LEPTON PAIR PRODUCTION AND SEARCH FOR A NEW HEAVY LEPTON IN e^+e^- ANNIHILATION

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We have measured the reaction $ee \to \mu\mu$ and $ee \to \tau\tau$ at center of mass energies from 9.4 to 31.6 GeV. The production cross sections are in agreement with the predictions of quantum electrodynamics, resulting in cutoff parameter limits of 70–100 GeV at 95% c.l. The branching ratio for $\tau \to \mu\nu\bar{\nu}$ has been determined as [17.8 ± 2.0(statist.) ± 1.8(syst.)]%. The existence of a new sequential heavy lepton with a mass < 14.5 GeV is excluded at 95% c.l.

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The production of lepton pairs in e^+e^- reactions at PETRA energies

$$e^+e^- \to L^+L^- \quad (L = \mu, \tau, ...)\,, \qquad (1)$$

is of threefold interest. Firstly, the pointlike nature of the muon and the τ lepton at Q^2 values around 1000 GeV^2 can be checked. Secondly, the above processes are a testing ground for electroweak interference effects. Finally reaction (1) is well suited for checking the existence of new sequential heavy leptons. In the standard gauge theory of electroweak interactions the existence of such leptons would also imply a new generation of heavy quarks. In this letter we present results on the energy and angular dependence of the cross sections for $e^+e^- \to \mu^+\mu^-$, $\tau^+\tau^-$as obtained with the PLUTO detector at the e^+e^- colliding beam facilities DORIS and PETRA. In addition we report on a search for the production of new heavy leptons at PETRA energies. A detailed study of electroweak effects including our data on Bhabha scattering will be published elsewhere [1].

The data reported here have been taken at c.m. energies around 9.4 GeV (DORIS) and between 12 and 31.6 GeV (PETRA). The data are based on accumulated luminosities of 370 nb^{-1} at DORIS and 3200 nb^{-1} at PETRA [2,3]. We first describe those parts of the PLUTO detector that are relevant for the analysis of lepton pairs presented here ‡1, the detector consists of:

(i) An inner detector, consisting of 13 cylindrical wire chambers and operating in a field of 1.65 T. It provides a momentum resolution of $\sigma_p/P = 3\% \cdot p$ for single tracks above p = 3 GeV. In a combined fit to two collinear tracks the resolution improves to $\sigma_p/p = 1\% \cdot p$.

(ii) Shower counters which surround the inner detector. They consist of two parts: (a) the "barrel", a cylindrical lead scintillator sandwich counter at a radius of 640 mm covering the region $|\cos\theta| < 0.6$ and (b) the "endcaps", also of the lead scintillator type, covering the region $0.6 < |\cos\theta| < 0.96$. Here θ is the polar angle between the μ^+ and the e^+ beam direction; ϕ is the azimuthal angle.

(iii) A time-of-flight system associated with the shower counters. In the barrel region the time difference between signals from opposite counter segments is measured with a rms resolution of σ = 0.6 ns. In the endcap region we use low gain phototubes (9 ns rise time) which allow the rejection of cosmic rays which do not traverse the detector in time coincidence with the beam.

(iv) A muon detection system, consisting of a double layer of proportional tube chambers behind an iron equivalent of 70 cm with an angular coverage of 80% of 4π (65% at DORIS), and another set of drift chambers after 100 cm iron equivalent covering 80% of the solid angle [4].

The analysis of μ pairs requires a high rejection factor against background from cosmic radiation. The following selection criteria were applied:

(i) We required two tracks in the angular region $|\cos\theta| < 0.75$, collinear within 10 degrees.

(ii) The momenta of the tracks had to be greater than 0.5 E_{beam} (0.67E_{beam}) for $E_{cm} > 20$ GeV (<20 GeV).

(iii) The distance between the interaction point and the origin of the tracks had to be smaller than 1.5 mm in the x–y plane and smaller than 40 mm along the z-direction (beam direction).

(iv) To reject Bhabha-scattering events the sum of the energy observed in the shower counters was required to be less than 1 GeV.

