1. Average detection efficiency per event ⟨ε⟩ versus CMS energy. (The symbols ɸ ɸ represent data taken at different times).

error to be 12%. We are making further studies of the systematic error by taking data with different trigger conditions and by changing the physical assumptions entering the Monte Carlo simulation.

The two prong cross section is interesting for the following reasons. By studying prong cross sections in addition to the total cross section one may hope to learn something about the decay mechanisms of the resonances produced in 4–4.5 GeV energy region. It has also been speculated that if a heavy lepton exists with mass near 2.0 GeV/c^2 [3] then its dominant decay modes are into channels with one charged particle [4]. The dominant decays of the pair of heavy leptons produced in e^+e^- annihilation would then produce a sizeable effect in the 2 prong channel.

The PLUTO detector detector has been described in detail elsewhere [5]. We review briefly the features important for the total cross section measurements. The superconducting coil procedures a 2T magnetic field parallel to the beam axis, with a useable magnetic volume of 1.4 m diameter × 1.05 m length. Inside the coil there are 14 cylindrical propertional wire chambers and two lead converters, a 2 mm converter at radius 37.5 cm and a 9 mm converter at radius 59.4 cm. The detector is triggered by a logic combination of signals from the proportional wire chambers. Track elements are recognized in groups of chambers inside and outside the lead converters. Events are accepted by the trigger if they satisfy at least one of the following conditions:

(i) at least two tracks inside the inner lead cylinder, with their azimuthal angles not belonging to two adjacent 45° sectors

(ii) at least three track elements outside one of the lead converters, with at least two of them not belonging to adjacent 45° sectors

(iii) two track elements outside the outer lead converter, if they are coplanar within ±13.5°.

The trigger solid angle is 86% of 4π and the transverse momentum cut-off for tracks recognized by the trigger is 240 MeV/c. The luminosity is monitored by small angle (130 mrad) $e\bar{e}$ scattering.

Hadronic events were selected by the following criteria

i) at least two tracks from the interaction region

ii) for two prong events the copianarity angle $\Delta\phi$ (difference between the azimuthal angles) must be less than 150°

iii) for three prong events, at least two of the $\Delta\phi$'s between pairs of tracks must be less than 150°.

The cuts ii) and iii) are required to separate the hadronic events from the QED processes $e\bar{e} \to \mu\bar{\mu}$ and $e\bar{e} \to e\bar{e}$.

The background from beam-gas interactions and cosmic ray events is subtracted using the distribution of reconstructed event vertices along the beam direction. The distribution of the hadronic events is centered

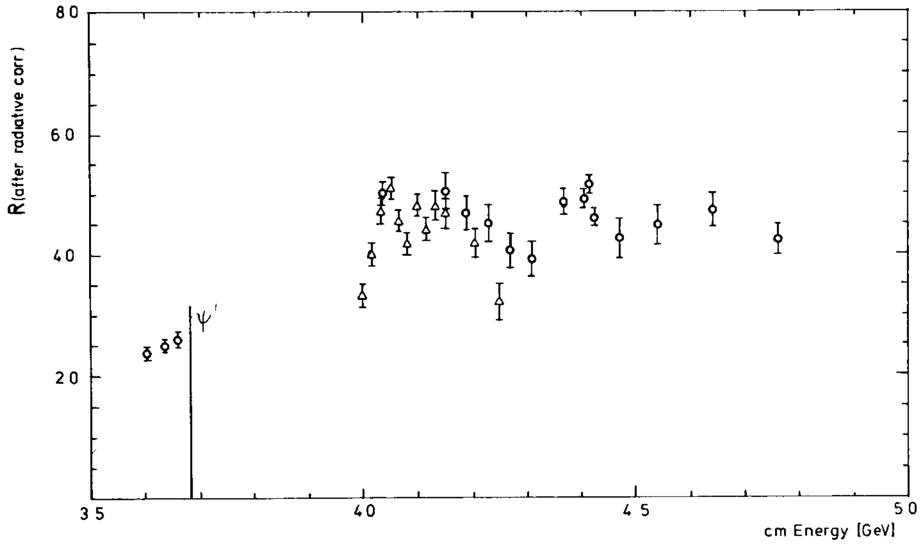

Fig. 2 The ratio $R = \sigma_{had}/\sigma_{\mu\mu}$ (allowing for radiative corrections) versus CMS energy

about the interaction point with FWHM of 20 mm, the background is flat. The fraction subtracted is 5–10% of the signal. A more detailed description of the subtraction procedure is given in ref. [6].

