HC

ERICE PREPRINT SERIES

«ETTORE MAJORANA» CENTRE FOR SCIENTIFIC CULTURE

EMCSC/94-02
CERN-LAA/94-27
16 August 1994

FOUNDATIONS OF SEQUENTIAL HEAVY LEPTON SEARCHES

A. Zichichi
CERN, Geneva, Switzerland

Abstract

The original contributions of the Bologna-CERN-Frascati (BCF) group to the discovery — via the acoplanar $(e^{\pm}\mu^{\mp})$ method — of the Heavy Lepton (*HL*, now called τ) are described. These contributions include: i) the idea of a new lepton in the GeV mass range, carrying its own leptonic number; ii) the search for the best production process: $e^+e^- \rightarrow HL^+HL^-$; iii) the invention of the acoplanar $(e^{\pm}\mu^{\mp})$ method with the associated technology and the proof that it works; iv) the implementation of the large solid-angle detector needed to establish the first upper limit on the *HL* mass at Frascati; v) the promotion of the *HL* searches at energies higher than ADONE. These original contributions started in 1960 at CERN with the construction of the first large solid-angle detector able to simultaneously detect electrons and muons with high rejection power against pions, thus allowing, already in 1964, to establish the validity of the $(e^{\pm}\mu^{\mp})$ method as the best one to detect Heavy Lepton pair production.

Presented at the International Conference on:
"The History of Original Ideas and Basic Discoveries in Particle Physics"
Erice, Italy, 29 July - 4 August 1994

(To be published in the Proceedings of the Conference)

EMCSC - Via Guarnotta 26 - 91016 Erice - Italy - Tel. (923) 869133 - Fax. (923) 869226

TABLE OF CONTENTS

1 Introduction

The Heavy Lepton (H_l) was discovered (and called τ) by Martin Perl et al. [1] in 1975, via the study of the production process:

$$e^+e^- \rightarrow H_l^+ H_l^- \quad (1)$$

and the decay channels:

$$H_l^{\pm} \longrightarrow \begin{cases} e^{\pm} + \nu_e + \nu_{H_l} \\ \mu^{\pm} + \nu_{\mu} + \nu_{H_l} \end{cases} \quad (2)$$

using the method of detecting acoplanar ($e^{\pm}\mu^{\mp}$) pairs. Reactions (1) and (2) are on page 7 of the INFN proposal, dated 1967, to search for Heavy Leptons with the ADONE (e^+e^-) collider at Frascati [2]. Figure 1.1 is the front page of the proposal and Figure 1.2 the page where the production reaction (1) and the decay channels (2) are given.

The acoplanar ($e^{\pm}\mu^{\mp}$) method was the key point of the Bologna-CERN-Frascati (BCF) proposal to INFN, which is, in turn, based on the fundamental idea that there is a new leptonic number associated with the Heavy Lepton.

As we will see in this report, thinking on how to search for a Heavy Lepton carrying its own leptonic number started at CERN in the late fifties during the first high precision measurements of the muon (g−2) [3]. This thinking brought in 1963 to the invention of the "early-shower development" method, now called "pre-shower" method [4-7], and to a series of experiments on lepton pair studies in hadronic interactions [8-17]. The other basic steps are the already mentioned INFN proposal (1967) [2] and the publications as from 1970 of the ADONE results proving that the experimental set-up was working and the acoplanar ($e^{\pm}\mu^{\mp}$) method was not swamped by background [18-39].

2 Lepton Pair Physics at CERN (1963-1968)

The 1967 INFN proposal [2] is based on a series of technological [4-10] and physical [11-17] research works performed at CERN where lepton pair production in hadronic processes was investigated.

The starting point was using collisions between hadrons (h),

$$h+h \rightarrow (e^+e^-) + X$$

but:

$$\frac{h + h \rightarrow (e^+e^-) + X}{h + h \rightarrow \text{hadrons}} \approx 10^{-6}$$

thus a powerful rejection against hadrons, in order to detect (e^+e^-) pairs, was needed. Figure 2.1 is the cover page of the CERN Yellow-Report [4] where the "pre-shower" technique was presented for the first time.

The "pre-shower" technique was able to reject pions in favour of electrons with a rejection power as good as

$$\pi/e \approx 10^{-3}.$$

Figure 2.2 shows the spectrum obtained for electrons and pions using this "pre-shower" technique associated with a lead-glass Čerenkov counter.

The Bologna-CERN group continued the development of the instrumentation to find a way to improve the π/e rejection to order of 10^{-4}. The set-up used is the first example of what would have in the future become an electromagnetic calorimeter.

Figure 2.3 shows the new detector [5], designed and proven to work with a rejection power better than 10^{-3}. This electron detector consists of five elements, each one being made of a lead layer followed by a plastic scintillation counter and a two-gap spark chamber. The results are shown in Figure 2.4.

As can be seen from this figure, the rejection power of the new detector against pions is of the order of $4 \cdot 10^{-4}$ and the efficiency for electron detection varies from 75% to 85% (right scale). The energy resolution can be as good as 10%, in the energy range 1.1 GeV to 2.5 GeV.

Comitato Nazionale per l'Energia Nucleare
ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Bologna
67/1

INFN/AE-67/3
20 Marzo 1967

M. Bernardini, D. Bollini, E. Fiorentino, F. Mainardi, T. Massam, L. Monari, F. Palmonari and A. Zichichi (Bologna-Cern-Frascati collaboration) : A PROPOSAL TO SEARCH FOR LEPTONIC QUARKS AND HEAVY LEPTONS PRODUCED BY ADONE. -

Reparto Tipografico
dei Laboratori Nazionali di Frascati

Fig. 1.1: Front page of ref. 2, i.e. the 1967 proposal to INFN by the Bologna-CERN-Frascati (BCF) group to search for a new sequential Heavy Lepton at ADONE.

7.

By studying the most favourable mechanisms which could produce the heavy leptons we reach the following conclusion. If in the process

$$e^+ e^- \rightarrow H_1^+ + H_1^-$$

we set at an energy E such that the ratio

$$\frac{E}{M_{H_1}} \simeq 1.2$$

as can be seen from Fig. 6 the cross-section is around 10^{-32} cm^2. Moreover, the two produced H_1^+ and H_1^- are non relativistic and very slow in the laboratory-system, their $\gamma = E/M$ is in fact ~ 1.2. The most favoured decay channels, as far as we can say now, are probably

$$H_1^{\pm} \rightarrow e^{\pm} + \nu_e + \nu_H$$
$$H_1^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu} + \nu_H$$

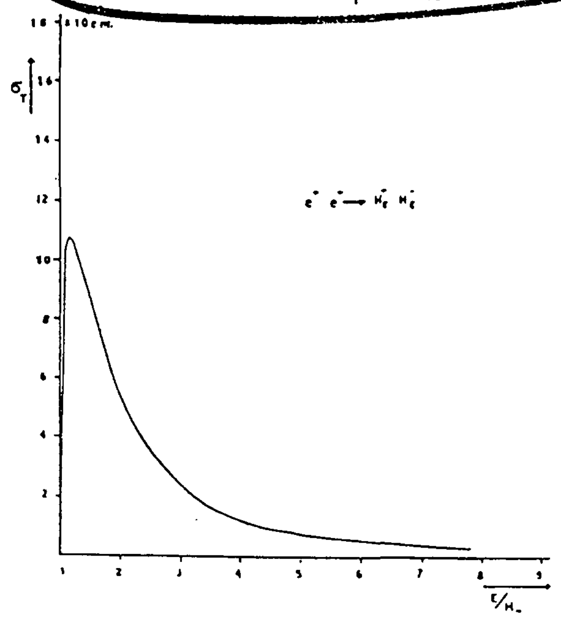
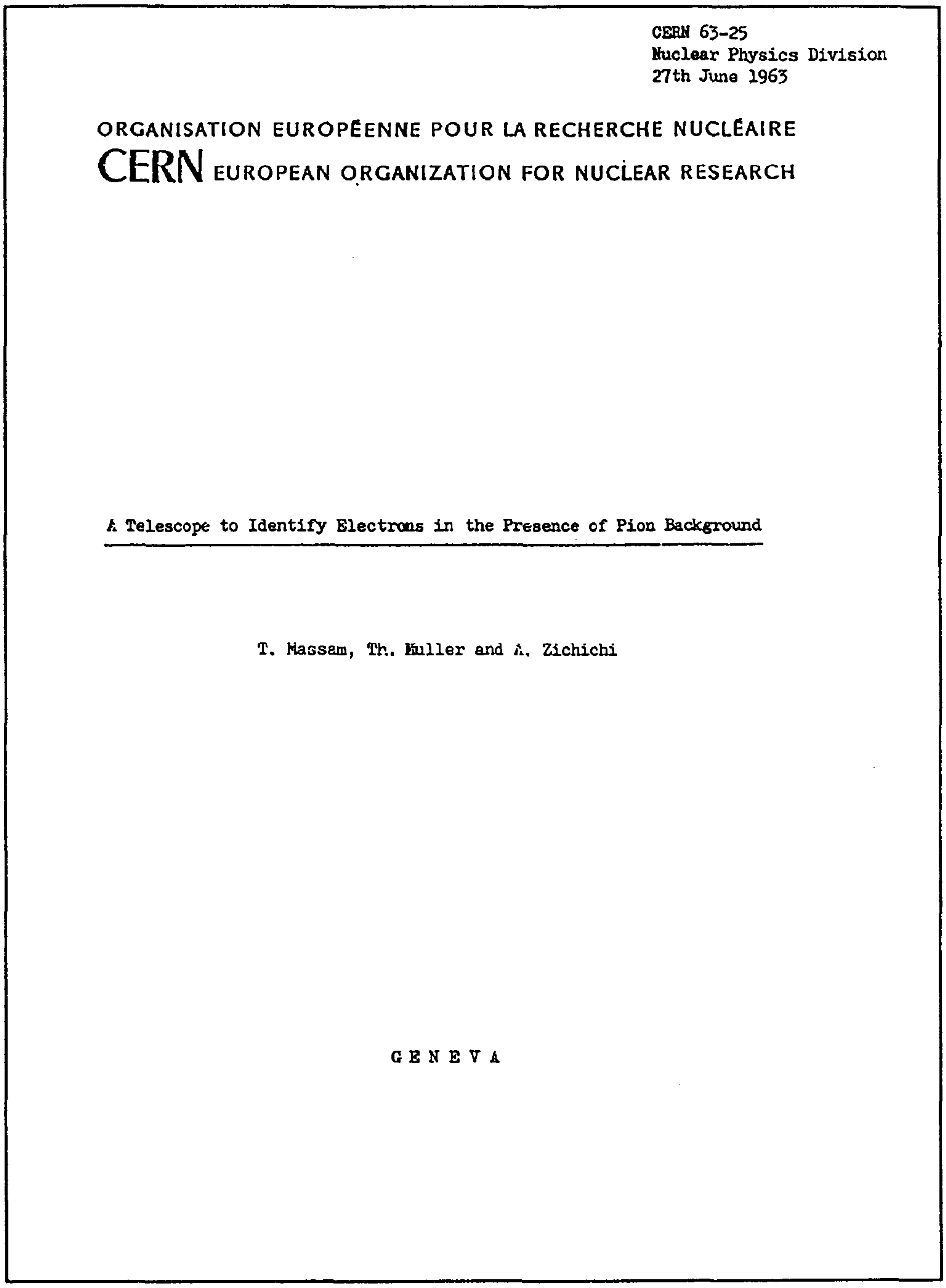


FIG. 6 - Total cross-section for production of heavy leptons versus E/M_{H_1}.

Fig. 1.2: Showing the page of ref. 2 where the most favourable production process and decay channels foreseen to search for a new sequential Heavy Lepton are reported.



CERN 63-25
Nuclear Physics Division
27th June 1963

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

A Telescope to Identify Electrons in the Presence of Pion Background

T. Massam, Th. Muller and A. Zichichi

GENEVA

Fig. 2.1: Front page of ref. 4 where the innovative "early-shower development" (i.e. "pre-shower") method for π/e rejection was presented.

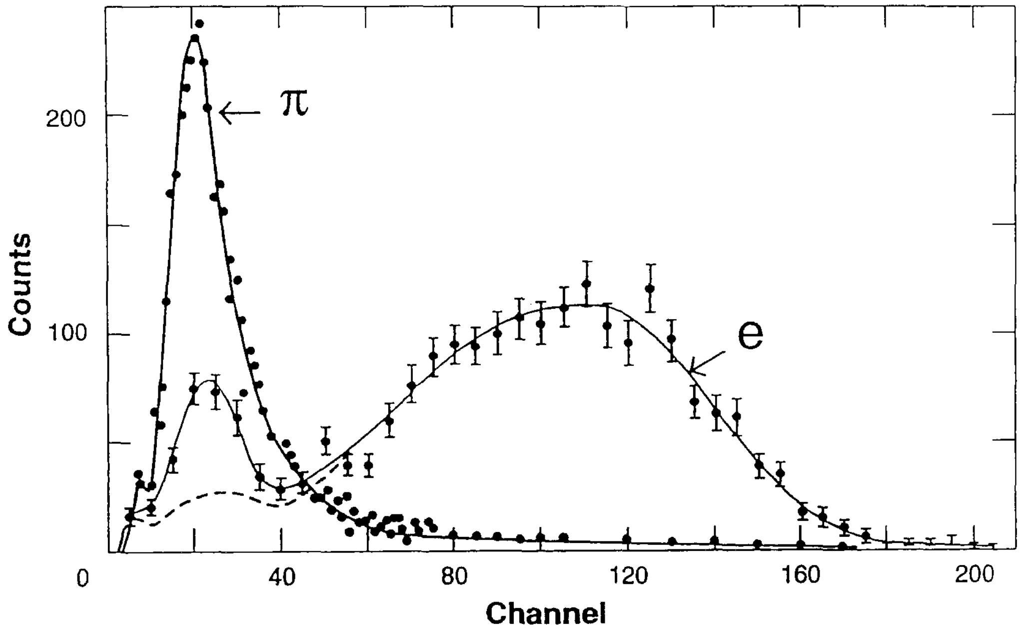


Fig. 2.2: The pulse height spectra obtained in a test beam with the "pre-shower" technique, coupled to a total absorption lead-glass Čerenkov counter. This allowed one to reach a π/e rejection of 10^{-3} [4].

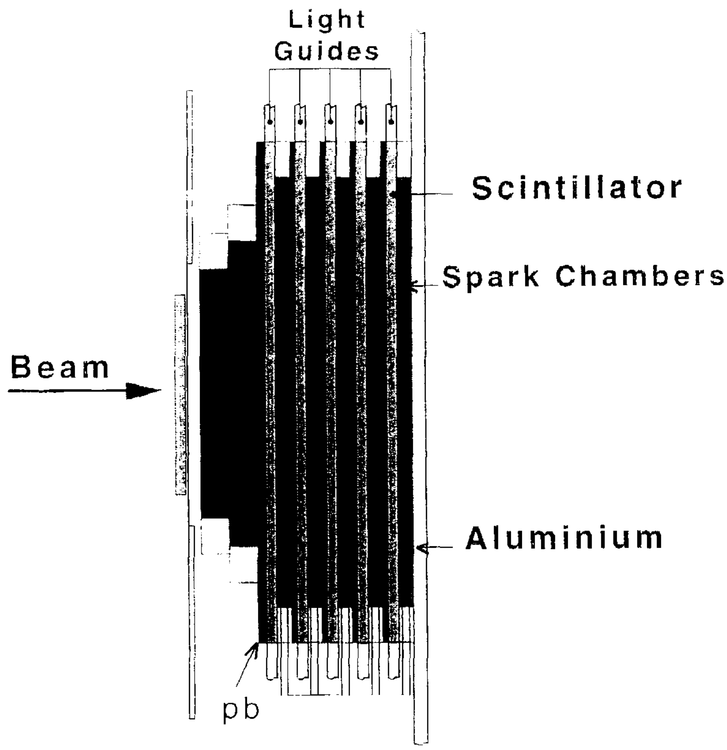


Fig. 2.3: The electron detector [5] consisting of five elements, each one being made of a lead-layer followed by a plastic scintillation counter and a two-gap spark chamber.

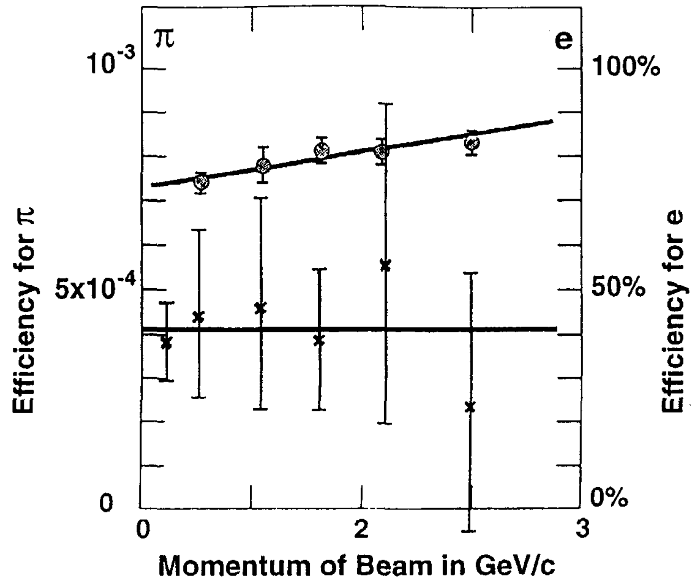


Fig. 2.4: The π (left scale) and e (right scale) efficiencies achieved with the set-up shown in Fig. 2.3 [5].

A crucial point of the research work at CERN was the simultaneous investigation, in addition to the (e^+e^-) pairs, of the $(\mu^+\mu^-)$ channel. As will be discussed below, these are experimental steps essential to the quest of the leading idea: the search for a new lepton carrying its own leptonic number.

As reported in our 1967 proposal to INFN, we were perfectly aware of the fact that, if a new lepton heavier than the muon (we had fixed its mass at the 1 GeV level) existed, this could have been produced in hadronic interactions, via time-like photons, but never seen because it would have decayed in a time interval as short as 10^{-11} sec. Notice that for this Heavy Lepton there could be no production process like $\pi \rightarrow \mu$, but only production via time-like photons. So, the crucial point was, first to study the abundance of time-like photons in hadronic interactions, and then to observe the typical signature of the Heavy Lepton decay, i.e. $(e\mu)$ pairs. The hadronic background had to be reduced in favour of electrons and muons in order to allow the $(e\mu)$ "signature" to be detected. Figures 2.5 and 2.6 are the results of many years of work started in 1960 [4-17]. The first results were published in 1963 and referred to the (e^+e^-) channel in $(\bar{p}p)$ annihilation [11-12].