(v) Timing cuts: in the barrel region a cut of 2.0 ns was imposed in the time difference of two back-to-back tracks normalized to normal incidence. The expected value is 0 for μ pairs and 4.25 ns for cosmic rays. In addition, all events outside a window of 20 (60) ns width in the barrel (endcap) region were rejected. The time window was centered at the bunch crossing time. The observed ratio of μ pairs to cosmic rays in the 60 ns window of the endcap region is 2.5 : 1. The cosmic ray background was eliminated by a sideband subtraction using the cosmic event rates in sidebands next to the time window.

After the cuts and subtractions we obtain 228 events. The ramaining background from cosmic rays is estimated to be less than 1.4% for $|\cos\theta| < 0.6$. Using Monte Carlo calculations and shower counter information the background from the reactions ee → hadrons, ee → ee and ee → ee $\mu\mu$ has been found to be negligible. The amount of τ pairs in the $\mu\mu$ candidates is estimated to be 2%. The efficiency of the selection depends on $\cos\theta$ and is 98.5% on the average. The trigger efficiency

‡1 The experimental setups at DORIS and PETRA were slightly different. Details are given in refs. [2,3].

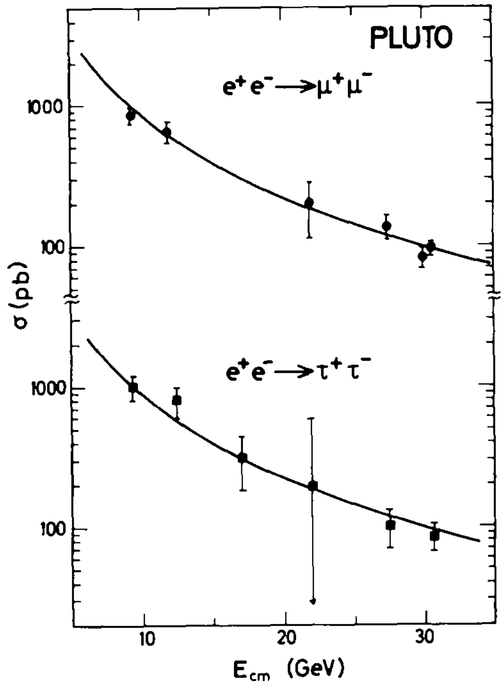

Fig. 1. Total cross section for reactions $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \tau^+\tau^-$ as a function of energy. The cross sections have been corrected for limited acceptance, detection efficiency and radiation. The curves give the first order QED cross section.

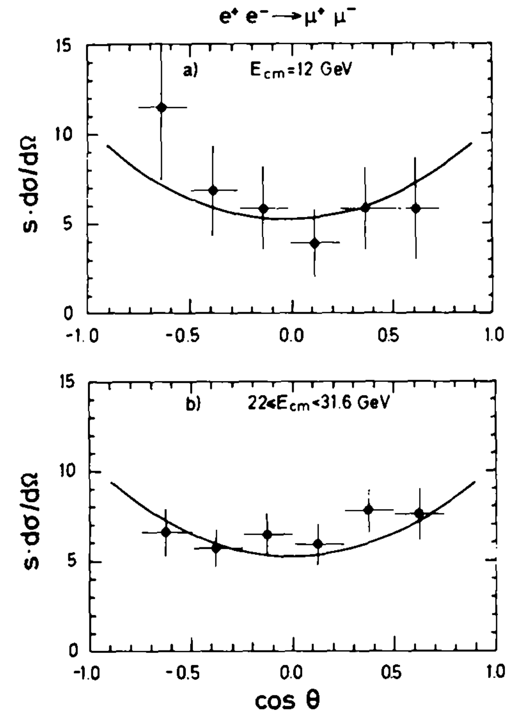

Fig. 2. Differential cross sections $s\, d\sigma/d\Omega$ for reaction $e^+e^- \rightarrow \mu^+\mu^-$ at (a) E_{cm} = 12 GeV and (b) $22 \leq E_{cm} < 31.6$ GeV. The data are corrected for radiation and detection efficiency. The curve is the first order QED prediction.

varies from 99% at 12 GeV to 98% at 30 GeV.