The contamination due to events from the two photon process is expected to be small at the energies at which data was taken. At our energies the dominant 2γ process is $e\bar{e} \to e\bar{e}\ell\ell$ with only the $\ell\bar{\ell}$ being seen in the detector. Calculations [7] show that the number of events with the 2 tracks having a coplanarity angle less than 150° is very small.

In order to determine the true number of events from the observed number we must use a Monte Carlo simulation to correct for the unobserved particles. Monte Carlo events are generated according to isotropic phase space and then the produced tracks are followed through the detector including a simulation of the photon conversion process. This last point is important because certain two prong events can be triggered by the presence of a converted photon (e.g. those with an opening angle less than 45° plus a photon shower). The Monte Carlo simulation is controlled by two parameters, the average charged multiplicity and the fraction of neutral to charged energy. Initially the charged and neutral multiplicities are chosen from independent Poisson distributions. As starting value for the charged multiplicity we have taken the observed results of SLAC-LBL [8], about 4 at the energies in question. The fraction of neutral particles included is chosen to make the ratio of neutral to total energy 0.5 on average.

We have checked that these parameters are reasonable by comparing the simulated and real data, for example the seen multiplicity distribution and the momentum spectrum for three or more charged particles. The calculation of the true number of events from the seen multiplicity distribution follows standard procedure [9]. (Further details are given in ref. [6]). For multiprongs our event detection efficiency is of the order of 95% and for two prongs we find an efficiency of the order of 45%. In fig. 1 we show a plot of the average efficiency $\langle\epsilon\rangle$ (averaged over all prong classes) versus energy. $\langle\epsilon\rangle$ is a slowly rising function of energy, 70% at 3.1 GeV and 80% above 4 GeV.

For the normalisation of the observed cross section, the beam luminosity is continuously monitored by small angle Bhabha scattering. An external monitor system was employed. Four identical telescopes, each equipped with three plastic scintillation counters and a lead-scintillator sandwich shower counter, were arranged symmetrically around the beam pipe outside the magnetic field région of the solenoid. The average scattering angle is

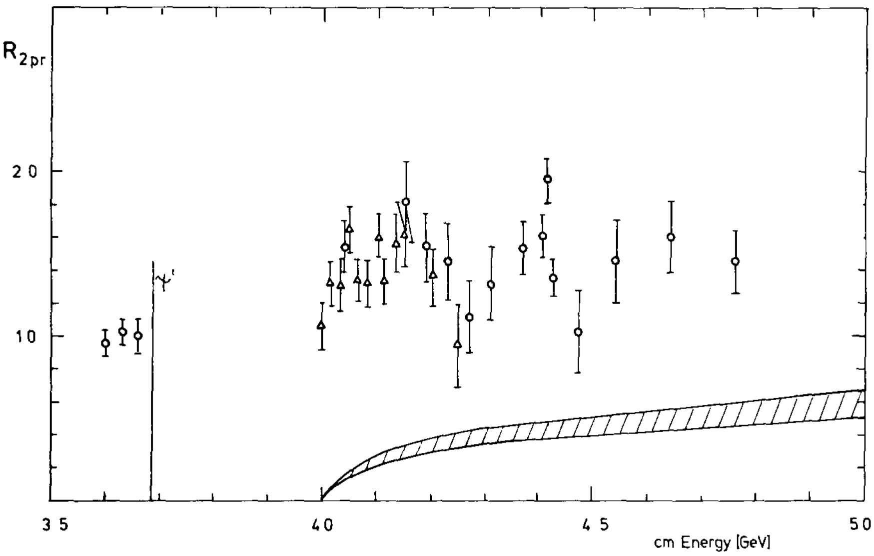

Fig. 3. The ratio $R_{2pr} = \sigma_{2pr}/\sigma_{\mu\mu}$ for $e\bar{e} \to$ 2 prongs (with radiative corrections applied) versus CMS energy. The curve indicates the contribution to R_{2pr} for a heavy lepton of 2.0 GeV mass.