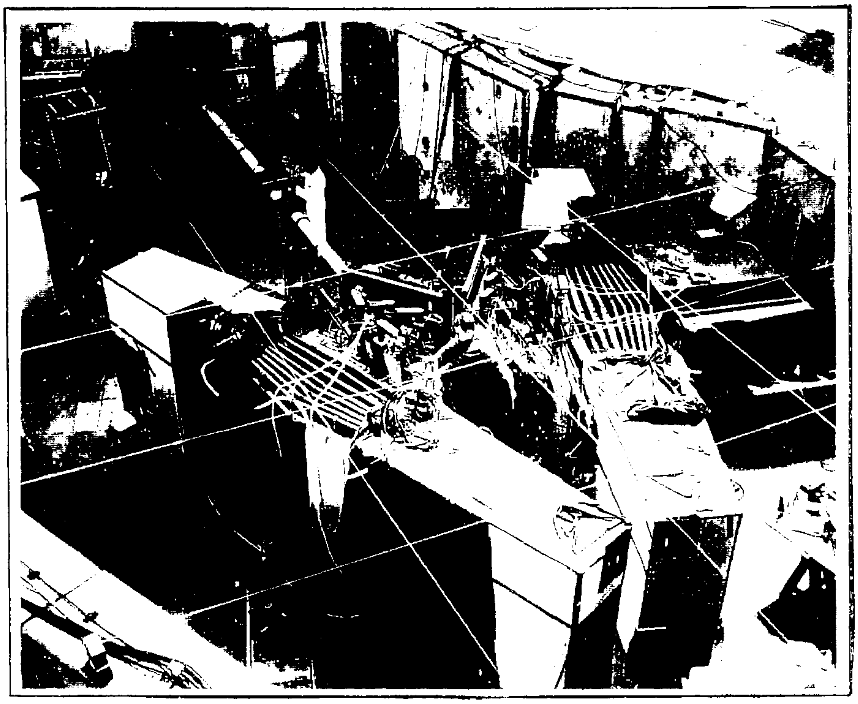


Fig. 2.5: General view of the experimental apparatus installed at the CERN PS to study the production of time-like photons yielding (e^+e^-), ($\mu^+\mu^-$) and ($e^\pm\mu^\mp$) pairs in ($\bar{p}p$) annihilation [11-14].

Fig. 2.6: General view of the experimental apparatus installed at the CERN PS to study the production of time-like photons in ($\pi^- p$) interactions [15-17].

If in the time-like region the proton were point like, this reaction would have been a powerful source of time-like photons. The investigation of the proton form-factor in the time-like region was therefore important. Figure 2.7a shows the first page of our 1963 paper [11].

Volume 5, number 3 PHYSICS LETTERS 1 July 1963

SEARCH FOR TIME-LIKE STRUCTURE OF THE PROTON

M. CONVERSI *, T. MASSAM, Th. MULLER ** and A. ZICHICHI
CERN, Geneva

Received 5 June 1963

While the electromagnetic structure of the proton has been widely investigated for space-like four-momentum transfers through electron-proton scattering experiments, no information is available as yet on the proton structure in the time-like region. We report here the results of a search for the process:

$$\bar{p} + p \to e^- + e^+ , \qquad (1)$$

the rate of which depends on the unknown time-like form factors. The negative result of the experiment places an upper limit to the cross section for reaction (1), thus yielding evidence against a "point-like" proton in the time-like region.

The physical significance of an experimental study of process (1) and its connection with the intrinsic properties of the reacting particles have recently been pointed out by Zichichi et al. [1]. The cross section can be unambiguously predicted for a point-like proton. At an antiproton momentum of 2.5 GeV/c its value is $\sim 0.25\ \mu$b.

The experiment was carried out at the CERN Proton Synchrotron with the apparatus *** sketched in fig. 1. The beam conditions and the geometry were chosen to maximise the rate of events from reaction (1). Consequently an antiproton momentum of 2.5 GeV/c with $\pm$ 1% momentum spread was chosen. The corresponding laboratory momenta for the secondary particles of a two-body process such as (1), were defined by the geometry of our apparatus to be in the range of 1.0 to 2.6 GeV/c.

Antiprotons from a partially separated beam **** enter (fig. 1) the cylindrical polyethylene target after crossing the monitoring plastic scintillators A and B and the anticoincidence counter D. D is a C_2H_4 gas Čerenkov counter sensitive to pions and lighter particles but not to $\bar{p}$ of 2.5 GeV/c momentum. Incident $\bar{p}$ are defined by an anticoincidence pulse $AB\bar{D}$.

The counters H consist of scintillator-Pb-scintillator sandwiches which form a "veto-house" around the target. The veto-house is sensitive to both charged particles and γ rays. It covers the whole solid angle not subtended by the two spark chambers, SC1, SC2, thus protecting against multi-pion events.

The essential part of the apparatus is a system of two similar telescopes. It is designed to accept the electron pair from process (1), while providing an efficient rejection of unwanted processes. Each telescope consists of three components:

i) an eight gap, thin foil spark chamber which allows kinematical reconstruction;

ii) counter M which is used to accept single

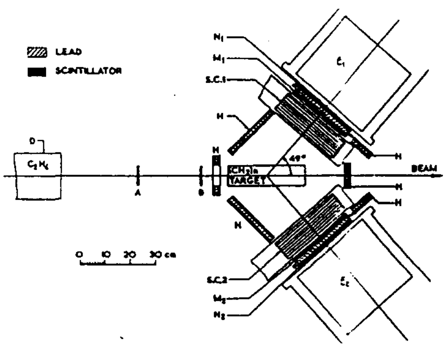


Fig. 1. Experimental layout. Plane view: D: [illegible] atm C_2H_4 Čerenkov counter; A, B: 1 cm thick, 8 cm diameter plastic scintillator, beam-defining counters; H: system of anticoincidence counters forming the "veto-house". They are made of two pieces of 1 cm plastic scintillator (seen by the same photomultipliers) with 1 cm lead in between; S.C.: 8 gap 0.025 mm Al foil spark chambers: M_1, M_2, N_1, N_2: 1 cm thick, 28 cm diameter plastic scintillators; $\check{C}_1$, $\check{C}_2$: lead-glass total absorption Čerenkov counters, 35 cm diameter, 30 cm thick ($\sim$ 8 radiation lengths).

* CERN Visiting Scientist, on leave of absence from the University of Rome, Italy.
** On leave from the Centre National de la Recherche Scientifique and Institut de Recherches Nucléaires, Strasbourg, France.
*** A more detailed description of the apparatus and of its performance will be given elsewhere.
**** This beam contained approximately equal numbers of $\bar{p}$ and π^- mesons. The $\bar{p}$ rate was about $10^3\ \bar{p}$/sec.

195

Fig. 2.7a: Front page of ref. 11 where the first evidence – using the e^+e^- channel – for the EM structure of the proton in the time-like region was presented.

Proceedings of the International Conference on "High-Energy Physics"
Dubna, USSR, 5-15 August 1964 (Atomizdat, Moscow, 1966), Vol. I, 857

[redacted]

PROTON ANTIPROTON ANNIHILATION INTO MUON PAIR

M. Conversi, T. Massam, Th. Muller, M. Schneegans and A. Zichichi
CERN, Geneva, Switzerland
(Presented by A. ZICHICHI)

The experiment I wish to talk about refers to the study of the process:

$$\bar{p}+p\rightarrow\bar{\mu}+\mu.$$

As is well known the interest of this experiment is twofold:
i) determination of the electromagnetic structure of the proton in the time-like region;
ii) check of the equality of the electromagnetic properties of the muon and the electron for time-like momentum transfers.

The experiment has been performed at CERN, using the new high intensity separated $\bar{p}$-beam [1] whose characteristics are probably worth recording:
with 50% of the total circulating proton beam of the CERN Proton-Syncrotron (which has been during the last week 10^{12} protons/pulse) we get 50000 $\frac{\bar{p}}{burst}$ with a π-contamination: $\frac{\pi}{\bar{p}}=3.5$; 250 m sec. spilling time and

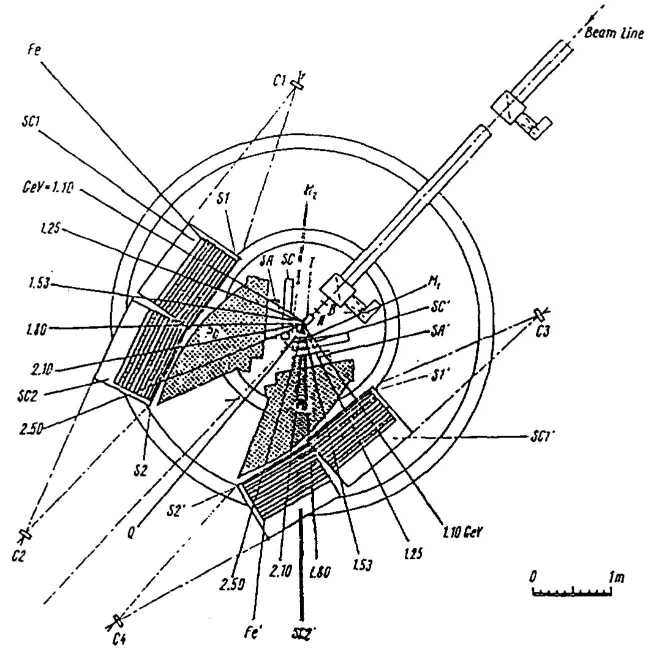


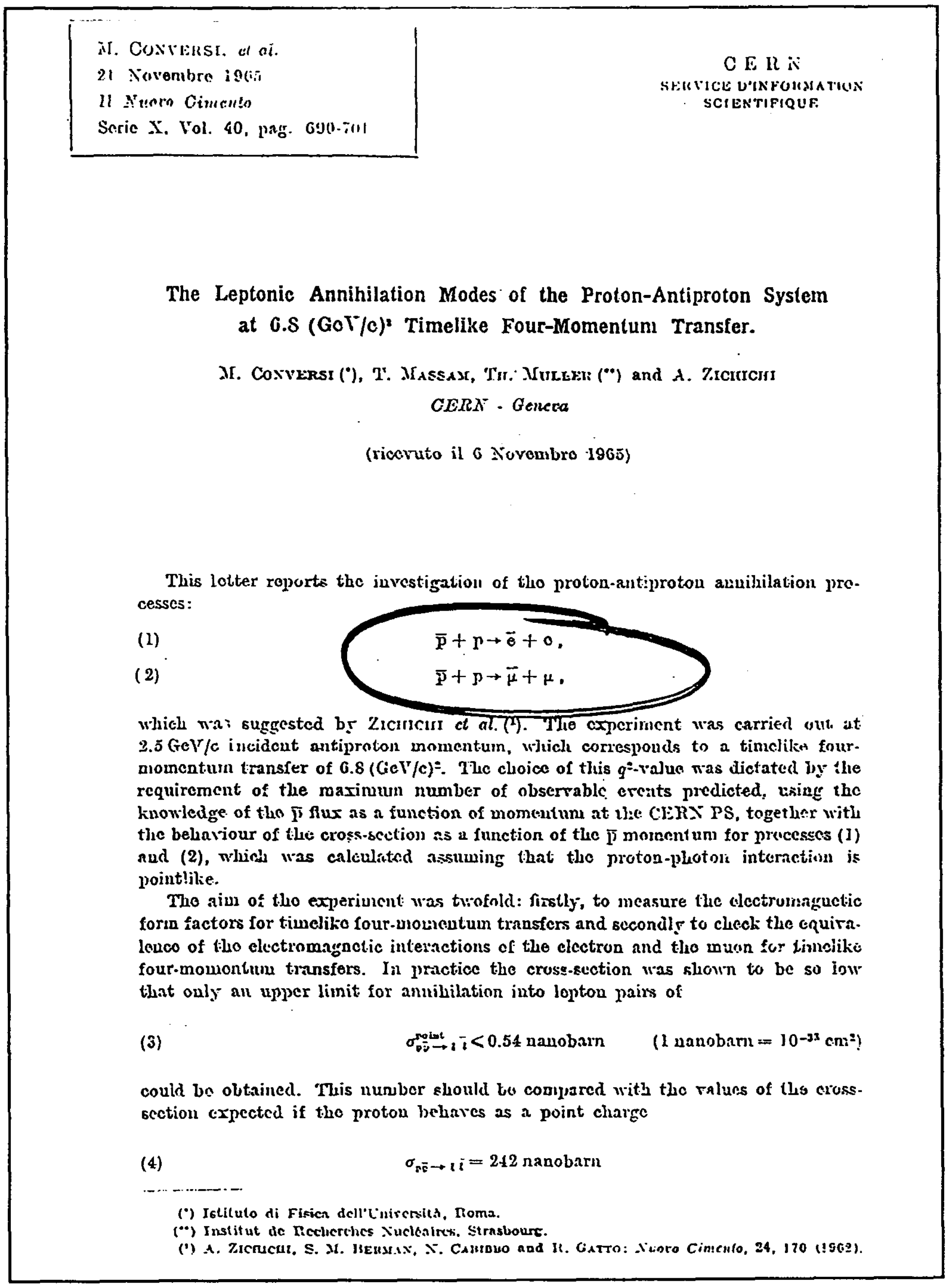
Fig. 1. Experimental set-up.

895

Fig. 2.7b: Front page of ref. 13 where the results on $\bar{p}p\rightarrow\mu^+\mu^-$ are presented.

Notice that we used for this search the already described "pre-shower" technique coupled with a pair of total absorption lead-glass Čerenkov counters.

One year later we presented in Dubna our results with the $(\mu^+\mu^-)$ channel [13]. Figure 2.7b shows the first page of our contribution, with a sketch of the $(\mu^+\mu^-)$ set-up. The results with simultaneous detection of (e^+e^-) and $(\mu^+\mu^-)$ pairs were published a year later (1965) [14]. Figure 2.8 shows the front page of this paper.



M. CONVERSI, *et al.*
21 Novembre 1965
Il Nuovo Cimento
Serie X, Vol. 40, pag. 690-701

CERN
SERVICE D'INFORMATION SCIENTIFIQUE

The Leptonic Annihilation Modes of the Proton-Antiproton System at 6.8 (GeV/c)² Timelike Four-Momentum Transfer.

M. CONVERSI (*), T. MASSAM, TH. MULLER (**) and A. ZICHICHI
CERN - Geneva

(ricevuto il 6 Novembre 1965)

This letter reports the investigation of the proton-antiproton annihilation processes:

(1) $\bar{p} + p \to \bar{e} + e\,,$

(2) $\bar{p} + p \to \bar{\mu} + \mu\,,$

which was suggested by ZICHICHI *et al.* (¹). The experiment was carried out at 2.5 GeV/c incident antiproton momentum, which corresponds to a timelike four-momentum transfer of 6.8 (GeV/c)². The choice of this q^2-value was dictated by the requirement of the maximum number of observable events predicted, using the knowledge of the $\bar{p}$ flux as a function of momentum at the CERN PS, together with the behaviour of the cross-section as a function of the $\bar{p}$ momentum for processes (1) and (2), which was calculated assuming that the proton-photon interaction is pointlike.

The aim of the experiment was twofold: firstly, to measure the electromagnetic form factors for timelike four-momentum transfers and secondly to check the equivalence of the electromagnetic interactions of the electron and the muon for timelike four-momentum transfers. In practice the cross-section was shown to be so low that only an upper limit for annihilation into lepton pairs of

(3) $\sigma^{\text{point}}_{p\bar{p}\to l\bar{l}} < 0.54$ nanobarn (1 nanobarn $= 10^{-33}$ cm²)

could be obtained. This number should be compared with the values of the cross-section expected if the proton behaves as a point charge

(4) $\sigma_{p\bar{p}\to l\bar{l}} = 242$ nanobarn

(*) Istituto di Fisica dell'Università, Roma.
(**) Institut de Recherches Nucléaires, Strasbourg.
(¹) A. ZICHICHI, S. M. BERMAN, N. CABIBBO and R. GATTO: *Nuovo Cimento*, 24, 170 (1962).

Fig. 2.8: Front page of ref. 14 on the leptonic $(e^+e^-, \mu^+\mu^-)$ annihilation modes of $(\bar{p}p)$ in the time-like region.

The experimental investigation on the proton form-factor in the time-like region is a basic one in its own right; it supplements the information obtained by R. Hofstadter in the space-like region. For the Heavy Lepton search, it gave two signals: (i) the $(e\mu)$ pair technology worked as expected: in fact the enormous background had indeed been perfectly mastered; (ii) the primary production process for the time-like photon could not be $(\bar{p}p)$.

Our result established the non-point-like behavior of the proton in the time-like region. We proved that the cross section was 500 times lower than the expected point-like value. Thus, for practical purposes, there could not be $(e^{\pm}\mu^{\mp})$ pairs, not because there was no production of a Heavy Lepton carrying its own leptonic number, but because

$$\frac{\sigma\left(\bar{p}p \rightarrow \begin{Bmatrix} \rightarrow e^+e^- \\ \rightarrow \mu^+\mu^- \end{Bmatrix}\right)^{\text{time-like structure}}}{\sigma\left(\bar{p}p \rightarrow \begin{Bmatrix} \rightarrow e^+e^- \\ \rightarrow \mu^+\mu^- \end{Bmatrix}\right)^{\text{point-like}}} \leq \frac{1}{500} \cdot$$

Hence there were no time-like photons available for its production. As originally pointed out by V.F. Weisskopf [40], the search for a new Heavy Lepton different from the known ones was outside the theoretical framework of that time, therefore a powerful set-up able to detect simultaneously electrons and muons had to be justified on the basis of accepted standard physics. For example the study of the electromagnetic (EM) structure of the proton in the time-like region was along this line [11-14]. The present status of this physics — 30 years later — is shown in Figure 2.9. Another example of "standard" physics is the $(\omega-\phi)$ mixing investigated using the (e^+e^-) channel alone, as reported in Figure 2.10 [15-17]. These are examples of the results obtained using the first large solid angle set-up able to detect simultaneously

$$\left\{ \begin{array}{l} (e^+e^-) \\ (\mu^+\mu^-) \\ (e^{\pm}\mu^{\mp}) \end{array} \right.$$

pairs produced in hadronic processes.

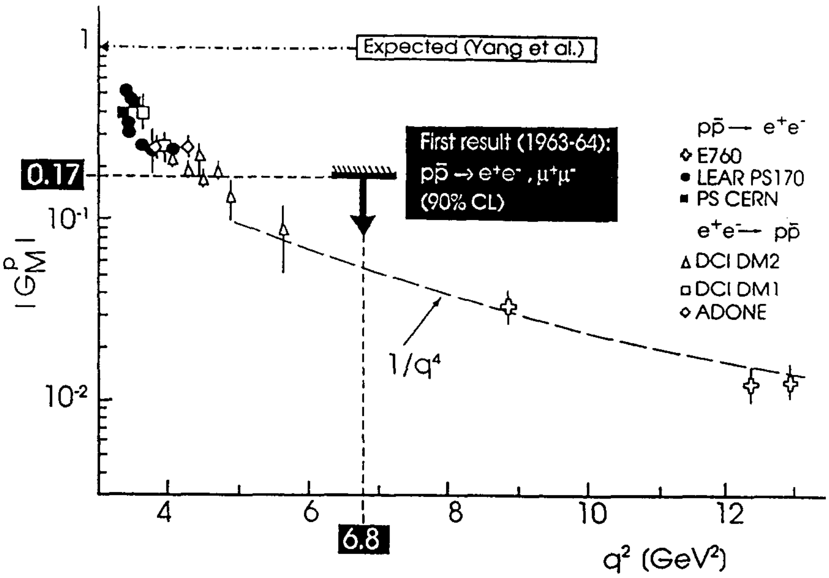


Fig. 2.9: The present status of the time-like EM form factor of the proton 30 years after the first evidence [11-14] by the Bologna-CERN group.