Fig. 1 shows the energy dependence of the radiatively corrected total cross section for $e^+e^- \rightarrow \mu^+\mu^-$ (full circles). The radiative corrections were computed according to refs. [5,6]. They vary between 3.6% (5.4%) for $\cos\theta = 0.75$ and –4.1% (–2.2%) for $\cos\theta = -0.75$ for E_{cm} = 12 (30) GeV, respectively. Fig. 2 shows the differential cross sections at 12 GeV and 22–31.6 GeV. The errors shown are statistical. The systematic errors are 4% (mainly from the overall normalization). The solid lines are the predictions of first order QED.

Deviations from QED are usually parametrized by introducing form factors which depend on cutoff parameters Λ [‡2].

$$\sigma = \sigma_{QED} |F(s)|^2 ,$$

$$F(s) = 1 \mp s/(s - \Lambda_{\mp}^2) , \quad \text{i.e} \quad F^2 \simeq 1 \pm 2s/\Lambda_{\mp}^2 .$$

‡2 For a recent review of possible QED modifications see ref. [7].

Using this parameterisation we obtain from a one parameter fit to the total $\mu^+\mu^-$ cross section as a functions of s

$$\Lambda_+ > 107 \text{ GeV} , \quad \Lambda_- > 101 \text{ GeV} ,$$

at 95% c.l. From the value of Λ_+ one can infer an upper limit for the charge radius of the muon of $\approx 2 \times 10^{-16}$ cm.

Next we discuss τ pair production. Here we restrict the analysis to final states in which at least one τ lepton decayed into only one charged particle (e, μ, π, ρ) plus neutrals. Hence the signatures of these $\tau\tau$ configurations are 2 and 4 prong topologies. Several cuts were applied in order to optimize the particle identification and to eliminate the various background sources, namely (i) Bhabha scattering and cosmics, (ii) μ pair and $\mu\mu\gamma$ production, (iii) beam–gas interactions, (iv) low multiplicity hadronic final states, and (v) two photon interactions. Specifically we required for the two prong sample:

(1) two oppositely charged tracks with $|\cos\theta| < 0.6$ originating from the interaction point, where one track has a momentum $p > 0.8$ GeV, and the other has $p > 0.5$ GeV;

(2) time of flight cuts as in the μ pair analysis; events with an acceptable collinear fit are rejected;

(3) missing mass computed from charged particles $> 0.25\ E_{cm}$;

(4) acoplanarity angle $> 18°$, if both tracks are associated with showers with energies $\geqslant 0.25\ E_{beam}$;

(5) invariant mass of the two tracks of > 2 GeV (>3 GeV) at energies $E_{cm} \leqslant 13$ GeV ($\geqslant 17$ GeV) and a total transverse momentum of the charged tracks > 0.5 GeV. In the DORIS data the direction of the missing momentum had to be $>20°$ relative to the beam.

Cut (2) discriminates against cosmic rays, cut (3) against $\mu\mu$ and $\mu\mu\gamma$ final states, cut (4) against Bhabhas and cut (5) against $\gamma\gamma$ interactions.

In the multiprong sample we analyze the topology

$$e^+e^- \to \tau \;(\hookrightarrow 1 \text{ charged part.} + \text{neutrals}) + \tau \;(\hookrightarrow 3 \text{ charged part.} + \text{neutrals})$$

We require $\leqslant 6$ observed charged tracks [‡3], where at least one track has a momentum > 0.4 GeV (0.5 GeV) at $E_{cm} \leqslant 13$ GeV ($\geqslant 17$ GeV) and is separated by more than 90° in the r–ϕ plane from the remaining tracks. It was verified that the effective mass of the three tracks, which were emitted opposite to a single track, was consistent with originating from a τ.

The residual small contamination of Bhabha scatters was removed in a visual scan. After applying these cuts we obtain 73 two prong candidates and 78 four prong candidates. The background from beam–gas and cosmic events is negligible. Background from 2γ processes and multihadronic final states were studied via Monto Carlo simulations. The estimated backgrounds are 3 events in the two prong sample and 9 events in the four prong sample.