130 mr, and about 2 msr solid angle are covered by each telescope.

From known uncertainties in the geometry of the monitor, and from the tails observed in the pulse-height distributions of the shower detectors, we estimate an uncertainty of ±5% in the absolute determination of the luminosity.

We have checked the reliability of the monitor by measuring the QED processes $e\bar{e} \to \mu\bar{\mu}$ and wide angle Bhabha scattering $e\bar{e} \to e\bar{e}$ seen in the detector. The μ pair reaction has been used to check the absolute normalisation. We can identify muons over 51% of 4π solid angle with a μ momentum cut-off of about 1 GeV/c. From the data at 3.6 GeV CMS energy we have, after background subtraction, 604 ± 37 events classified as $e\bar{e} \to \mu\bar{\mu}$ (2 prong collinear events with at least one track identified as a muon). From QED we expect 603 ± 12 events in agreement with the data. We have allowed for a 5% radiative correction to the measured integrated luminosity, and an 11% radiative correction to $e\bar{e} \to \mu\bar{\mu}$ [10]. To check the relative normalisation we have compared the rate for the wide angle Bhabhas with the monitor rate. The ratio of the rates is a constant with respect to the CMS energy.

Having determined the true numbers of events N and integrated luminosity we calculate the total cross section $\sigma_{tot} = N/Lt$ where Lt is the integrated luminosity (in nb^{-1}) as measured by the small angle Bhabha scattering monitor.

To obtain the true cross section for the two narrow resonances we applied radiative corrections following standard procecures [11]. The observed excitation curves have been fitted with the mass, area, and machine energy resolution as free parameters, after allowing for radiative correction of the monitor [12]. The results for the integrated resonance cross section are, including systematic errors,

$$\int \sigma_t \mathrm{d}E_{cm} = \begin{matrix} 9700 \pm 1200 \text{ nb MeV at } J/\psi(3.1) \\ 3060 \pm 400 \text{ nb MeV at } \psi(3.7) \end{matrix}$$

For the nonresonant cross section the radiative correction consists of three terms, i) the monitor correction, ii) the $J/\psi(3.1)$ and $\psi(3.7)$ radiative tails and finally iii) the correction from the integral over the cross section for $E_{cm} < 2E_{beam}$ [11, 13]. The results for $R = \sigma_{had}/\sigma_{\mu\mu}$ after allowing for radiative corrections, are shown in fig. 2. R has a value of 2.5 at 3.6 GeV, it rises steeply in the vicinity of 4.0 GeV to reach a value of the order of 5. Between 4 and 4.4 GeV the ratio R shows further structure, ranging in value between 4 and 5. Above 4.4 GeV R drops again to a value of the order of 4. Our data indicate a peak at 4.4 GeV and a more complicated structure in the 4–4.2 region. The structure between 4–4.2 GeV is to be seen in both 2 prongs and multiprongs, in comparison the 4.4 GeV effect is stronger in the 2 prongs.

In order to ensure that this structure is really due to the total cross section, and not simulated by rapid changes in event characteristics, we have investigated the energy dependence of the average observed energy for events with ⩾ 3 charged particles, and the average observed multiplicity. Neither one shows any structure.

At present we estimate systematic errors in the overall normalisation of the order of 12%, mainly from the trigger and Monte Carlo unfold.

In fig. 3 we show the quantity $R_{2pr} = \sigma_{2prong}/\sigma_{\mu\mu}$ for the process $e^+e^- \to$ 2 prongs + neutrals. The 2 prong cross section follows the structure seen in the total cross section fairly well. The steep rise at 4.0 GeV and the bump at 4.4 GeV are common to both data.

Our results for $R = \sigma_{had}/\sigma_{\mu\mu}$ agree with those of the SLAC-LBL group within systematic errors. We find our cross sections to be 10–15% lower than those of SLAC-LBL on the narrow J/ψ resonances [14] and at higher energies [15]. In fact the agreement on the energy dependence and structure of the total cross section between 3.6 and 4.8 GeV CMS energy is very good. We emphasize once more that the accuracy with which R can be measured is limited by systematic errors, which amount to almost one unit in R in the above energy range. This uncertainty must be borne in mind when any attempt is made to draw theoretical references from the measured value of R.