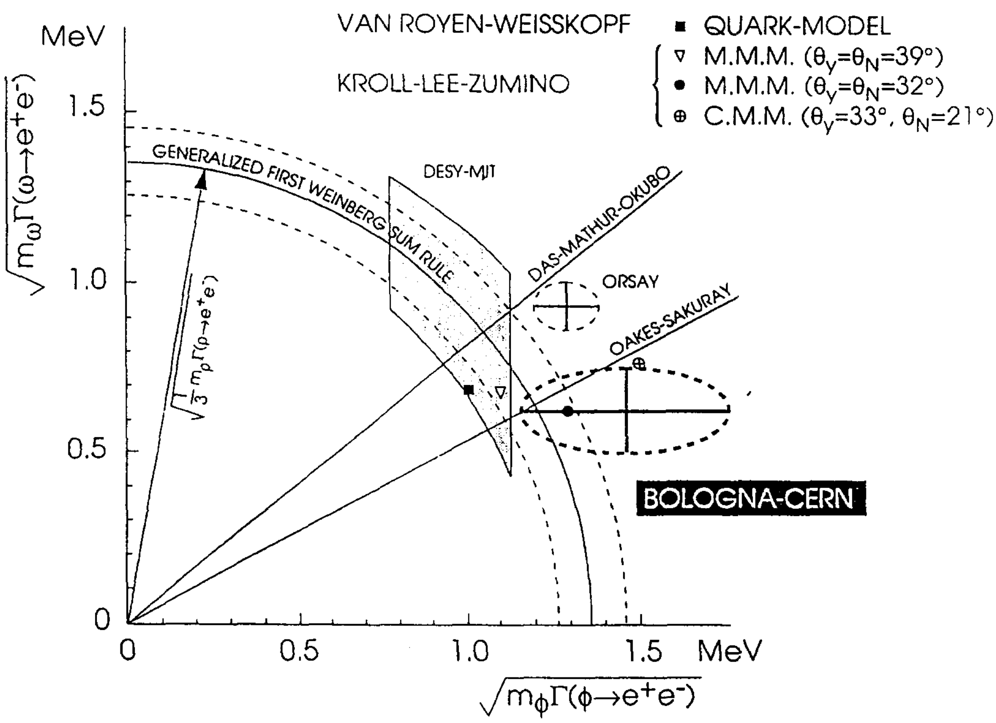


Fig. 2.10: The (ω-ϕ) mixing: the Bologna-CERN result [15-17] compared with the various theoretical expectations.

3 Excited Leptons (e^*, μ^*) and Long Lived Heavy Muons (1960-1970)

To the best of our knowledge, during 1960-1970 nowhere but in the BCF group: 1) the idea of a Heavy Lepton with its own neutrino was seriously studied 2) nor the way to look for it was investigated, worked out with a definite experimental proposal, 3) and proved to work.

The interest in Heavy Leptons, at that time, was very weak. The theoretical trend was "there are too many leptons". Before the discovery $\nu_\mu \neq \nu_e$, Leon van Hove, at CERN, was saying: "Nature cannot be so stupid to have two neutrinos to do the same thing". When Lederman-Schwartz-Steinberger discovered that there were two neutrinos, the only Heavy Leptons considered worthy of some attention were of the type excited electrons (e^*) and/or muons (μ^*). None of these carries a new lepton number.

These excited states were expected to decay in the known leptons plus a γ:

$$\begin{aligned} e^* &\to e\gamma \\ \mu^* &\to \mu\gamma. \end{aligned}$$

In order to recall the theoretical and experimental thinking of that time, let me show the first page of a theoretical paper [41] by Francis Low (Figure 3.1), where the heavy electrons and muons were theoretically investigated, and the first page of an experimental paper [42] on a search for heavy stable muons by Martin Perl and collaborators (Figure 3.2) where heavy stable muons were searched for with a single-arm spectrometer (Figure 3.3).

Even later, when "theoretically wanted" Heavy Leptons came, in the attempt to avoid divergent neutrino cross sections, the Heavy Leptons advocated were again electron-like (E) and muon-like (M) [43].

The distinction with the known "electron" and "muon" was the assignment of opposite electron and muon lepton numbers, respectively. The positively charged heavy electron (E^+) was given the positive lepton number identical to the lepton number of the known negative electron. Likewise, the positively charged heavy muon (M^+) was given the positive lepton number identical to the lepton number of the known negative muon. All this is shown in Figure 3.4.

VOLUME 14, NUMBER 7 PHYSICAL REVIEW LETTERS 15 FEBRUARY 1965

HEAVY ELECTRONS AND MUONS*

F. E. Low
Physics Department and Laboratory of Nuclear Science,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 15 January 1965)

The quantum electrodynamics (QED) of electrons, muons, and photons has so far been found to be in agreement with experiment.[1-3] This agreement has usually been expressed in terms of a fictitious "radius" down to which the theory has been found to hold.[4] In this language, an experimental deviation from the theory would reveal a "cutoff," or perhaps even a "cut-on."

A much more natural theoretical way of describing a breakdown of QED (and a more likely way for such a breakdown to occur) is in terms of coupling of electrons and muons to other particles.[5] This is consistent with the ideas of ordinary quantum field theory (or S-matrix theory), and is the only theoretically consistent way that we have to describe a real breakdown. In this language, continued experimental confirmation of the predictions of QED would be expressed in terms of upper limits to the coupling strengths and lower limits to the masses of hypothetical particles coupled to electrons, muons, and photons.

This point of view suggests a class of experiments which would search directly for such particles by looking for correlations in the mass spectrum of groups of final electrons and photons just as is done in strong-interaction physics. These experiments would be direct checks of QED. They would in many cases have the additional advantage of isolating the electrodynamic system from the nuclear target without the necessity of waiting for storage rings.

We discuss briefly three possible ways in which a breakdown might occur in the physics of electrons. Evidently, all remarks apply equally well to muons, although the experimental problems in that case are much harder.

(1) The electron might be coupled to a heavy electron, e', with a magnetic coupling of the form

$$\lambda\bar{\psi}_{e'}\sigma_{\mu\nu}\psi_e f_{\mu\nu} + \text{H.c.} \qquad (1)$$

This is the most favorable case from the experimental point of view. Assuming a mass of the e' in the several hundred MeV range, existing experiments are consistent with a coupling strength $\lambda \sim e/m_{e'}$, provided a reasonable cutoff is assumed and provided the decays $K^{\pm} \to e'^{\pm} + \nu$ and $K^0 \to e'^{\pm} + \nu + \pi^{\mp}$ are moderately forbidden. Otherwise, we must have $m_{e'} > 500$ MeV. The interaction (1) is neither minimal nor renormalizable. It would presumably be the low-energy manifestation of a minimal, renormalizable interaction (necessarily involving other particles) which would provide an automatic cutoff.

The simplest reaction to produce the e' would be

$$p + e \to p + e' \quad \llcorner e + \gamma \;(\tau \sim 10^{-21}\,\text{sec}). \qquad (2)$$

The e' would be observed as a sharp missing-mass peak in the recoil proton energy and angle distribution. This would be direct experimental evidence of an excited state of the electron. It could also be observed directly in a mass plot of the final $e + \gamma$.

The e' could also be produced by photons in the reaction

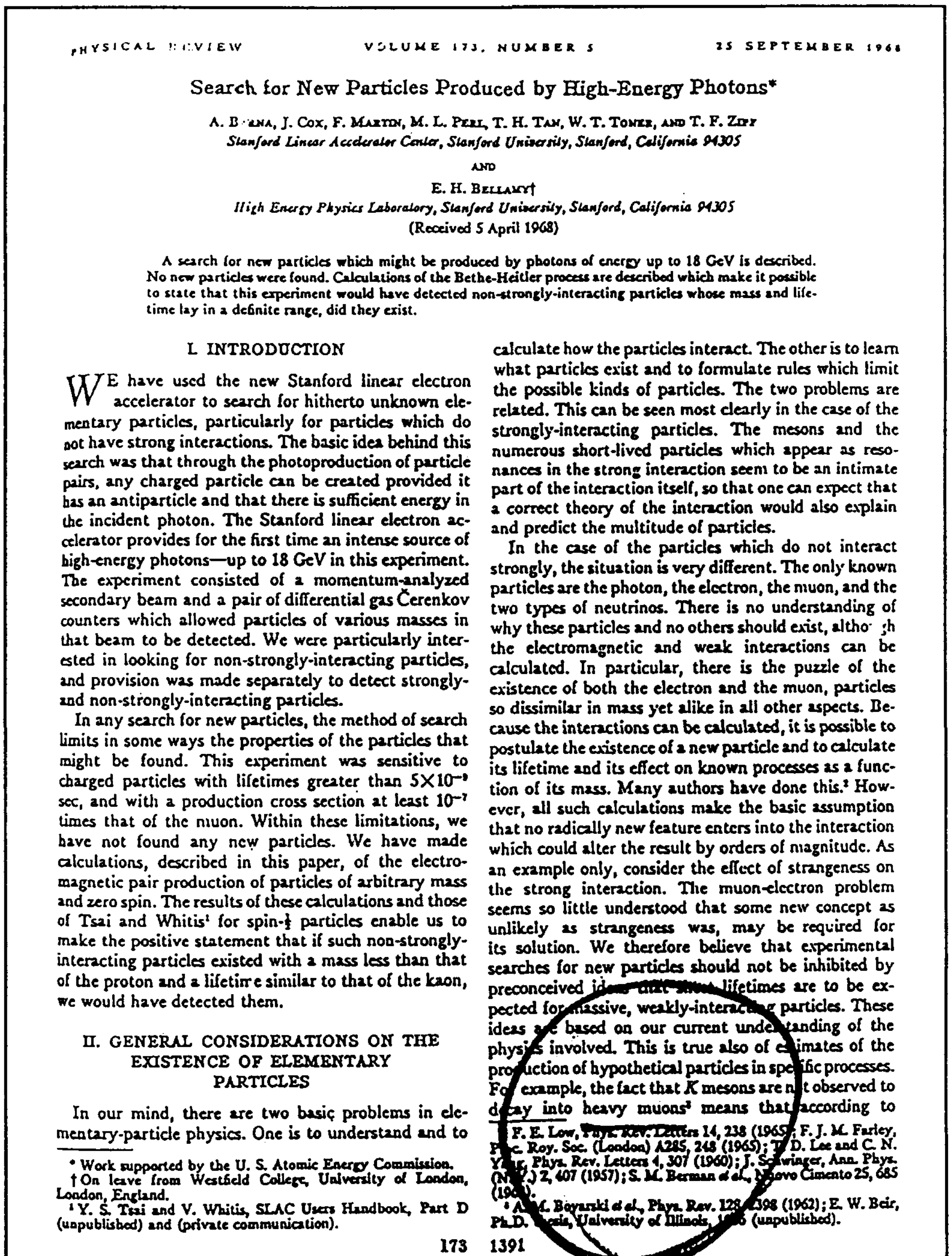
$$\gamma + p \to p + e + e' \quad \llcorner e + \gamma. \qquad (3)$$

If the photons are tagged for energy, the e' could again be observed as a missing mass. With untagged photons, one could still observe a threshold in the missing mass as a function of maximum photon energy, or else detect directly a peak in the e-γ mass spectrum. Depending on the precise experiment under consideration it might be advantageous to use a heavy target instead of hydrogen.

A further consequence of the existence of the e' (and of the minimal interactions coupling it to the electron) would be an anomalous Compton scattering of electrons and photons (at center-of-mass energies comparable to $m_{e'}$), as well as an anomalous electron-positron pair-production cross section at corresponding values of the electron-positron mass, possibly of the kind referred to in reference 3.

(2) The electron might be coupled to a boson,

Fig. 3.1: Front page of ref. 41, where the Heavy Leptons considered are only excited electrons (e^*) or muons (μ^*).


PHYSICAL REVIEW VOLUME 173, NUMBER 5 25 SEPTEMBER 1968

Search for New Particles Produced by High-Energy Photons*

A. B·ANA, J. COX, F. MARTIN, M. L. PERL, T. H. TAN, W. T. TONER, AND T. F. ZIPF
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

AND

E. H. BELLAMY†
High Energy Physics Laboratory, Stanford University, Stanford, California 94305

(Received 5 April 1968)

A search for new particles which might be produced by photons of energy up to 18 GeV is described. No new particles were found. Calculations of the Bethe-Heitler process are described which make it possible to state that this experiment would have detected non-strongly-interacting particles whose mass and lifetime lay in a definite range, did they exist.

I. INTRODUCTION

WE have used the new Stanford linear electron accelerator to search for hitherto unknown elementary particles, particularly for particles which do not have strong interactions. The basic idea behind this search was that through the photoproduction of particle pairs, any charged particle can be created provided it has an antiparticle and that there is sufficient energy in the incident photon. The Stanford linear electron accelerator provides for the first time an intense source of high-energy photons—up to 18 GeV in this experiment. The experiment consisted of a momentum-analyzed secondary beam and a pair of differential gas Čerenkov counters which allowed particles of various masses in that beam to be detected. We were particularly interested in looking for non-strongly-interacting particles, and provision was made separately to detect strongly- and non-strongly-interacting particles.

In any search for new particles, the method of search limits in some ways the properties of the particles that might be found. This experiment was sensitive to charged particles with lifetimes greater than 5×10^{-9} sec, and with a production cross section at least 10^{-7} times that of the muon. Within these limitations, we have not found any new particles. We have made calculations, described in this paper, of the electromagnetic pair production of particles of arbitrary mass and zero spin. The results of these calculations and those of Tsai and Whitis[1] for spin-½ particles enable us to make the positive statement that if such non-strongly-interacting particles existed with a mass less than that of the proton and a lifetime similar to that of the kaon, we would have detected them.

II. GENERAL CONSIDERATIONS ON THE EXISTENCE OF ELEMENTARY PARTICLES

In our mind, there are two basic problems in elementary-particle physics. One is to understand and to calculate how the particles interact. The other is to learn what particles exist and to formulate rules which limit the possible kinds of particles. The two problems are related. This can be seen most clearly in the case of the strongly-interacting particles. The mesons and the numerous short-lived particles which appear as resonances in the strong interaction seem to be an intimate part of the interaction itself, so that one can expect that a correct theory of the interaction would also explain and predict the multitude of particles.

In the case of the particles which do not interact strongly, the situation is very different. The only known particles are the photon, the electron, the muon, and the two types of neutrinos. There is no understanding of why these particles and no others should exist, although the electromagnetic and weak interactions can be calculated. In particular, there is the puzzle of the existence of both the electron and the muon, particles so dissimilar in mass yet alike in all other aspects. Because the interactions can be calculated, it is possible to postulate the existence of a new particle and to calculate its lifetime and its effect on known processes as a function of its mass. Many authors have done this.[2] However, all such calculations make the basic assumption that no radically new feature enters into the interaction which could alter the result by orders of magnitude. As an example only, consider the effect of strangeness on the strong interaction. The muon-electron problem seems so little understood that some new concept as unlikely as strangeness was, may be required for its solution. We therefore believe that experimental searches for new particles should not be inhibited by preconceived ideas that short lifetimes are to be expected for massive, weakly-interacting particles. These ideas are based on our current understanding of the physics involved. This is true also of estimates of the production of hypothetical particles in specific processes. For example, the fact that K mesons are not observed to decay into heavy muons[3] means that according to

* Work supported by the U. S. Atomic Energy Commission.
† On leave from Westfield College, University of London, London, England.
[1] Y. S. Tsai and V. Whitis, SLAC Users Handbook, Part D (unpublished) and (private communication).
[2] F. E. Low, Phys. Rev. Letters 14, 238 (1965); F. J. M. Farley, Proc. Roy. Soc. (London) A285, 248 (1965); T. D. Lee and C. N. Yang, Phys. Rev. Letters 4, 307 (1960); J. Schwinger, Ann. Phys. (N.Y.) 2, 407 (1957); S. M. Berman *et al.*, Nuovo Cimento 25, 685 (1962).
[3] A. M. Boyarski *et al.*, Phys. Rev. 128, 2398 (1962); E. W. Beir, Ph.D. thesis, University of Illinois, 1966 (unpublished).

173 1391

Fig. 3.2: Front page of ref. 42 on the experimental search for heavy stable muons in photoproduction processes at Stanford.

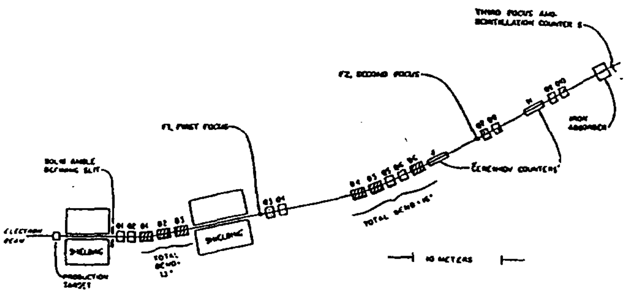


FIG. 6. Schematic diagram of the experiment.

a scintillation counter S was placed behind an iron absorber 5 ft thick. Weakly-interacting particles would have the signature HJS. The experiment consisted of fixing the beam momentum and varying the pressure of the gas in the Čerenkov counters in order to sweep through a range of masses, while recording HJ and HJS. The known particles provide indications of the operation of the system. In particular, the muons and pions provide a basic normalization of the experiment which does not depend upon the acceptance of the transport system or the efficiencies of the Čerenkov counters. Since the muon yield has been measured separately[14] and is understood theoretically, the muon normalization is particularly useful.

B. Apparatus

The target in which the secondaries were produced consisted of 3.6 radiation lengths of beryllium followed by ten radiation lengths of water-cooled copper, a further foot of beryllium, and ten radiation lengths of lead. The production of weakly-interacting particles in this target is adequately described by the calculations given in Sec. IV for production on beryllium, since there is very little particle production beyond the first 3.6 radiation length. The rest of the target was used to absorb the power (up to 20 kW) in the electron beam, and to reduce the number of electrons in the secondary beam to a few percent of the muon flux. Negatively charged secondaries from this target consist mainly of muons and pions. The composition of the beam at momenta of 5.0 and 9.0 GeV/c was measured to be approximately 70% muons, 30% pions.

The beam transport system shown in Fig. 6 was designed and built to provide a muon beam[15] for a muon-scattering experiment. It produces an almost dispersion-free beam in the Čerenkov counters with a diameter of less than 10 cm, a divergence of less than 4 mrad, and a momentum bite of ±1.5%. The second focus F2 is 212 ft from the target. Counter J was 19 ft upstream from F2; counter H was 33 ft downstream from F2. The scintillation counter S was at the third focus, 63 ft downstream from F2.

The differential Čerenkov counters were modeled closely on a counter described by Kycia and Jenkins.[16] The present counters are designed to operate at pressures up to 960 psi. In this experiment, CO_2 was used at pressures up to 600 psi. Figure 7(a) is a schematic diagram of a counter. The radiator region is 80 in. long and the counter is designed to be used with beams up to 12.5 cm in diam. Čerenkov light from particles of the correct velocity is focused onto an annular ring aperture. The aperture is split in two across a diameter and the light from each half is collected separately onto two phototubes. A coincidence is required for a particle to be counted. The quartz windows are arranged so that a stray track in the general direction of the beam cannot go through both. Light which falls near, but not on, the annular aperture is reflected from a spherical mirror in which the aperture is set and is collected onto a phototube put in anticoincidence. Without this, a particle of the wrong velocity at an angle to the beam could be counted, as illustrated in Fig. 7(b). The width of the annular aperture was chosen to give an angular acceptance of ±10 mrad about a mean Čerenkov angle of 75 mrad. This dominated the mass resolution of the counters, giving $\Delta m/m \sim 0.075(p^3/m^2)\times 10^{-4}$, where m is the mass and p is the momentum of the particle. This resolution was adequate to separate out the peaks of the known particles, but allowed a finite mass range to be covered at each pressure setting and sufficient tolerance so that we did not have difficulty in operating the two counters together. The pressure vessels of the two counters were connected together by a common feed pipe. We found that no special precautions were necessary to make the mass peaks coincide in the two counters, although the counters were located out of doors and the ambient temperature varied from 5°C at night to 27°C during the day.