The efficiency of the event selection and the radiative corrections [6,8] were determined with a Monte Carlo program which simulates the τ pair production and decay and the detector response of the events (for details see ref. [9]). The τ detection efficiency, including geometrical and kinematical cuts and the restriction to the 2 and 4 prong channels, is $(18 \pm 2)\%$ at 12 GeV and $(15 \pm 2)\%$ at the other energies. When breaking up the event sample into separate final states we find agreement with the published branching ratios of the τ [10]. In particular, the measured branching ratio for $\tau \to \mu\nu\bar{\nu}$ is $[17.8 \pm 2.0$ (statist.) ± 1.8 (syst.)$]\%$ as compared with the world average of $(17.9 \pm 1.5)\%$ [10].

The resulting total τ pair cross section corrected for radiation is shown in fig. 1 (squares). A systematic uncertainty of 15% has been included in the error bars. We find good agreement with first order QED (curve). The QED cutoff parameters were determined from the cross sections at 30–31.6 GeV. We obtain 95% c.l. limits of

$$\Lambda_+ > 79\ \text{GeV}, \quad \Lambda_- > 63\ \text{GeV}.$$

These limits as well as those on reaction $e^+e^- \to \mu^+\mu^-$ are in agreement with the results from other PETRA experiments [11–14].

The cutoff parameters for μ and τ pair production generally check deviations of the vertex and propagator functions from first order QED. Since both have been tested for μ pair production with greater accuracy, the present values can be considered as a test of the $\tau\tau\gamma$ vertex. In this sense the value of Λ_+ corresponds to an upper limit of 2.5×10^{-16} cm for the charge radius of the τ.

Finally we have performed a search for a new heavy lepton. The possible existence of additional charged

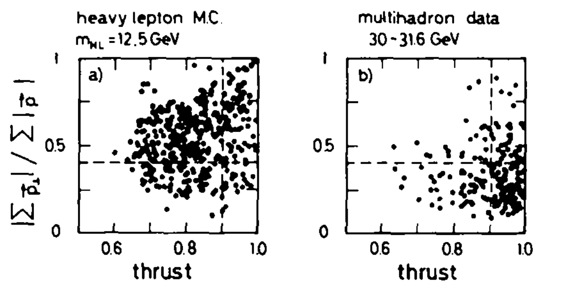

Fig. 3. Sum of the normalized transverse momenta versus the thrust for charged particles from multiparticle final states. (a) Heavy lepton Monte Carlo (m_{HL} = 12.5 GeV); (b) data at E_{cm} = 30–31.6 GeV. $p_\perp$ is measured relative to the beam axis. The events were selected according to the following criteria: (i) 2–12 vertex tracks, (ii) an excess of positive charged tracks <3 and (iii) a total energy >3 GeV.

‡3 We allow for up to 6 prongs in order to include 4 prongs with a $\gamma \to e^+e^-$ conversion.

leptons has been discussed widely (see e.g. ref. [15]. In this analysis we will concentrate on sequential spin 1/2 leptons with pointlike coupling to the standard electroweak current. We assume that the new lepton has the decay modes given in ref. [16], namely for a lepton mass of 14 GeV: $e\bar{\nu}$, $\mu\bar{\nu}$, $\tau\bar{\nu}$ (10% each), $u\bar{d}$ (35%), $c\bar{s}$ (35%) [‡4]. Most of the resulting multihadron events thus contain two or four acollinear quark jets. In order to study the new topology we generated Monte Carlo events at a c.m. energy of 30 GeV with lepton masses of 4, 6, 10, 12, 14 and 14.5 GeV, respectively [9]. The fragmentation of the quarks was simulated according to the prescription of Feynman and Field [17] with appropriate adaptations (inclusion of c quarks).

The analysis proceeds in three increasingly restrictive steps. First we determine the potential contribution of the new lepton to the measured τ cross section by passing the Monte Carlo heavy lepton events through the standard τ analysis chain. From the results and the measured τ cross section at E_{cm} = 30 GeV we can exclude contributions of a new lepton with a mass < 10 GeV at the 95% c.l.