We now turn our attention to the results for the 2 prong cross section. As shown in the previous section the 2 prong cross section follows the structure seen in the total cross section. There is no a priori reason to expect such a result. That it does so is consistent with the fact, mentioned in the previous section, that the average multiplicity shows no striking energy dependence. This observation has also been made by the SLAC-LBL group [1]. Our data show that the new states responsible for the rise in R above 4 GeV also contribute strongly to two prong final states.

However at energies above 4 GeV the e^+e^- 2 prong cross section could be complicated by the addition of a contribution from a heavy lepton. The anomalous $e\mu$ events seen by the SLAC-LBL group have been interpreted as being due to the existence of a heavy lepton with a mass in the range 1.8–2 GeV [3]. The standard models for the decays of such heavy leptons [4] indicate that their contribution to the cross section for e^+e^- annihilation into hadrons (as presently defined) will be mostly in the 2 prong channel. To show how large this effect could be we have plotted in fig. 3 the expectation for a point like heavy lepton of mass 2 GeV/c^2 with probability for a pair to decay into 2 prongs in the range 60–80% [4]. We can see from the figure that at the highest energies (4.8 GeV) the heavy lepton would account for almost half of the two prong cross section.

We thank H. Ahrens, R. Cyriacks, B. Eichhorn, K. Finke, H. Kock, W. Kuffner, A. Marxen, W. Mehrgardt, H. Schultz and A. Stuben for their invaluable contribution in the construction and operation of the detector. We are indebted to the storage ring group for their excellent support during this experiment. We are grateful to the computer center for efficient cooperation We are indebted to G. Ripken for the computation of the radiative corrections for the luminosity monitor. We also thank all technicians of the cryogenic and gas services for their continuous efforts to keep the detector going.

The non-DESY members of the PLUTO-group want to thank the DESY-Direktorium for the kind hospitality extended to them.

References

[1] J. Siegrist et al., Phys. Rev. Lett. 36 (1976) 700.
[2] I Peruzzi et al., Phys. Rev. Lett. 37 (1976) 569; J. Burmester et al., Phys Lett 64B (1976) 369; W. Braunschweig et al., Phys. Lett. 63B (1976) 471.
[3] M.L Perl et al., Phys. Lett 63B (1976) 466.
[4] Y.S. Tsai, Phys Rev D4 (1971) 2821, K. Fujikawa, N. Kawamoto, DESY 76/01 (1976).
[5] L Criegee et al., Proc. 1973 Int. Conf. on Instrumentation for High Energy Physics, 707 (1973), E. Lohrmann, Journal de Physique 37, Coll C-2 (1976) 15.
[6] J. Burmester et al , DESY Report 76/53 (unpublished).
[7] N. Artega-Romero, A. Jaccharini et P. Kessler, C.R. Acad. Sc. Paris, Serie B, 269 (1969) p. 153, S.J Brodsky, T. Kinoshito and H. Terazawa, Phys. Rev. D4 (1971) 1532.
[8] R.F. Schwitters in 1975 Int. Symp. on Lepton and photon interactions at high energies, Stanford p. 5.
[9] A Litke et al., Phys. Rev. Letters 30 (1973) 1189, G. Tarnopolsky et al., Phys. Rev. Letters 32 (1974) 432; G. Tarnopolsky, D. Sc Thesis, Technion, Haifa, Israel 1973 (unpublished).

[10] F.A. Berends, K.J.F. Gaemers and R. Gastmans, Nucl. Phys. B57 (1973) 381.
[11] D.R. Yennie, Phys. Rev. Letters 34 (1975) 239;
J.D. Jackson and D.L. Scharre, Nucl. Inst. & Methods 128 (1975) 13.
[12] F.A. Berends, K.J.F. Gaemers and R. Gastmans, Nucl Phys. B68 (1974) 541.
[13] G. Bonneau and F. Martin, Nucl. Phys. B27 (1971) 381.
[14] SLAC-PUB-1599 presented by V. Lüth at the International Conference on High Energy Physics Palermo (1975).
[15] J.-E. Augustin et al., Phys. Rev. Lett. 34 (1975) 764;
J.S. Siegrist et al., Phys. Rev. Lett. 36 (1976) 700.