Block diagrams of the electronic circuits are shown in Fig. 8. The three tubes on each counter were fed through

[14] A. Barna *et al.*, Phys. Rev. Letters 18, 360 (1967).

[15] SLAC Users Handbook, Part D (unpublished); Stanford Linear Accelerator Center Laboratory Report No. SLAC-PUB 434 (unpublished); see also Ref. 13.

[16] T. F. Kycia and E. W. Jenkins, *Nuclear Electronics* (International Atomic Energy Agency, Vienna, 1963).

Fig. 3.3: The page of ref. 42 showing the schematic diagram of the single-arm spectrometer used in the Stanford experiment.

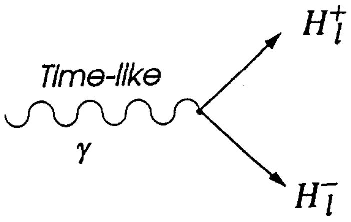
$$
\begin{array}{llll}
E^+ & \rightarrow \nu_e + e^+ + \nu_e & E^- & \rightarrow \bar{\nu}_e + e^- + \bar{\nu}_e \\
 & \rightarrow \nu_\mu + \mu^+ + \nu_e & & \rightarrow \bar{\nu}_\mu + \mu^- + \bar{\nu}_e \\
 & \rightarrow \nu_e + \text{Hadrons} & & \rightarrow \bar{\nu}_e + \text{Hadrons} \\
 & & & \\
M^+ & \rightarrow \nu_\mu + \mu^+ + \nu_\mu & M^- & \rightarrow \bar{\nu}_\mu + \mu^- + \bar{\nu}_\mu \\
 & \rightarrow \nu_\mu + e^+ + \nu_e & & \rightarrow \bar{\nu}_\mu + e^- + \bar{\nu}_e \\
 & \rightarrow \nu_\mu + \text{Hadrons} & & \rightarrow \bar{\nu}_\mu + \text{Hadrons}
\end{array}
$$

Fig. 3.4: The decay modes of the "theoretically wanted" electron-like (E) and muon-like (M) Heavy Leptons.

Heavy Leptons carrying their own lepton number, different from the electron and muon ones, were not within the theoretical framework of that time and, except for our search, also outside the experimental way of thinking.

4 Design Considerations for our Proposal

Suppose you had the idea of a new lepton (in addition to the known ones: e, μ) and suppose that this type of lepton is much heavier than the known ones — say 1 GeV — and carries its own leptonic number. Question 1: What would be the best production process? Question 2: How would it decay? This type of lepton is supposed to be the least exotic particle. Therefore, it is like: a Standard Dirac Particle, insofar as its QED properties are concerned; and a Standard Fermi Particle, insofar as its weak properties are concerned. There is nothing unknown in the production and decay rates, if its mass is given. The best production process would be via time-like photons:



But a series of experiments carried out by us at CERN showed that "nucleons are very poor sources of time-like photons", as recalled once again in a paper [*Nuovo Cimento 43, 227 (1966)*] by T. Massam and myself.

Muons (the heaviest leptons known at that time) are very abundant in hadronic collisions. But a one GeV new lepton carrying its own leptonic number would have escaped detection in all hadronic experiments. Let me quote what has been written in the 1967 INFN proposal [2]. "If Heavy Leptons exist would they have been detected?" "... The lifetime of a Heavy Lepton with 1 GeV mass would be of the order of 10^{-11} sec and could never have been detected as a decaying particle ..." "Moreover the production of μ is copious only because of the fact that it is the decay product of the π. There is no equivalent mechanism for the production of a 1 GeV Heavy Lepton: in proton-machines they could only be produced in pairs via time-like photons, a process of which the low rate has already been discussed. Moreover the lack of stability of this particle is consistent with its apparent absence." Therefore, production and decay of a new sequential Heavy Lepton would be as follows.

i) Production: if a sequential Heavy Lepton exists, to search for it at hadron machines is hopeless. In fact, as we have seen in Section 2, it had been looked for at CERN where a powerful set-up for the detection of $(e^{\pm}\mu^{\mp})$ pairs was already working in 1964. The construction of this set-up started in the early sixties [40]. The production of time-like photons in hadronic collisions was found to be indeed very poor. The best way to produce Heavy Leptons was (and is) therefore via the reaction:

$$e^+e^- \to H_l^+ H_l^- .$$

ii) Decay: as the new Heavy Lepton is expected to be universally coupled to the known leptons, its decays will be:

$$H_l^{\pm} \longrightarrow \begin{cases} e^{\pm} + \nu_e + \nu_{H_l} \\ \mu^{\pm} + \nu_\mu + \nu_{H_l} \end{cases} .$$

Many years of experimental, technological and phenomenological research work brought us to the conclusion that the only way to detect this new sequential Heavy Lepton was via the acoplanar $(e^{\pm}\mu^{\mp})$ pairs produced in (e^+e^-) annihilations. But $e^+e^- \rightarrow e^{\pm}\mu^{\mp}\gamma$ will produce acoplanar $(e^{\pm}\mu^{\mp})$ pairs. Question 1: Is $e^+e^- \rightarrow e^{\pm}\mu^{\mp}$ possible? Question 2: Do radiative corrections really follow the "peaking approximation" (see Figure 4.1)? Question 3: Is QED correct at these high q^2-values? Question 4: What is the background from $e^+e^- \rightarrow$ hadrons $\rightarrow e^{\pm}\mu^{\mp}X$?

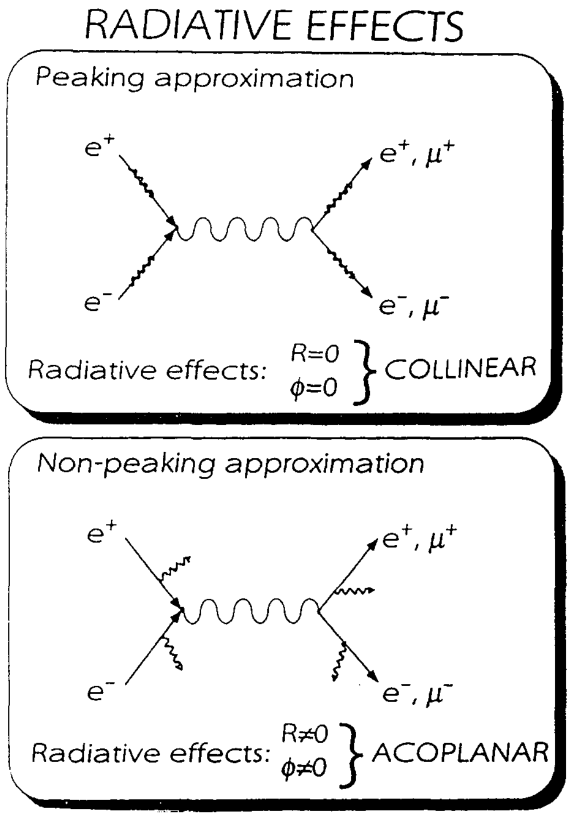


Fig. 4.1: Radiative effects with and without "peaking approximation" in (e^+e^-) annihilation [22]. R and ϕ are the acollinearity and acoplanarity angles, respectively. Obviously $\phi \neq 0$ implies $R \neq 0$, while the opposite is not true.

Moreover, in order to be sure that what is expected is indeed correctly observed in the experimental set-up, where acoplanar ($e^{\pm}\mu^{\mp}$) events have to be identified as a clear signature for the production of Heavy Lepton pairs, the proof is needed that the standard QED processes:

$$e^+e^- \to e^+e^-$$
$$e^+e^- \to \mu^+\mu^-$$

follow the theoretical QED predictions. This means a series of high-precision checks of QED in the same energy range. Therefore, the programme was very clear: the search for a new Heavy Lepton needed:

- the check of the validity of $e \neq \mu$ at high q^2-values;
- a detailed study of acoplanar radiative effects;
- high precision QED tests;
- the understanding of hadron production.

To detect ($e^{\pm}\mu^{\mp}$) pairs in an (e^+e^-) collider, a large solid angle detector is needed. This detector should be highly selective for electrons and muons, despite its large dimensions.

5 The BCF Proposal (1967), the Experiment and the First Results (1970)

As already pointed out earlier, the preparatory work started at CERN after the first high precision measurements of the muon (g–2) [3] with the invention of the "pre-shower" technique [4-7], and the construction of the large solid angle set-up for detection of ($e^{\pm}\mu^{\mp}$) pairs in hadronic collisions where time-like photons able to produce Heavy Lepton pairs were searched for [11-14]. All this work culminated in 1967 with the INFN proposal by the Bologna-CERN-Frascati group [2] to search for Heavy Leptons at ADONE. In Section 1 we have shown the front page of our proposal (Figure 1.1) and the page where the production and decay reactions were given (Figure 1.2). The comprehensive programme to study:

$$
\begin{aligned}
e^+e^- &\rightarrow e^+e^- \text{ or } \mu^+\mu^- \\
e^+e^- &\rightarrow e^\pm\mu^\mp \\
e^+e^- &\rightarrow h^+h^- + \text{anything} \\
e^+e^- &\rightarrow H_l^+H_l^- \rightarrow e^\mp\mu^\pm + \text{missing energy}
\end{aligned}
$$

needed a large solid angle detector specially designed for this purpose. The INFN Officials were asking for evidence that this type of large solid angle device could be built and could work as expected.

Our credentials were the CERN work on lepton-pair production in hadronic interactions.

On the basis of this work we could show that large solid angle detectors with high rejection power against different kinds of background had been built and proven to work in conditions worse than at Frascati. In fact, at CERN, the π-rejection needed at least three orders of magnitude to allow the identification of electrons and muons:

$$
\begin{aligned}
\pi / e &\leq 10^{-3} \\
\pi / \mu &\leq 10^{-3} .
\end{aligned}
$$

At Frascati the experimental conditions were expected to be much more favourable. Nevertheless, during the experiment (before the acoplanar (μe) method was shown to work), the scientific community in Frascati was divided. The majority was very much against both the experiment and the method. Everybody was saying that the search was going to be swamped by background: because in (e^+e^-) colliders there are plenty of electrons and spurious muons (from pion decays). The standard comment was: "Zichichi cerca farfalle", i.e. "Zichichi is looking for butterflies".

The perspective of the experimental apparatus [24], transverse to the colliding (e^+e^-) beam-line, is shown in Figure 5.1a. The corresponding picture of the apparatus is shown in Figure 5.1b. The top-view [18] is shown in Figure 5.2a and its corresponding picture in Figure 5.2b.

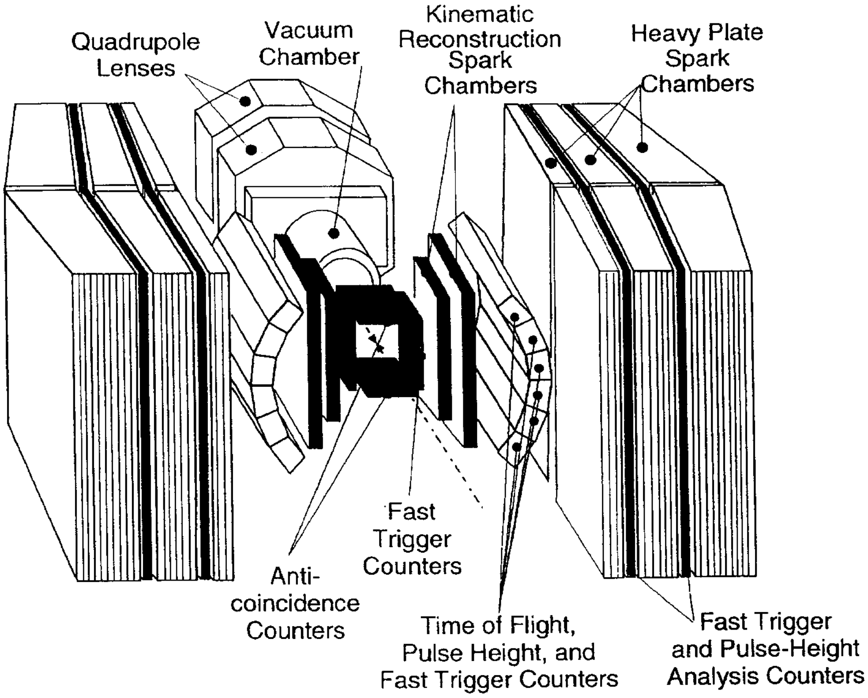


Fig. 5.1a: Perspective of the experimental apparatus used at ADONE [24], transverse to the (e^+e^-) beam-line.

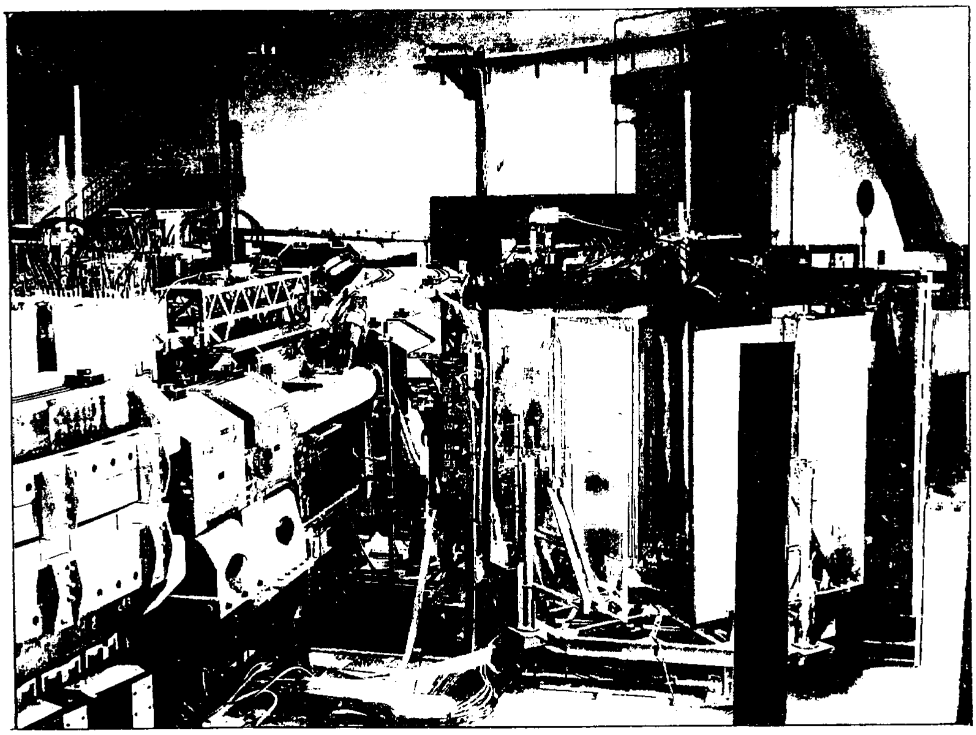


Fig. 5.1b: A photograph of the apparatus whose detailed drawing is in Fig. 5.1a.

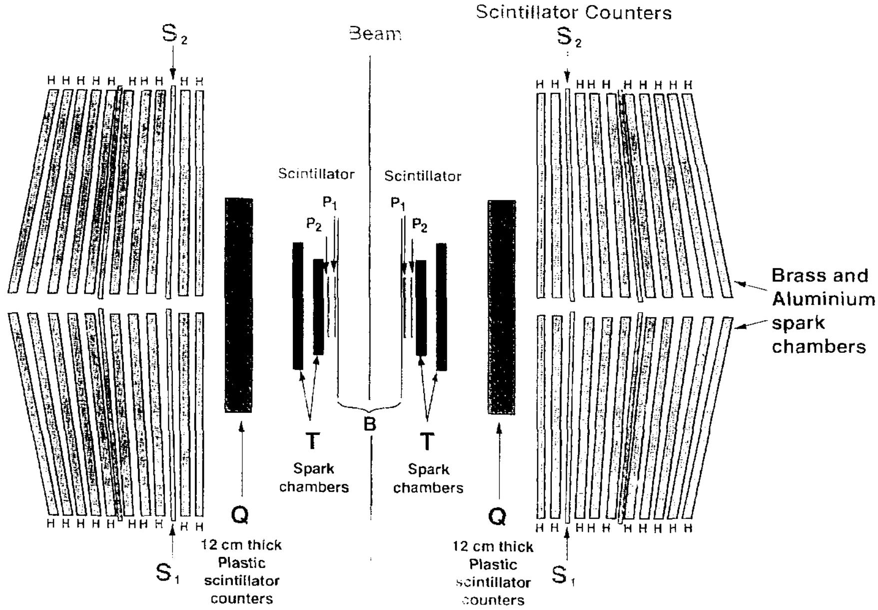


Fig. 5.2a: Top view of the ADONE apparatus [18].

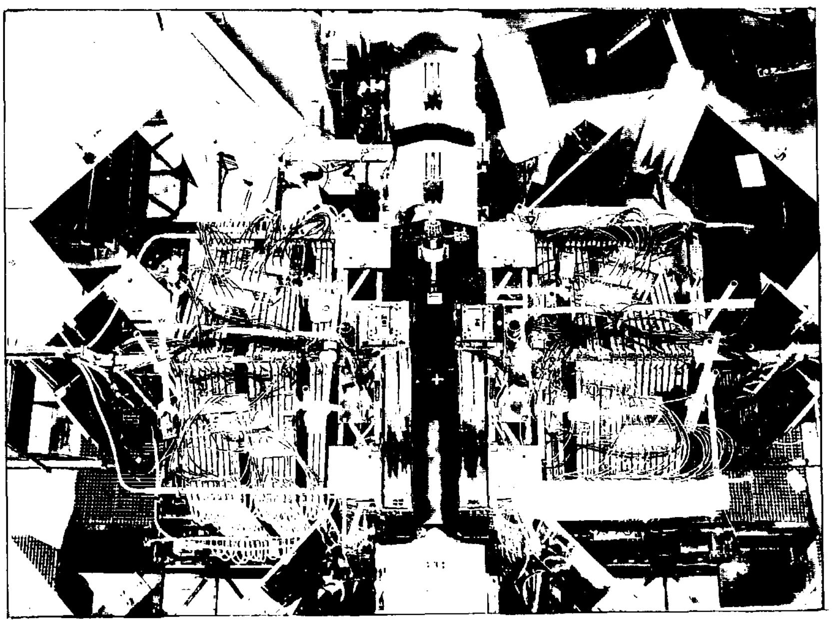


Fig. 5.2b: The photograph corresponding to the Fig. 5.2a.

The essential elements of the set-up were:

i) a system of high precision thin-plate spark chambers for kinematic reconstruction;

ii) a system of high resolution time-of-flight counters (TOF);

iii) a system of heavy-plate spark chambers.

Let me spend a few words on these essential elements.

The kinematic chambers provided a very clean peak at the vertex of the event thus rejecting a lot of unwanted background (Figure 5.3) [23].