Next we exploit the decay topology of the new lepton. The production of heavy lepton pairs close to threshold (i.e. m_{HL} = 10–14.5 GeV for E_{beam} = 15 GeV) results in events which are more isotropic than regular hadronic jet events (reflecting in low values of thrust) and which have large missing momentum from undetected neutrinos. This is demonstrated in fig. 3, which shows a scatter plot of the total normalized transverse momentum relative to the beam axis $|\Sigma p_\perp| / \Sigma |p|$ versus the thrust of charged tracks from (a) Monte Carlo events for m_{HL} = 12.5 GeV and (b) experimental multihadron events at E_{cm} = 30–31.6 GeV. Since heavy lepton events lead to smaller average multiplicities than hadronic jet events the data samples are restricted to events with 2–12 observed charged tracks. In order to enhance a possible signal for heavy leptons we apply two additional cuts: (1) thrust <0.9 and (2) $|\Sigma p_\perp| / \Sigma |p| > 0.4$. After performing a beam–gas background subtraction 24 multihadronic candidates remain. This potential signal is compared in fig. 4a with the expected number of heavy lepton events as func-

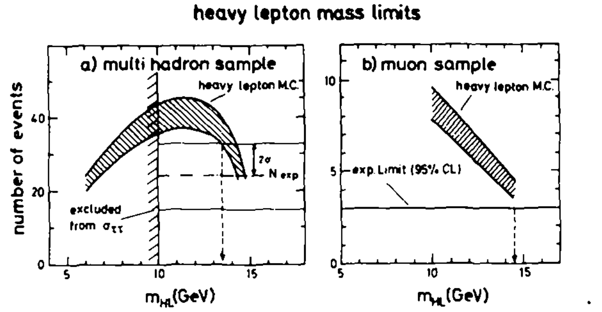

Fig. 4. Limits on the mass of a new sequential heavy lepton with standard coupling to leptons and quarks; (a) potential lepton signal with multihadronic decays (dash–dotted line with 2σ error limits); the shaded band is the expected signal as a function of heavy lepton mass from the Monte Carlo program. The width of the band indicates the statistical error plus the systematic uncertainty of the Monte Carlo simulation. The region below m_{HL} = 10 GeV is excluded from the measured value of $\sigma(e^+e^- \to \tau^+\tau^-)$. (b) 95% c.l. upper limit of the number of heavy lepton events at least one detectable muon (full line). The shaded band is the expected signal from the Monte Carlo program. The event selection cuts are described in the text.

tion of mass (shaded band). If all 24 events are attributed to heavy lepton production one can exclude heavy leptons with masses <13.5 GeV at 97.7% c.l. We note that this lower bound is a conservative estimate, because we did not subtract the genuine hadronic final states expected to survive the selection criteria mentioned above. Actually all events are consistent with the expectation for multihadron production.

In a final step the data are restricted further by considering only the muonic decay of a heavy lepton. We select multihadronic events with muon candidates i.e. tracks with $p > 1.4$ GeV firing the outer muon chambers. The cuts were loosened to $T < 0.95$ and $|\Sigma p_\perp| / \Sigma |p| > 0.3$ in order to take into account the reduced multiplicity of muonic heavy lepton decays. Muons in multihadronic events originate from c and b decays inside jets. Hence small angles between the μ and the other hadrons are favored. We can reduce this background by requiring a minimum angle of 20° in the r–ϕ plane between the muon track and any other track. We find no event satisfying the above criteria.

In fig. 4b the expected number of heavy lepton events predicted by the Monte Carlo program is plotted versus the lepton mass m_{HL} (shaded band). At m_{HL} = 14.5 GeV 4.0 ± 0.5 events are expected whereas no

[‡4] Here we made some simplifications, i.e. we added the small $u\bar{s}$ mode to the $u\bar{d}$ mode and the $c\bar{d}$ + $c\bar{b}$ modes to the $c\bar{s}$ mode.

events are observed. Hence we can exclude a heavy lepton with a mass of less than 14.5 GeV with a confidence level of more than 95%. Similar limits were derived from the data of other PETRA experiments [12, 18, 19].

In conclusion, μ and τ pair production is described well by QED up to $s \approx 1000\ \mathrm{GeV}^2$. The μ and τ behave as pointlike particles down to distances of smaller than 2.5×16^{-16} cm. The existence of additional charged sequential leptons can be excluded in the mass range 4–14.5 GeV (95% c.l.), provided they couple to leptons and quarks through the standard weak current.

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