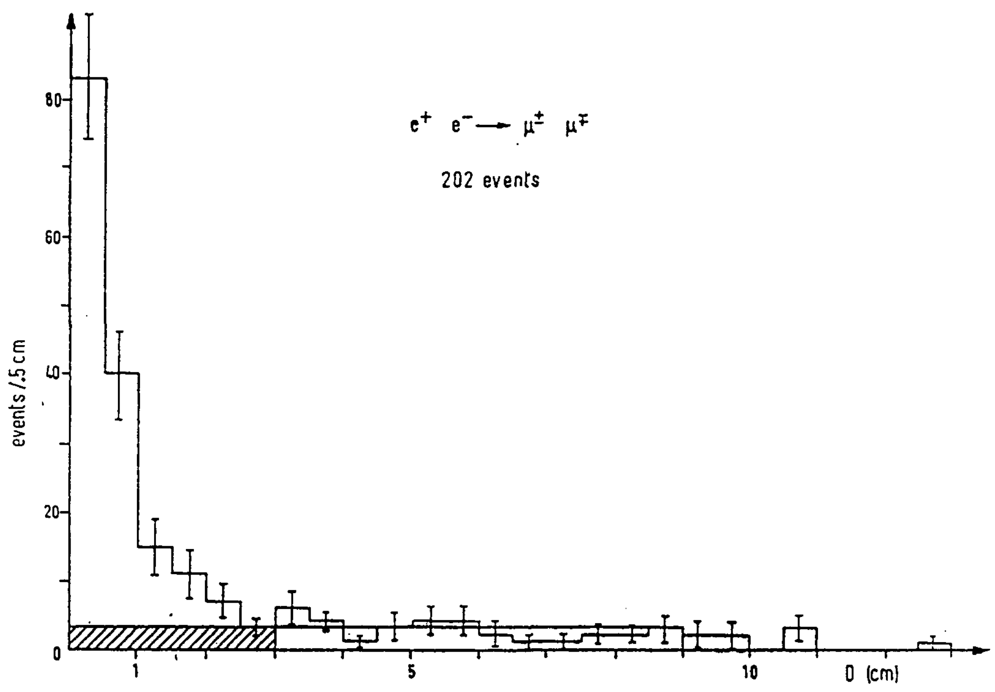


Fig. 5.3: Distribution of the minimum distance D between the beam axis and the reconstructed trajectory for ($\mu^{\pm}\mu^{\mp}$) pair events contaminated by cosmic-ray muons. The shaded area is our estimate of the cosmic-ray contribution in the selected ADONE events [23].

The thick plastic scintillation counters provided high precision TOF measurements with $\Delta T = (\pm\ 0.35)$ nsec (Figure 5.4). Notice that the system consisted of 24 counters and the relative timing could be done within 0.1 nsec (Figure 5.5) [10].

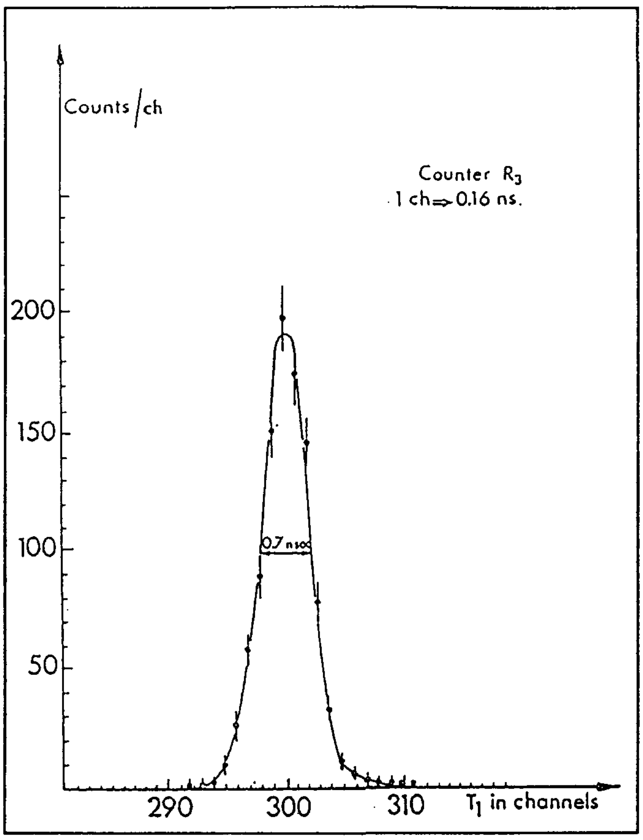


Fig. 5.4: Time-of-flight spectrum obtained using a relativistic pion beam, showing the achieved resolution [10]: $\Delta T = \pm 0.35$ nsec.

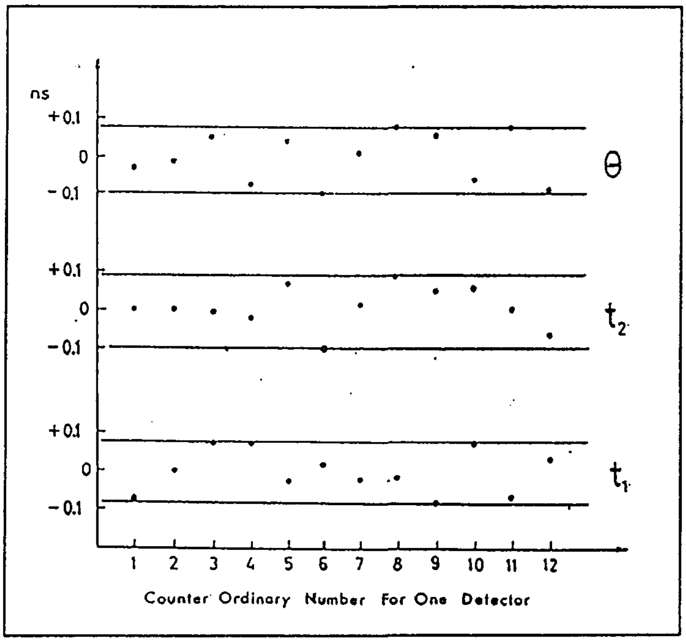


Fig. 5.5: Showing the accuracy (± 0.1 nsec.) of the relative timing amongst the various TOF counters [10].

An example of the value of this TOF system to reject cosmic muons is shown in Figure 5.6 [23]. Cosmic muons were at the 30% level, compared with the ADONE ($\mu^+\mu^-$) rate. The TOF system was able to reject this background very efficiently.

The heavy-plate spark chambers allowed a clear distinction between "e" and "μ" [23]. A typical (e^+e^-)-pair event is shown in Figure 5.7. A typical ($\mu^+\mu^-$)-pair event is shown in Figure 5.8.

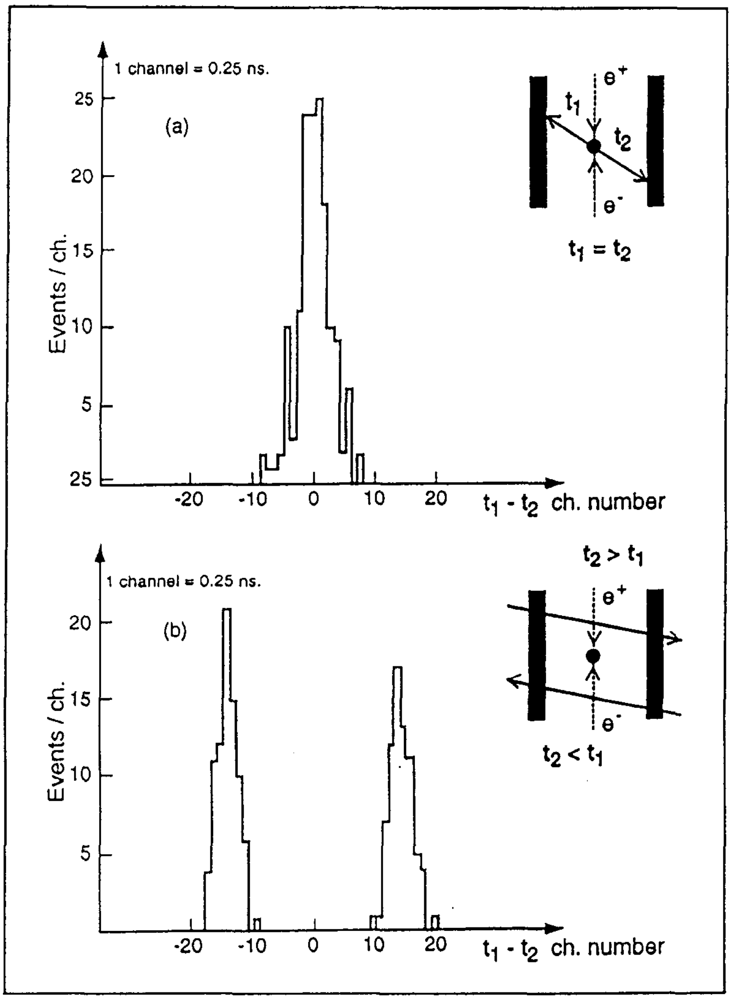


Fig. 5.6: Time-of-flight distribution for: a) selected ADONE events; b) cosmic rays with ADONE off [23].

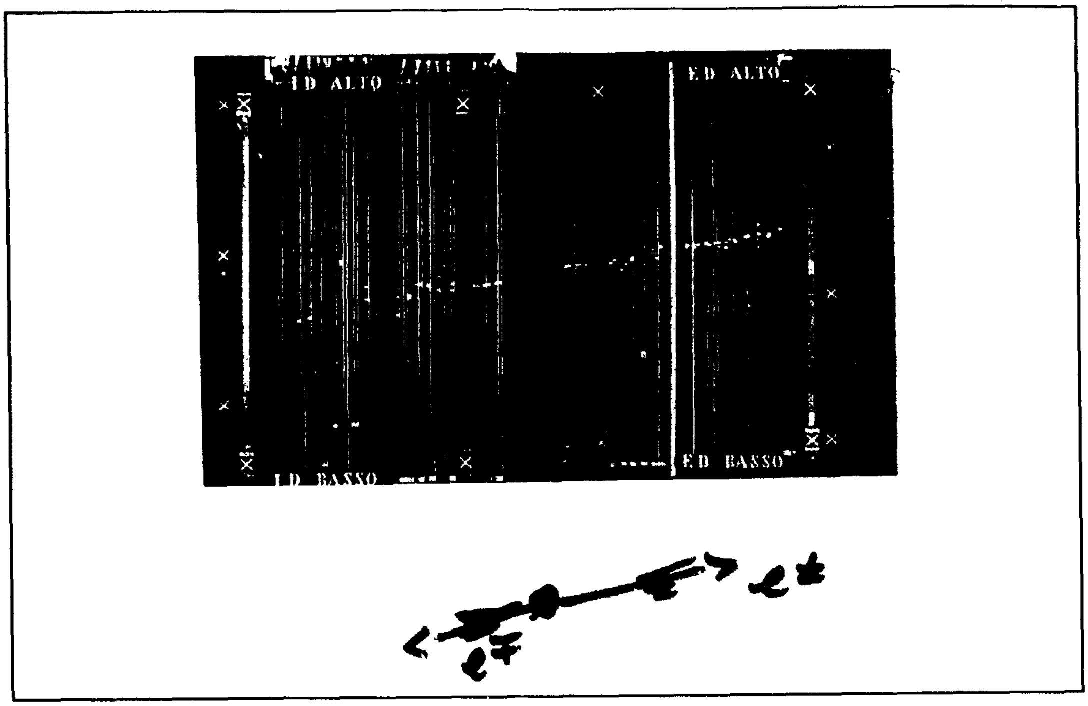


Fig. 5.7: Typical electron-pair event, as observed in the set-up of Figs. 5.1 and 5.2 at ADONE.

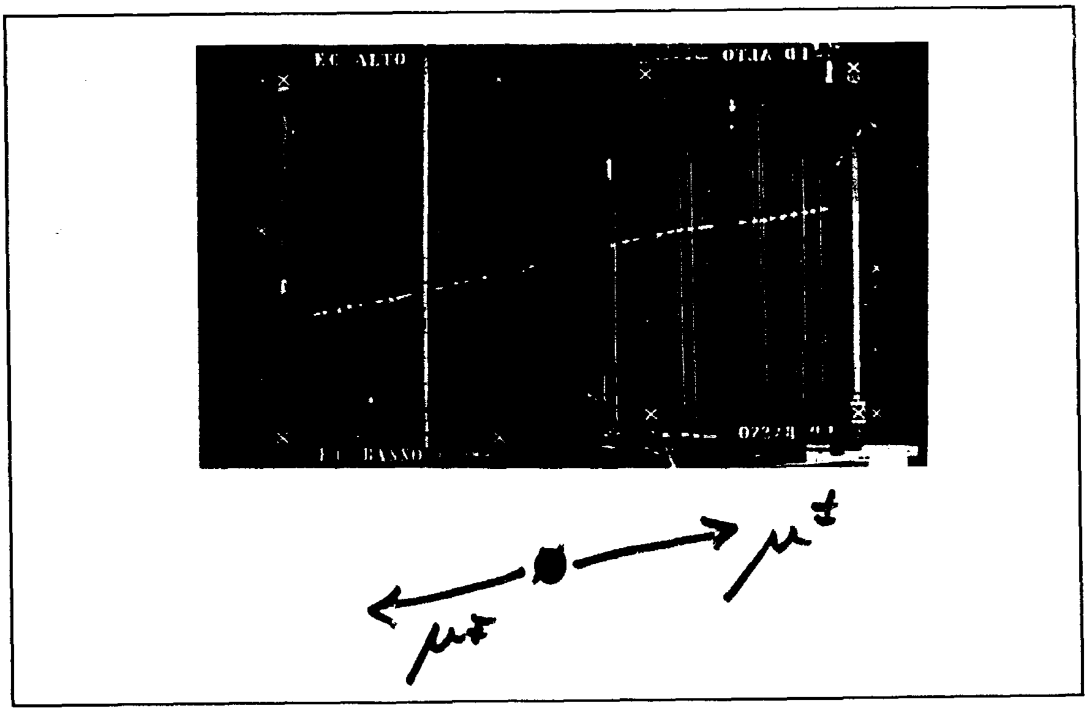


Fig. 5.8: Typical μ-pair event, as observed in the set-up of Figs. 5.1 and 5.2 at ADONE.

Notice how clean the electron-pair and muon-pair events are.

And this is how we reached the year 1970, when the first results were published by the BCF group:

i) on the Heavy Lepton searches at ADONE [19];

ii) on a series of experiments to demonstrate that, if $(e^{\pm}\mu^{\mp})$ acoplanar events were found, these could not be due to the violation of the leptonic number $(e \neq \mu)$ at high q^2-values (time- and space-like), coupled to acoplanar radiative corrections. These detailed studies showed that everything was following QED expectations for (e^+e^-) and $(\mu^+\mu^-)$ pairs produced in (e^+e^-) interactions [18, 20].

In Figure 5.9 the front page of the paper [19] on the first limit for Heavy Lepton production is shown, and in Figure 5.10a, the one relative to the first paper on the study of the validity of the leptonic number selection rules $(e \neq \mu)$ [18]. Figure 5.10b shows the relevant page of this paper, where the quantitative result is given.

Let me report what has been published by us on the test of lepton-number conservation from $e^+e^- \to e^{\pm}\mu^{\mp}$ [20]. "The study of this reaction allows one to establish the validity of the leptonic number selection rules for high space-like and time-like q^2-values. Collinear events with an electron and a muon in the final state would represent a proof that the presently known leptonic selection rules are violated.

No events of type $e^+e^- \to e\mu$ were found, and from the total number of observed lepton pairs, we get:

$$\frac{e^+e^- \to e^{\pm}\mu^{\mp}}{e^+e^- \to \text{lepton} + \text{antilepton}} \leq 2 \cdot 10^{-3} \quad \text{with 95\% confidence ...}$$

Background sources for this reaction are proved to be absent, from beam-gas interaction, cosmic radiation, or from simulation by $(e^{\pm}e^{\mp})$ or $(\mu^{\pm}\mu^{\mp})$ final states."

In the same year 1970 other results were reported by the BCF group at the Erice School. The front page of the corresponding preprint is reproduced in Figure 5.11.

LETTERE AL NUOVO CIMENTO VOL. IV, N. 24 12 Dicembre 1970

Limits on the Electromagnetic Production of Heavy Leptons.

V. Alles-Borelli, M. Bernardini, D. Bollini, P. L. Brunini, T. Massam, L. Monari, F. Palmonari and A. Zichichi

CERN - Geneva
Istituto Nazionale di Fisica Nucleare - Sezione di Bologna
Istituto di Fisica dell'Università - Bologna
Laboratori Nazionali del CNEN - Frascati (Roma)

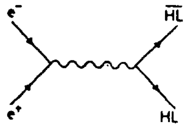
(ricevuto il 6 Novembre 1970)

A comparison between the long list of hadronic states and the very short list of leptonic states exposes one of the most striking puzzles of particle physics. It is therefore in order to ask whether heavy leptons could have been detected in previous experiments. If universality for the coupling of this new lepton to the known leptons is assumed, then the lifetime of a heavy lepton is predicted to be $\sim 3\cdot 10^{-10}$ s at 500 MeV and $\sim 2\cdot 10^{-11}$ s at 1000 MeV mass values. Thus, for masses in the region of 1 GeV, they could never have been detected as a decaying quasi-stable particle, but only as a resonance in the lepton system. Furthermore, it should be noted that the production of the heaviest lepton known so far (the muon) is copious only because it is the decay product of a very commonly produced particle, the π. There is no equivalent mechanism for the production of a heavy lepton with a mass of about 1 GeV. In proton machines they could only be produced in pairs via timelike photons, but it is known that nucleons are very poor sources of timelike photons (1), owing to the rapid decrease of their form factors as the four-momentum transfer increases (2).

The most favourable mechanism for the production of a heavy lepton HL is

$$e^+e^- \to HL + \overline{HL}\,, \tag{1}$$

which, in the one-photon approximation, is described by the Feynman diagram



(1) T. Massam and A. Zichichi: *Nuovo Cimento*, 44 A, 309 (1966). The deep inelastic effect discovered at SLAC could alter this statement. However, as yet no firm experimental results exist on this possible consequence of the SLAC results. This point will be discussed further in a forthcoming note.

(2) M. Conversi, T. Massam, Th. Muller and A. Zichichi: *Nuovo Cimento*, 40 A, 690 (1965).

1156

Fig. 5.9: Front page of ref. 19 on the first limit for the production of a new sequential Heavy Lepton in (e^+e^-) annihilation.

V. ALLES-BORELLI, *et al.*
12 Dicembre 1970
Lettere al Nuovo Cimento
Serie I, Vol. 4, pag. 1151-1155

Validity of the Leptonic Selection Rules for the ($\mu e \gamma$) Vertex at High Four-Momentum Transfers.

V. ALLES-BORELLI, M. BERNARDINI, D. BOLLINI, P. L. BRUNINI, T. MASSAM, L. MONARI, F. PALMONARI and A. ZICHICHI

CERN - Geneva
Istituto Nazionale di Fisica Nucleare - Sezione di Bologna
Istituto di Fisica dell'Università - Bologna
Laboratori Nazionali del CNEN - Frascati (Roma)

(ricevuto il 6 Novembre 1970)

Using the Frascati (e^+e^-) colliding-beam machine (ADONE) [1] we have performed an experiment to look for the possible existence of the process

$$e^+e^- \to \mu^{\mp}e^{\pm}, \tag{1}$$

which, in the one-photon approximation, can take place if at the μ-e-γ vertex the currently known leptonic selection rules are violated. The available experimental information does not allow a distinction to be made between the two alternative classes of selection rules [2] which distinguish the «electron world» from the «muon world»: namely: *a*) two additive selection rules: *b*) an additive and a multiplicative selection rule. Both sets of rules would be violated by the existence of process (1). For very low q^2 values ($q^2 \simeq 0.01\ (\text{GeV})^2$) it is known that process (1) is strongly depressed. Examples are the unobserved processes

$$\mu^{\pm} \to e^{\pm} + \gamma, \tag{2}$$

$$\mu^- + \text{nucleus} \to (\text{nucleus})' + e^-. \tag{3}$$

However, as nobody knows the reason for the existence of these two leptonic quantum numbers, it is of interest to study their validity *vs.* q^2.

The data presented here result from the analysis of e^+e^- collisions, with energies ranging from 0.8 GeV to 1 GeV, in the angular range $(45 \div 135)^\circ$. The corresponding range of momentum transfer associated with the photon at the ($\mu e \gamma$) vertex is ($(0.38 \div 3.4)\ (\text{GeV})^2$) spacelike, and ($(2.6 \div 4.0)\ (\text{GeV})^2$) timelike.

(1) F. AMMAN *et al.*: *Notiziario del CNEN*, 10, 16 (March 1964); *ADONE, the Frascati 1.5 GeV electron-positron storage ring*, LNF-65/26 (Frascati, 30/8/1965).
(2) A. ZICHICHI: *Suppl. Nuovo Cimento*, 2, 894 (1965).

Fig. 5.10a: Front page of ref. 18 on the study of the validity of the leptonic number selection rules ($e \neq \mu$).

The selection of e's and μ's turns out to be simple in this set-up because they carry strikingly different and clearly distinguishable signatures. Electrons and positrons give very clear electromagnetic showers in the heavy-plate chambers. A typical electron-pair event is shown in Fig. 2 and a typical muon-pair event is shown in Fig. 3.

The analysis of the data, taken at the various energies and with the luminosities quoted in Table I, has presented no good candidate for a (muon-electron) pair event.

From the total number of observed leptons pairs, $N(\text{lepton}+\text{antilepton}) = 1762 \pm 45$, we obtain the following upper limit for the branching ratio

$$\frac{e^+e^- \to e^\pm\mu^\mp}{e^+e^- \to \text{lepton} + \overline{\text{lepton}}} < 2\cdot 10^{-3} \qquad (4)$$

with 95% confidence.

If we express in terms of a form factor $F^{\mu e\gamma}(q^2)$ a possible violation of the leptonic selection rules, our results imply that

$$\Bigg|\underbrace{\int\limits_{0.38\,(\mathrm{GeV})^2}^{3.4\,(\mathrm{GeV})^2} F^{\mu e\gamma}(q^2)\,\mathrm{d}q^2}_{\text{spacelike}} + \underbrace{\int\limits_{2.56\,(\mathrm{GeV})^2}^{4.0\,(\mathrm{GeV})^2} F^{\mu e\gamma}(q^2)\,\mathrm{d}q^2}_{\text{timelike}}\Bigg|^2 < 2\cdot 10^{-3}\,.$$

If we assume that the leptonic selection rules are violated only in the spacelike range then

$$\Bigg|\int\limits_{0.38\,(\mathrm{GeV})^2}^{3.4\,(\mathrm{GeV})^2} F^{\mu e\gamma}(q^2)\,\mathrm{d}q^2\Bigg|^2 < 2\cdot 10^{-3}\,;$$

while if only the timelike range is responsible for the violation, the limit turns out to be

$$\Bigg|\int\limits_{2.56\,(\mathrm{GeV})^2}^{4.0\,(\mathrm{GeV})^2} F^{\mu e\gamma}(q^2)\,\mathrm{d}q^2\Bigg|^2 < 10^{-2}\,.$$

* * *

This experiment is a collaboration between the University of Bologna and CERN, started at the time when Prof. V. F. WEISSKOPF was Director General at CERN and Prof. G. PUPPI Director of Research. It is thanks to their support that this collaboration has been established. We are very grateful to them and would like to thank Profs. B. P. GREGORY, P. PREISWERK and G. COCCONI for having maintained the support.

The technicians of our group have devoted their greatest efforts towards the success of the experimental programme, and we would like to express our appreciation for the skilful work and friendly assistance at all stages of the experiment to G. BACCHERINI, J. BERBIERS, F. MARTELLI, F. MASSERA, G. MOLINARI and O. POLGROSSI.

Finally our gratitude is extended to those who are responsible for the invention, design, construction and running of the colliding-beam facility: Profs. B. TOUSCHEK, F. AMMAN, M. PLACIDI, and their collaborators.

Fig. 5.10b: The page of ref. 18 where the relevant quantitative result is given, i.e. the 95% CL limit on the $(e^+e^- \to e^\pm\mu^\mp / e^+e^- \to l\,\bar{l})$ branching ratio, with $l = e, \mu$.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

STUDY OF CHARGED FINAL STATES PRODUCED IN e^+e^- INTERACTIONS

V. Alles-Borelli, M. Bernardini, D. Bollini,
P.L. Brunini, E. Fiorentino, P.L. Frabetti,
T. Massam, L. Monari, F. Palmonari and A. Zichichi

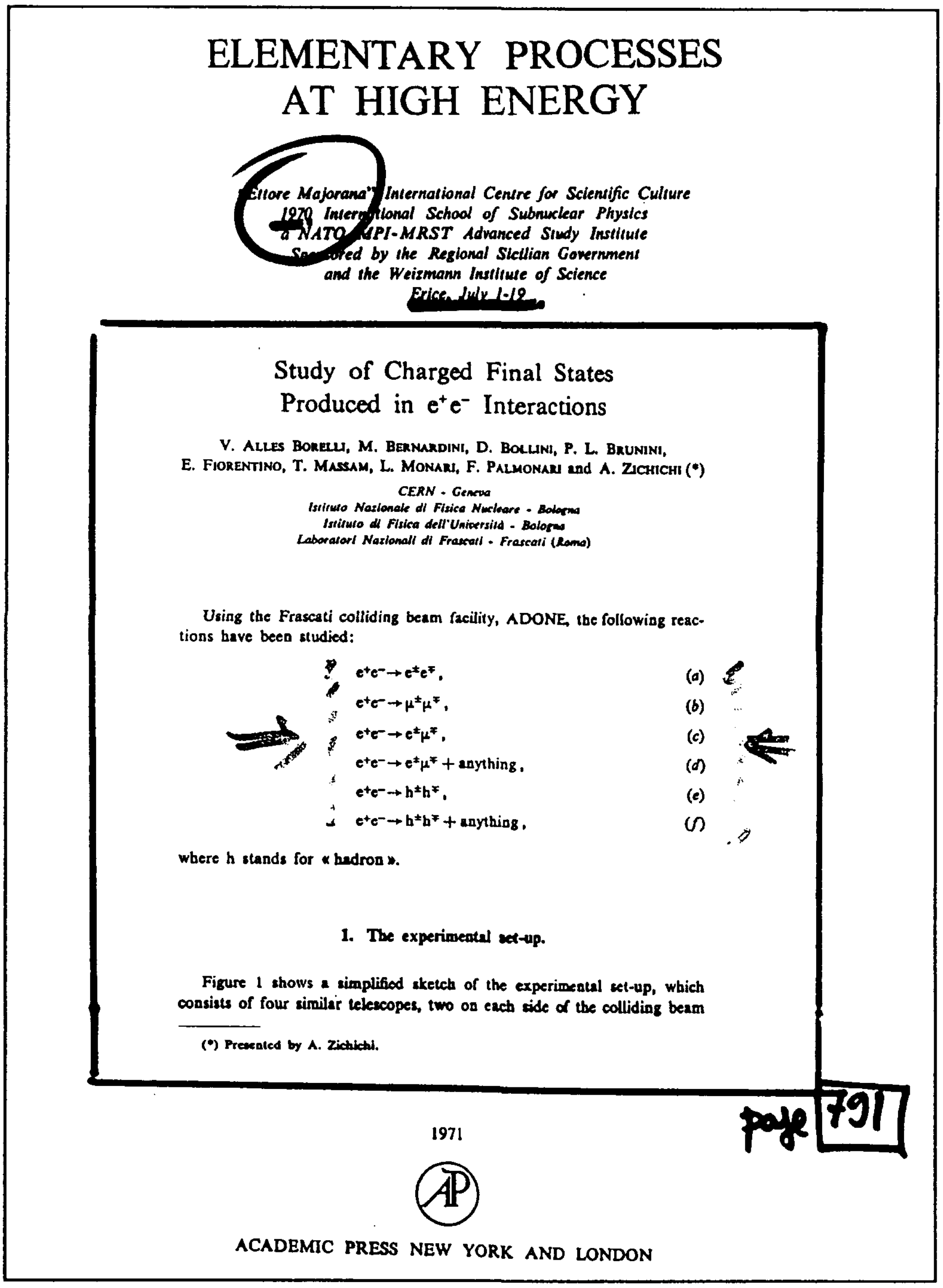
(Presented by A. Zichichi)

CERN, Geneva, Switzerland
Istituto Nazionale di Fisica Nucleare, Bologna, Italy
Istituto di Fisica dell'Università, Bologna, Italy
Laboratori Nazionali di Frascati, Italy

Paper presented at the E. Majorana International School of Physics
Erice 1 - 19 July 1970
To be published in: "Elementary Processes at High Energy" - Academic Press -
New York and London

Fig. 5.11: Front page of the CERN preprint (later published as ref. 20) where all the relevant results by the BCF group on lepton and hadron production in (e^+e^-) annihilation at ADONE were presented.

These results were later published in [20-39]: Physics Letters, Nuovo Cimento and the Proceedings of the 1970 "Ettore Majorana" International School of Subnuclear Physics (issued in 1971). Figure 5.12 is the first page of the 1970 Erice Lecture, as appeared in the Proceedings one year later [20].



ELEMENTARY PROCESSES AT HIGH ENERGY

"Ettore Majorana" International Centre for Scientific Culture
1970 International School of Subnuclear Physics
a NATO-MPI-MRST Advanced Study Institute
Sponsored by the Regional Sicilian Government
and the Weizmann Institute of Science
Erice, July 1-19

Study of Charged Final States Produced in e^+e^- Interactions

V. Alles Borelli, M. Bernardini, D. Bollini, P. L. Brunini, E. Fiorentino, T. Massam, L. Monari, F. Palmonari and A. Zichichi (*)

CERN - Geneva
Istituto Nazionale di Fisica Nucleare - Bologna
Istituto di Fisica dell'Università - Bologna
Laboratori Nazionali di Frascati - Frascati (Roma)

Using the Frascati colliding beam facility, ADONE, the following reactions have been studied:

$$e^+e^- \to e^\pm e^\mp, \qquad (a)$$
$$e^+e^- \to \mu^\pm \mu^\mp, \qquad (b)$$
$$e^+e^- \to e^\pm \mu^\mp, \qquad (c)$$
$$e^+e^- \to e^\pm \mu^\mp + \text{anything}, \qquad (d)$$
$$e^+e^- \to h^\pm h^\mp, \qquad (e)$$
$$e^+e^- \to h^\pm h^\mp + \text{anything}, \qquad (f)$$

where h stands for « hadron ».

1. The experimental set-up.

Figure 1 shows a simplified sketch of the experimental set-up, which consists of four similar telescopes, two on each side of the colliding beam

(*) Presented by A. Zichichi.

1971

ACADEMIC PRESS NEW YORK AND LONDON

Fig. 5.12: Front page of ref. 20 (corresponding to the CERN preprint already issued in 1970).

The results proved that, in an (e^+e^-) collider, the acoplanar $(e^{\pm}\mu^{\mp})$ method to search for a new Heavy Lepton accompanied by its own neutrino was clean and not swamped by background. From the first limit on HL published in 1970 [19] the notion of a Heavy Lepton (indicated first as $H_l^{\pm}$ later as $HL^{\pm}$, and finally as $L^{\pm}$ in the publications by the BCF group) and the method to look for it, i.e. the detection of acoplanar $(e^{\pm}\mu^{\mp})$ pairs, became known the world over and stimulated other searches, at Frascati and elsewhere.

6 The Heavy Lepton and the Acoplanar $(e\mu)$ Method from 3 GeV to Higher Energy (1971-1975)

Our 1970 paper [19] triggered a lot of interest. For instance Martin Perl published a paper in Physics Today [44] (July 1971), where he refers to this first Heavy Lepton paper (1970). The relevant page where he quotes ref. 5 (our 1970 results, i.e. ref. 19 of the present report) is reproduced in Figure 6.1.

It is interesting to read what he says: "Fortunately these problems can be overcome in the newly developed electron-positron colliding-beam accelerators where charged leptons can be copiously produced through the process[5]

$e^+e^- \rightarrow \mu'^+ + \mu'^-$ ($\mu' \equiv HL$ of BCF group in ref. 5, i.e. ref. 19 of the present report).

Within five years, through this process, we shall know if the electron-muon family has additional members with masses in the several-GeV ranges".

In 1971 we published our results on the first observation of acoplanar radiative effects [22]. Figure 6.2a reproduces the front page of our paper, and Figure 6.2b the page where we established the effect to be (2.8 ± 0.4) % in our experimental conditions. We had also checked the validity of crossing symmetry in QED [21], as shown in Figure 6.3.

for this second direction to be fruitful, one must either measure known properties with greater precision or one must measure properties that have not been previously measured. The recent high-precision measurements[3] of the gyromagnetic ratio of the muon are an illustration of the first type of measurement. The deep inelastic-scattering experiment (see figure 1), which I will describe later, is an illustration of the second type of measurement.

A larger family?

To the question: "Are the muon and the electron part of a larger family of charged leptons?" we must give an unsatisfactory answer; as far as we know there are no other charged leptons, but this knowledge does not go very far. The evidence can be summarized:

- Numerous experiments, many having to do with the decay of the K meson, have shown *no* additional leptons with masses below 0.5 GeV.
- No leptons with masses above 0.5 GeV have been found. But all searches for such particles have been incomplete. One reason for this incompleteness is that as the mass of the charged lepton increases, its lifetime becomes shorter and shorter, making direct detection more and more difficult.[4] Thus a lepton with a mass near 1 GeV will have a lifetime of about 10^{-11} seconds due to the decay processes in equations 2 and 3. A second reason for the incompleteness of past searches is that reactions that could copiously produce heavy charged leptons were not available.

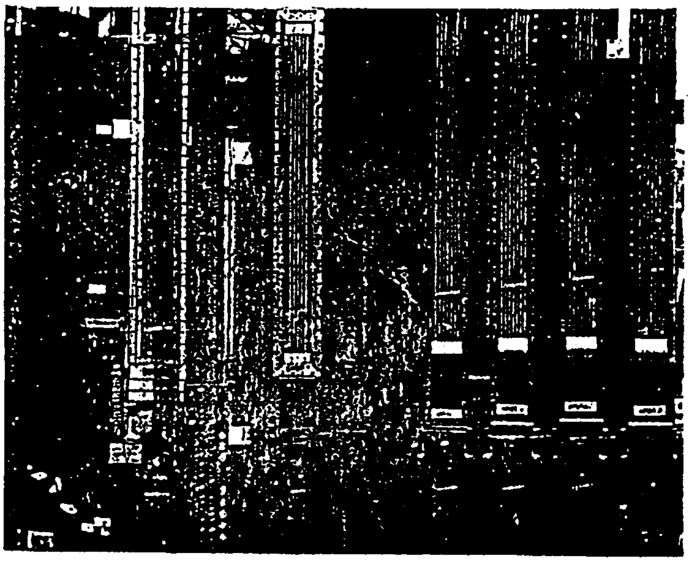
Fortunately these problems can be overcome in the newly developed electron-positron colliding-beam accelerators where charged leptons can be copiously produced through the process[5]

$$e^+ + e^- \rightarrow \mu'^+ + \mu'^-$$

Within five years, through this process, we shall know if the electron-muon family has additional members with masses in the several-GeV ranges.

Static properties

One of the beautiful aspects of the search for muon–electron differences is the tremendous range of techniques that have been used. These techniques range from radiofrequency measurements of the hyperfine structure of muonium[2,3] (4500 MHz equivalent to 1.9×10^{-14} GeV) to measurements of muon-proton elastic and inelastic scattering at energies above 10 GeV. In surveying the results from this range of techniques I will first discuss the static properties of the muon and then discuss



Measuring muon–proton inelastic scattering at SLAC. Muons scattered in a hydrogen target (out of sight at the left) pass through the magnet (left center) and then through six spark chambers (right). Mirrors provide the stereoscopic view (lower set of tracks). See also cover photograph and figure 6. **Figure 1**

PHYSICS TODAY / JULY 1971 35

Fig. 6.1: The page of the article by M. Perl [44] where the first Heavy Lepton paper published by the BCF group [19] is referenced as ref. 5 (superscript).

Volume 36B, number 2 PHYSICS LETTERS 23 August 1971

EXPERIMENTAL PROOF OF THE INADEQUACY OF THE PEAKING APPROXIMATION IN RADIATIVE CORRECTIONS

V. ALLES BORELLI, M. BERNARDINI, D. BOLLINI,
P. L. BRUNINI, E. FIORENTINO, T. MASSAM, L. MONARI,
F. PALMONARI and A. ZICHICHI
CERN, Geneva, Switzerland
Istituto Nazionale di Fisica Nucleare, Bologna, Italy
Istituto di Fisica dell'Università, Bologna, Italy
Laboratori Nazionali di Frascati, Italy

Received 5 July 1971

49 e^+e^- non-collinear, non-coplanar events have been observed in a study of 1824 e^+e^- interactions at total centre-of-mass energies from 1.6 GeV to 2.0 GeV. The inadequacy of the peaking approximation in radiative corrections is measured to be $(2.3 \pm 0.4)\%$, in these experimental conditions of observation.

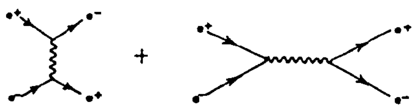
First-order radiative corrections with peaking approximation [1], when applied to the reaction

$$e^+e^- \to e^{\pm}e^{\mp}\,, \qquad (1)$$

predict that the final-state electron-positron pair could have a large acollinearity angle, but be in a plane containing the colliding beam axis.

We have studied reaction (1) using the Frascati colliding beam facility ADONE for total c.m. energies from 1.6 to 2.0 GeV, and for scattering angles from 45° to 135°. The experimental apparatus has been described elsewhere [2].

In the one-photon approximation, reaction (1) is described by the two Feynman diagrams and by their interference:



The first-order radiative corrections with peaking approximation essentially consist in adding to any one of the four electronic legs, a photon whose direction is assumed to be along the electron or positron line of flight. Thus, photons emitted in the final state do not destroy the collinearity of the pair; photons emitted in the initial state impart a non-zero velocity to the e^+e^- centre-of-mass system, which results in the angular distribution properties stated above.

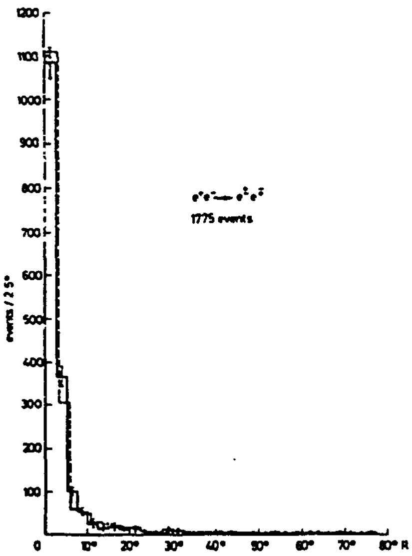


Fig. 1. Collinearity distribution integrated over all energies. The dotted histogram is the theoretical prediction based on the first-order radiative corrections with peaking approximation.

Fig. 6.2a: Front page of ref. 22 on the first observation of acoplanar radiative effects at ADONE.

$$\alpha = \frac{\text{number of non-coplanar } (e^{\pm}e^{\mp}) \text{ events}}{\text{number of coplanar } (e^{\pm}e^{\mp}) \text{ events}} = \frac{49}{1775} = (2.8 \pm 0.4)\%$$

is our measurement of the inadequacy of the peaking approximation.

Obviously the understanding of these 49 events is crucial, not only from the pure QED point of view but also in connection with other possible sources of non-collinear, non-coplanar leptonic events, as for example the heavy lepton [3]. They are also of particular importance in the measurement of multi-hadron production cross-sections where they contribute a latent background level as high as ~ 100% of the pion point-like cross-section. The R-ϕ correlation of these events is shown in fig. 2.

In order to see if these events could be accounted for by removing the peaking approximation in the calculation of the radiative corrections, we have computed the shape of the $|\phi|$ distribution for $(e^{\pm}e^{\mp})$ events following the work of Bonneau and Martin [4]. This expected $|\phi|$ distribution is compared with the experimental data in fig. 3, and the agreement appears to be satisfactory $[P(\chi^2) \sim 15\%]$. It should be noticed that the work of Bonneau and Martin, originally planned to calculate radiative corrections for (e^+e^-) annihilation into hadrons, did not include the radiative emission occurring in the final (e^+e^-) state. However, the shape of the $|\phi|$ distribution is essentially given by the angular and momentum spectrum of the radiated photons, and this spectrum is expected to remain almost the same if initial or final leptons radiate.

We have thus show that in order to understand one of the cleanest QED processes, reaction (1), it is necessary to calculate radiative corrections without the so-called peaking approximation. The inadequacy of this approximation in our experimental conditions of observation has been measured to be $(2.8 \pm 0.4)\%$.

References

[1] S. Tavernier, Thèse de Doctorat (3e cycle), Orsay, RI 68/7 (1968).

[2] V. Alles Borelli, M. Bernardini, D. Bollini, P. L. Brunini, E. Fiorentino, T. Massam, L. Monari, F. Palmonari and A. Zichichi, Direct check of QED in e^+e^- interactions at high q^2 values, to be published.

[3] V. Alles Borelli, M. Bernardini, D. Bollini, P. L. Brunini, T. Massam, L. Monari, F. Palmonari and A. Zichichi, Nuovo Cimento Letters 4 (1970) 1156.

[4] G. Bonneau and F. Martin, Nucl. Phys. B 27 (1971) 381.

* * * * *

Fig. 6.2b: The page of ref. 22 where the relevant quantitative result on acoplanar radiative effects measured at ADONE is given.

LETTERE AL NUOVO CIMENTO VOL. 2, N. 7 14 Agosto 1971

Experimental Check of Crossing Symmetry in the Electromagnetic Interaction of Leptons.

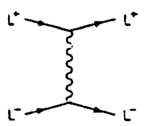
V. Alles Borelli, M. Bernardini, D. Bollini, P. L. Brunini, E. Fiorentino, T. Massam, L. Monari, F. Palmonari and A. Zichichi

CERN - Geneva
Istituto Nazionale di Fisica Nucleare - Sezione di Bologna
Istituto di Fisica dell'Università - Bologna
Laboratori Nazionali - Frascati

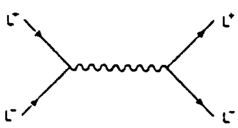
(ricevuto il 2 Luglio 1971)

A fundamental theorem of quantum field theory is crossing symmetry [1]. QED being the only working example of field theory, it is indeed crossing symmetric.

A straightforward check of QED crossing symmetry would be possible through a comparison between timelike and spacelike lepton-photon processes. In the one-photon approximation, this is shown in the diagrams below, where L stands for either electron or muon.



I) Timelike diagram.



II) Spacelike diagram.

If we call $F^{LL\gamma}(q^2)$ the vertex function which describes the electromagnetic interaction between the lepton and the photon, crossing symmetry says that this vertex function is the same analytic function for timelike and spacelike processes, the only change being the value of the variable q^2.

The experimental check we propose for this QED crossing symmetry is based on comparison of the following two leptonic processes:

(1) $e^+e^- \to e^\pm e^\mp$,

(2) $e^+e^- \to \mu^\pm\mu^\mp$,

which have been studied at Frascati using the colliding-beam facility Adone.

(1) M. Gell-Mann and M. L. Goldberger: *Phys. Rev.*, **96**, 1433 (1954).

376

Fig. 6.3: Front page of ref. 21 on the study of QED crossing symmetry at ADONE.

IL NUOVO CIMENTO Vol. 7 A, N. 2 21 Gennaio 1972

A Check of Quantum Electrodynamics and of Electron-Muon Equivalence.

V. Alles-Borelli, M. Bernardini, D. Bollini, P. L. Brunini, E. Fiorentino, T. Massam, L. Monari, F. Palmonari and A. Zichichi

CERN - Geneva
Istituto Nazionale di Fisica Nucleare - Sezione di Bologna
Istituto di Fisica dell'Università - Bologna
Laboratori Nazionali - Frascati

(ricevuto il 28 Maggio 1971; manoscritto revisionato ricevuto l'8 Luglio 1971)

Summary. — A study of the timelike reaction $e^+e^- \to \mu^\pm\mu^\mp$ and of its comparison with the spacelike dominated reaction $e^+e^- \to e^\pm e^\mp$ allows us to establish the validity of QED in terms of production angular distributions, absolute rates, energy dependence and angular correlations between the pair of final-state leptons, in two very different ranges of invariant four-momentum transfer. No sign of QED break is detected in the electromagnetic interaction of leptons and the muon behaves like a heavy electron, within the accuracy of the present investigation.

1. – Introduction.

We report here a study of the timelike process

$$e^+e^- \to \mu^\pm\mu^\mp \tag{1}$$

and its comparison with the spacelike dominated process

$$e^+e^- \to e^\pm e^\mp . \tag{2}$$

330

Fig. 6.4: Front page of ref. 23 on the study of the electron-muon QED equivalence at ADONE.

Later on we published all our results on QED checks for electrons and muons as shown: in Figure 6.4 for the electron-muon QED equivalence [23]; in Figure 6.5 for a measurement, with ten times more statistics, of the acoplanar radiative effects for (e^+e^-) final states [25]; in Figures 6.6a and 6.6b for a high precision QED test of the energy dependence of $e^+e^- \rightarrow e^+e^-$ [24, 26]; in Figure 6.7 for the energy dependence of $e^+e^- \rightarrow \mu^+\mu^-$ [30]. The final result on the validity of the $(e \neq \mu)$ leptonic selection rule at the $7 \cdot 10^{-5}$ level is shown in Figure 6.8 [45], and on the study of the acoplanar $e^+e^- \rightarrow \pi^{\pm}\pi^{\mp} + X$ reaction [20] in Figure 6.9.

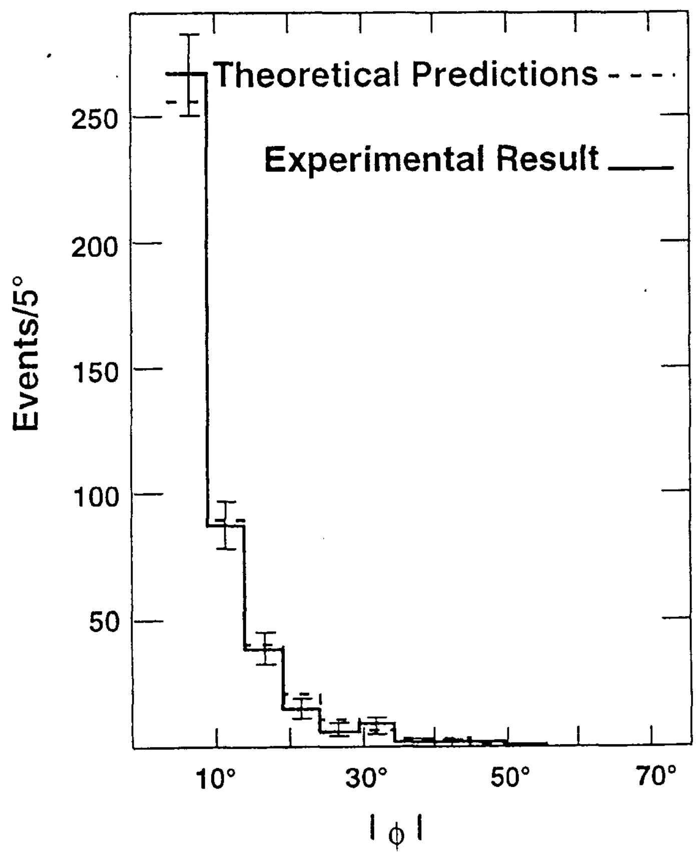


Fig. 6.5: Measurement of the acoplanar radiative effects for (e^+e^-) final states at ADONE [25], showing the acoplanarity angle (ϕ) distribution for 429 (e^+e^-) pairs with $|\phi| > 5°$.

Volume 45B, number 5 PHYSICS LETTERS 20 August 1973

ACCURATE MEASUREMENT OF THE ENERGY DEPENDENCE OF THE PROCESS $e^+ + e^- \rightarrow e^\pm + e^\mp$, IN THE s-RANGE 1.44–9.0 GeV^2

M. BERNARDINI, D. BOLLINI, P.L. BRUNINI, E. FIORENTINO,
T. MASSAM, L. MONARI, F. PALMONARI, F. RIMONDI and A. ZICHICHI

CERN, Geneva, Switzerland
Istituto Nazionale di Fisica Nucleare, Bologna, Italy
Istituto di Fisica dell 'Università, Bologna, Italy
and Laboratori Nazionali del CNEN, Frascati-Roma, Italy

Received 14 June 1973

The analysis of 12 827 $e^+ + e^- \rightarrow e^\pm + e^\mp$ events observed in the s-range 1.44-9.0 GeV^2 allows measurement of the energy dependence of the cross-section for the most typical QED process, with ±2% accuracy. Within this limit the data follow QED, with first-order radiative corrections included.

Using the Bologna-CERN set-up, the reaction

$$e^+ + e^- \rightarrow e^\pm + e^\mp \quad (1)$$

has been studied at the ADONE colliding beam machine in Frascati. The purpose of this work was to check the validity of QED in the s-range 1.44-9.0 GeV^2.

The apparatus consisted of : i) thin-plate spark chambers of kinematic reconstruction; ii) heavy-plate spark chambers for particle identification (electrons make showers; muons show only Coulomb scattering; pions and kaons produce the typical hadronic patterns); iii) a system of plastic scintillation counters for accurate time-of-flight (±0.5 ns) and for other fast-trigger purposes. Details of the set-up have already been published [1, 2] and will not be repeated here.

The QED check we report here is based on a comparison between "large-angle" and "small-angle" data from reaction (1). The small-angle data are used for luminosity measurements and cover a very low t-range, with an average t-value over the small-angle telescope of -2×10^{-3} GeV^2 (spacelike). The theoretical implications of this study have already been discussed in a previous work [2]. Table 1 shows the luminosities, the total number of large-angle ($e^\pm e^\mp$) events, and the t-ranges, corresponding to the various energies investigated with the present work. The results obtained are based on the analysis of 12 827 events.

These events have been reconstructed in space and fully analysed in order to exclude background contamination from beam-gas interactions and cosmic rays. The background level of these sources has been shown to be negligible (see refs. [2] and [3] for a discussion of backgrounds). What is not negligible is the contribution due to first-order radiative corrections. These have been calculated following the work of Tavernier [4] and of Calva-Tellez [5]; so by comparing our results with the theoretical predictions we can establish if QED is valid to the third-order in the electromagnetic coupling.

Table 1

E_{beam} (MeV)	L_I (nb^{-1})	$N_{(e^\pm e^\mp)}$ $R < 10°$ $\lvert\Phi\rvert < 5°$	t-range (GeV^2)
600	4.98	570	−(0.241 − 1.2)
650	8.02	665	−(0.283 − 1.41)
700	10.95	765	−(0.328 − 1.63)
750	27.15	1565	−(0.377 − 1.87)
800	10.23	460	−(0.429 − 2.13)
850	13.05	516	−(0.484 − 2.41)
950	60.95	1900	−(0.605 − 3.00)
970	23.61	668	−(0.623 − 3.13)
1050	186.09	4240	−(0.739 − 3.67)
1200	44.90	684	−(0.965 − 4.79)
1500	81.64	794	−(1.507 − 7.49)
Totals	431.57	12827	

† R is the deviation from collinearity; $R = 0$ means collinear event. The acoplanarity angle Φ is the angle between the two planes, which contain the two particles of the final state in reaction (1) and the beam axis.

510

Fig. 6.6a: Front page of ref. 26 on the precision measurement of the energy dependence of $\sigma(e^+e^- \rightarrow e^+e^-)$ at ADONE.

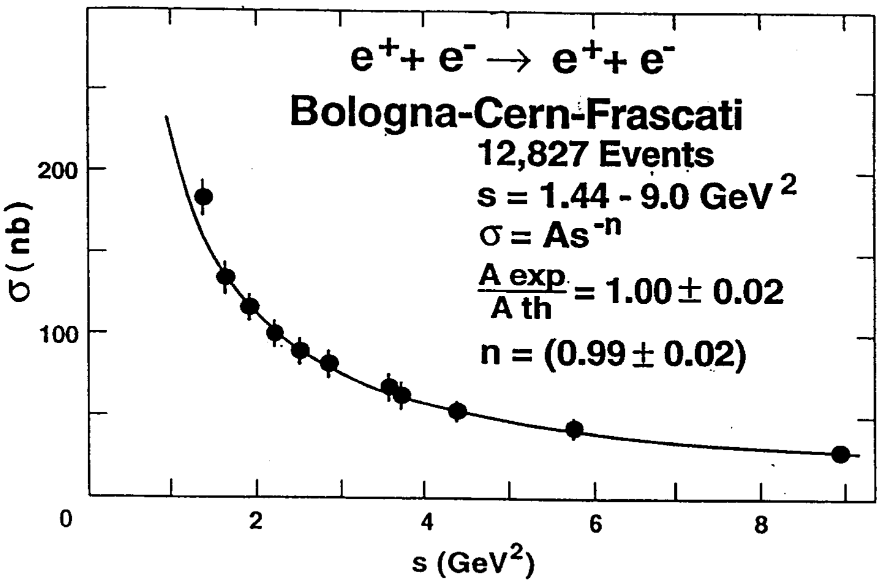


Fig. 6.6b: The cross section $\sigma(e^+e^- \to e^+e^-)$ vs. s, as measured at ADONE [26].

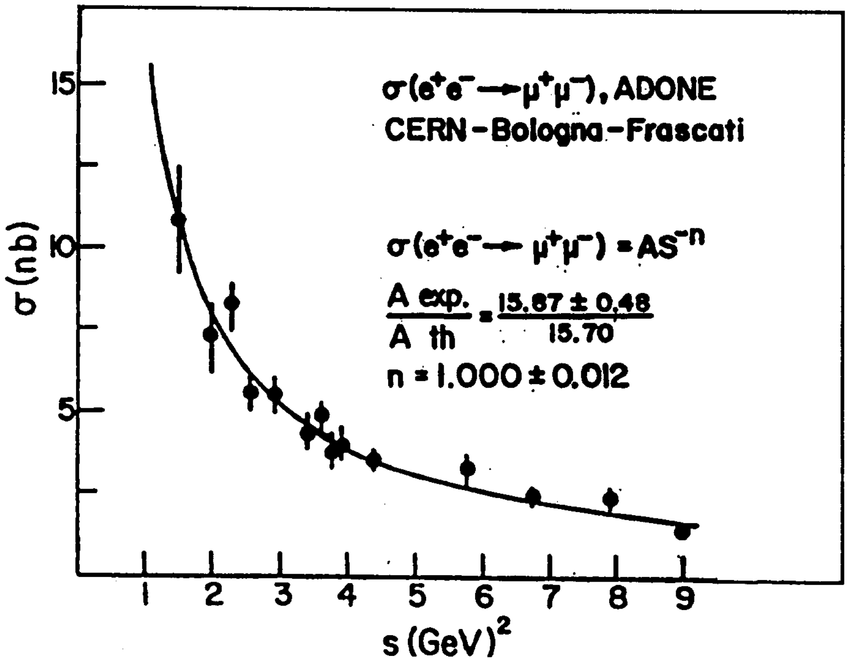


Fig. 6.7: The cross section $\sigma(e^+e^- \to \mu^+\mu^-)$ vs. s, as measured at ADONE [30].

Now the point is experimental. So far no states with $C = +1$ have been observed, and the experimental investigation has just started with the study of the purely electromagnetic processes

$$e^+e^- \to e^+e^-e^+e^- ,$$

$$e^+e^- \to e^+e^-\mu^+\mu^- ,$$

observed at Novosibirsk [34] and Frascati [35].

There is a straightforward way [36] to detect $C = +1$ states; this is via the determination of the turning point in the production angular distribution. High-energy machines will certainly have the privilege of taking up this field of great interest for hadrodynamics.

9. – Validity of the leptonic selection rules.

In the field of weak interactions we know that the transition $\mu \leftrightarrow e$ is forbidden by the known leptonic selection rules. The available experimental information does not allow a distinction to be made between the two alternative classes of selection rules [37] which distinguish the « electron world » from the « muon world »: namely: *a*) two additive selection rules, *b*) an additive and a multiplicative selection rule. Both sets of rules would be violated by the existence of the process

$$e^+e^- \to \mu^\pm e^\mp .$$

For very low q^2 values ($q^2 \simeq 0.01$ (GeV)^2) it is known that the transition $\mu \leftrightarrow e$ is strongly depressed. Examples are the unobserved processes

$$\mu^\pm \to e^\pm + \gamma ,$$

$$\mu^- + \text{nucleus} \to (\text{nucleus})' + e^- .$$

However, as nobody knows the reason for the existence of these two leptonic quantum numbers, it is of interest to study their validity *vs.* q^2. For example, in the Pati-Salam [38] theory with the leptonic number taken as the 4th colour, there is no place for this selection rule, a way out being its violation at some value of q^2. We have looked for collinear ($\mu^\pm e^\mp$) pairs in our sample of events, where $\sim 14\,000$ (e^+e^-) and 1000 ($\mu^+\mu^-$) were observed. The ranges of s and of t are given in Table II. From the total number of observed lepton pairs, $N(\text{lepton} + \text{antilepton}) = 15\,000$, we obtain the following limit for the branching ratio:

$$\frac{e^+e^- \to \mu^\pm e^\mp}{e^+e^- \to \text{lepton} + \text{antilepton}} < 7 \cdot 10^{-4} .$$

FINAL

Fig. 6.8: Page of ref. 45 where the final, high-statistics limit obtained at ADONE on the branching ratio ($e^+e^- \to \mu^\pm e^\mp / e^+e^- \to l\,\bar{l}$), with $l = e, \mu$, is reported.

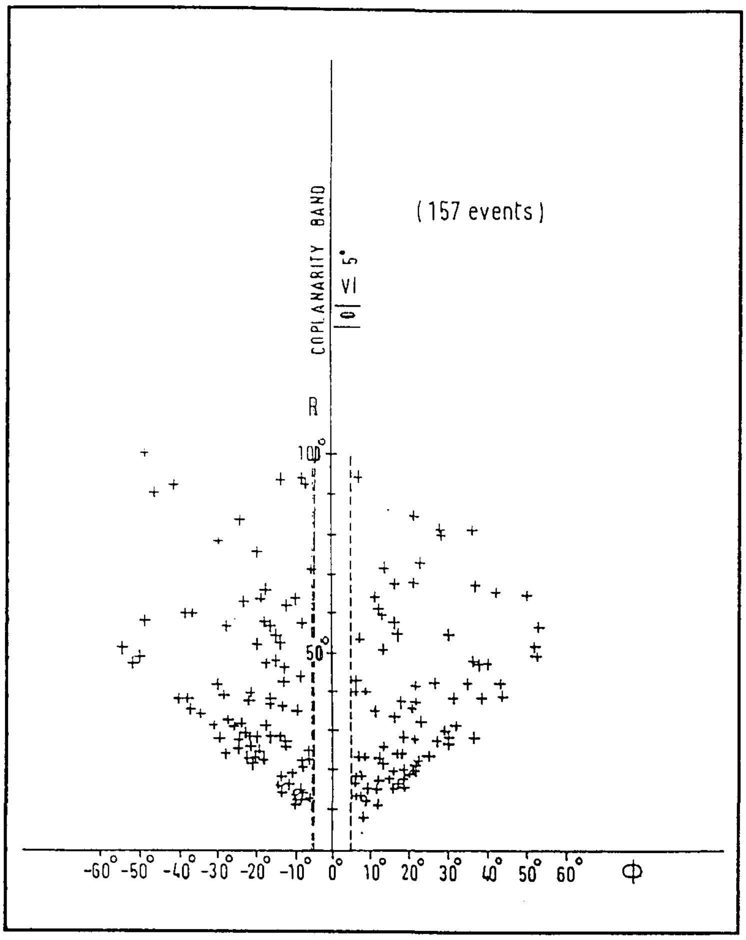
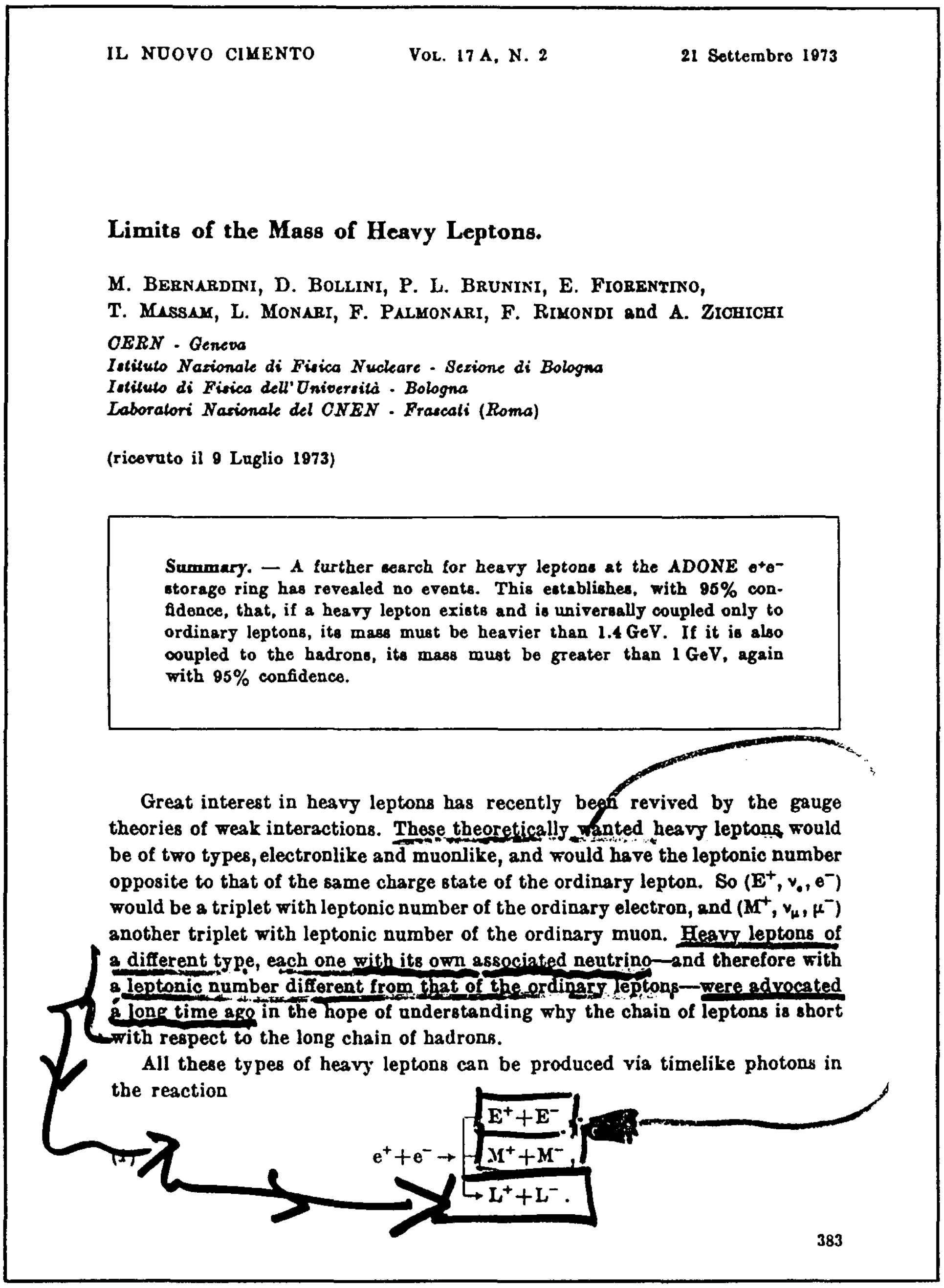


Fig. 6.9: R (acollinearity angle) vs. ϕ (acoplanarity angle) scatter diagram for ($\pi^{\pm}\pi^{\mp}$) outside the coplanar band (i.e. $|\phi| > 5°$), as observed at ADONE [20]. The non-collinear, non-coplanar events correspond to $e^{+}e^{-} \rightarrow \pi^{\pm}\pi^{\mp}$ + anything.

This hadronic channel was particularly relevant as a background for our searched ($e^{\pm}\mu^{\mp}$) acoplanar events.

By the time we concluded our experiment at Frascati, a new class of Heavy Leptons was proposed by theorists, as we have reported in our final Frascati paper [27], whose first page is reproduced in Figure 6.10. This is in fact our 1973 final result on the limits on the mass of the Heavy Lepton via the study of acoplanar ($e^{\pm}\mu^{\mp}$) pairs. In Figure 6.11 the details on the ADONE energies and the corresponding integrated luminosities are given.



IL NUOVO CIMENTO VOL. 17 A, N. 2 21 Settembre 1973

Limits of the Mass of Heavy Leptons.

M. BERNARDINI, D. BOLLINI, P. L. BRUNINI, E. FIORENTINO,
T. MASSAM, L. MONARI, F. PALMONARI, F. RIMONDI and A. ZICHICHI

CERN - Geneva
Istituto Nazionale di Fisica Nucleare - Sezione di Bologna
Istituto di Fisica dell'Università - Bologna
Laboratori Nazionali del CNEN - Frascati (Roma)

(ricevuto il 9 Luglio 1973)

Summary. — A further search for heavy leptons at the ADONE e^+e^- storage ring has revealed no events. This establishes, with 95% confidence, that, if a heavy lepton exists and is universally coupled only to ordinary leptons, its mass must be heavier than 1.4 GeV. If it is also coupled to the hadrons, its mass must be greater than 1 GeV, again with 95% confidence.

Great interest in heavy leptons has recently been revived by the gauge theories of weak interactions. These theoretically wanted heavy leptons would be of two types, electronlike and muonlike, and would have the leptonic number opposite to that of the same charge state of the ordinary lepton. So (E^+, ν_e, e^-) would be a triplet with leptonic number of the ordinary electron, and (M^+, ν_μ, μ^-) another triplet with leptonic number of the ordinary muon. Heavy leptons of a different type, each one with its own associated neutrino—and therefore with a leptonic number different from that of the ordinary leptons—were advocated a long time ago in the hope of understanding why the chain of leptons is short with respect to the long chain of hadrons.

All these types of heavy leptons can be produced via timelike photons in the reaction

$$(1)\qquad e^+ + e^- \to \begin{cases} E^+ + E^-, \\ M^+ + M^-, \\ L^+ + L^-. \end{cases}$$

Fig. 6.10: Front page of ref. 27 where the final results on the Heavy Lepton search by the BCF group at ADONE are reported.

Limits on the Mass of Heavy Leptons

Table I

Beam Energy (MeV)	Integrated Luminosity (x 10^{32} cm^{-2})
600	50
650	80
700	74
750	175
800	102
850	130
950	630
970	235
1050	1861
1200	449
1500	800

If the heavy lepton is coupled only to ordinary leptons (with the universal weak coupling constant), the 95% confidence level for the mass is:

$$m_{HL} \geq 1.45 \text{ GeV}$$

If the heavy lepton is universally coupled to both ordinary leptons and hadrons, the 95% confidence level for the mass is:

$$m_{HL} \geq 1.0 \text{ GeV}$$

Fig. 6.11: Details on the ADONE energy and integrated luminosity used to derive the final results reported in ref. 27 on the Heavy Lepton mass limits.

In Figure 6.12 the Frascati results are presented in a graphical synthesis: for a Heavy Lepton having its own neutrino and being universally coupled with ordinary leptons and hadrons the mass limit is (at 95% CL) 1.0 GeV/c^2.

After the final results by the BCF group were published in 1973 [27], the proposal for further searches at energies higher than ADONE was promoted in a series of conference reports: at the 1972 EPS Wiesbaden Conference, at the 1973 Pavia Symposium, at the 1973 Frascati Meeting and at the 1973 Bielefeld International Discussion Meeting.

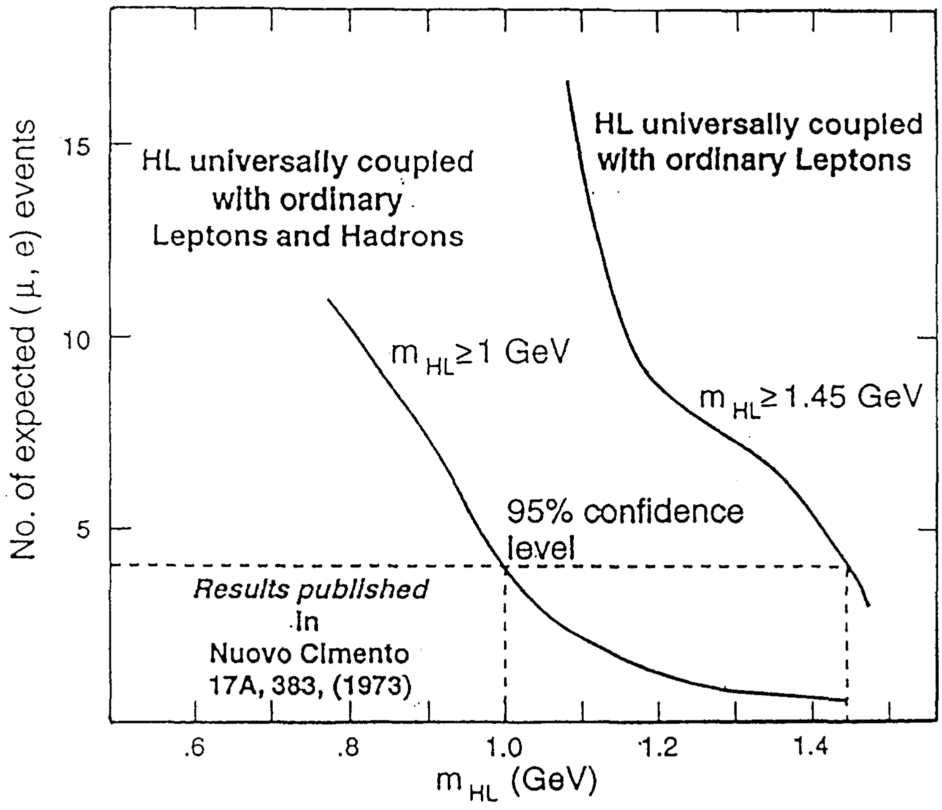


Fig. 6.12: The expected number of $(e^{\pm}\mu^{\mp})$ pairs vs. m_{HL}, i.e. the Heavy Lepton mass, for two types of universal weak couplings of the Heavy Lepton [27].

I decided to publish a synthesis of all these reports, with the title "Why $(e^{+}e^{-})$ physics is fascinating" [45]. In this review paper, whose first page is shown in Figure 6.13, I discuss the newly "theoretically wanted" Heavy Leptons. In Figure 6.14 the relevant page with what I say of these "theoretically wanted Heavy Leptons" (already described in Section 3 of the present report) is reproduced. The pages of my $(e^{+}e^{-})$ synthesis, where I discuss the importance of studying decay correlations, decay spectra and decay rates in order to disentangle the sequential Heavy Lepton from the "theoretically wanted" ones, are shown in Figures 6.15a and 6.15b.

RIVISTA DEL NUOVO CIMENTO VOL. 4, N. 4 Ottobre-Dicembre 1974

Why (e^+e^-) Physics is Fascinating (*).

A. Zichichi (**)
CERN - Geneva

(ricevuto il 12 Aprile 1974)

Summary

The results obtained by the Bologna-CERN-Frascati Collaboration during about three years of work at Frascati are reviewed and taken as a basis to show the impact of (e^+e^-) physics in understanding the laws of subnuclear phenomena.

1. – Introduction: (e^+e^-) machines in the world.

At this Conference you have heard how the basic laws of hadrodynamics can be investigated when the initial state of a reaction consists of hadrons.

The purpose of this talk is to show what we can learn when the initial state consists only of leptons, and more precisely of a lepton-antilepton pair. The

(*) This paper is an updated version of two unpublished invited review papers presented at the EPS *Conference, Wiesbaden, 3-6 October 1972* and at the *IV International Symposium on Multiparticle Hadrodynamics, Pavia, 31 August-4 September 1973*. The data on $\sigma(e^+e^- \to \text{hadrons})$ have been presented at: i) the *XVI International Conference on High-Energy Physics, Batavia, Ill., 1972*; ii) the *Informal Meeting on Recent Developments in High-Energy Physics, Frascati, 26-31 March 1973*; iii) the *International Discussion Meeting on (e^+e^-) Annihilation, Bielefeld, 19-21 September 1973.*

(**) On leave of absence from the University of Bologna.

498

Fig. 6.13: Front page of ref. 45, i.e. the final review paper on all the results obtained by the BCF group on (e^+e^-) collider physics at ADONE.

WHY (e^+e^-) PHYSICS IS FASCINATING

508 A. ZICHICHI

From the data on the reaction

$$e^+ + e^- \rightarrow \mu^+ + \mu^-$$

we conclude that a timelike vertex behaves like a spacelike vertex within $\pm 1\%$, as implied by crossing symmetry, a basic theorem of local relativistic quantum field theory [2].

We can close this Section by stating that so far we have every reason to believe that local relativistic quantum field theory is indeed an excellent tool for describing processes where leptons are involved. This is why this tool can be used for the more complex phenomena involving hadrons.

3. – Is it possible to renormalize weak interactions? Other heavy leptons?

A word of caution is needed here. For a long time physicists have been puzzled by the existence of only two types of leptons: the electronlike and the muonlike. When these are compared with the enormous variety of hadrons, the call for leptons outside the electron and the muon class becomes very natural. Such leptons have nothing to do with the leptons required by the gauge theories.

Fig. 6.14: The page of ref. 45 where the relevant point about "theoretically wanted" Heavy Leptons is outlined.

statistics and taking into account the fact that the calculated background and the observed number of events were both equal to 2.

If the heavy lepton is coupled only to ordinary leptons (with the universal weak-coupling constant), the 95% confidence level for the mass is

$$m_{HL} > 1.45\ \text{GeV}\,.$$

If the heavy lepton is universally coupled to both ordinary leptons and hadrons, then the 95% confidence level for the mass is

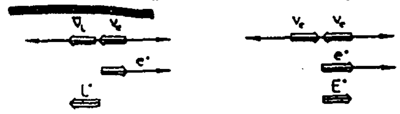
$$m_{HL} > 1.0\ \text{GeV}\,.$$

Notice that the above mass limits apply to any type of heavy lepton (E, M, L, l) quoted above. The present investigation thus establishes that neither heavy leptons required by the gauge theories of weak interactions nor heavy leptons of the old standard type exist with masses below 1.0 GeV.

Nevertheless, colliding (e^+e^-) beams will remain a very clean tool with which to search for heavy leptons. It is perhaps interesting to recall that if ($e^{\pm}\mu^{\mp}$) pairs were observed, their origin in terms of E, M, L could finally be established because there are three sources of information, which differ for the various leptons, *viz.* decay correlations, decay spectra, decay rates. For example, let us consider the decay of L^+ and E^+ (the double arrow indicates spin, a single arrow indicates momentum).

Decay correlations.

$L^+ \to e^+ + \nu_e + \bar{\nu}_L$ $\qquad$ $E^+ \to e^+ + \nu_e + \nu_e\,.$



Owing to the different neutrinos emitted in the decay of L^+ and E^+, the positive electron will be emitted in the opposite direction with respect to the L^+ spin, but along the E^+ spin, respectively. This is an interesting source for decay correlations.

Decay spectra. [redacted]he highest-energy configuration for e^+ is allowed in the [redacted]nd forbidden for E^+ decay:

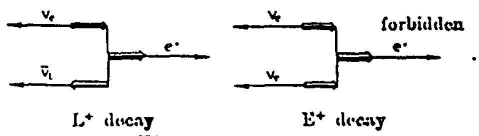
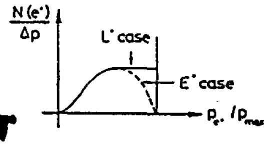


Fig. 6.15a: Showing the main items presented in ref. 45, i.e. the importance of studying decay correlations and decay spectra to identify the new sequential Heavy Leptons.

The Michel spectrum will obviously be different because the highest-energy configuration must vanish for E^+ decays:



Decay rates. The decay rates for the purely leptonic channels compare as follows:

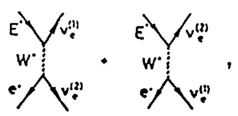
$$\text{rate}\,(L^+\to e^+\nu_e\bar{\nu}_L) = \text{rate}\,(L^+\to\mu^+\nu_\mu\bar{\nu}_L) = \text{rate}\,(E^+\to\mu^+\nu_\mu\nu_e) = \text{rate}\,(M^+\to e^+\nu_e\nu_\mu)\,.$$

But

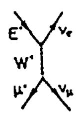
$$\text{rate}\,(E^+\to e^+\nu_e\nu_e) = 2\ \text{rate}\,(E^+\to\mu^+\nu_\mu\nu_e)\,,$$

$$\text{rate}\,(M^+\to\mu^+\nu_\mu\nu_\mu) = 2\ \text{rate}\,(M^+\to e^+\nu_e\nu_\mu)\,.$$

To see the origin of this factor of 2, let us take as example the E^+ decay; there are two diagrams contributing



while for the μ^+-channel there is only one diagram



because the two neutrinos in the final states are not equal.

When compared to the μ^+-channel, the rate of the e^+-channel is therefore 2^2 (because of the two amplitudes obtained by interchanging the two identical neutrinos, labelled $\nu_e^{(1)}$ and $\nu_e^{(2)}$ in the diagram above), times one-half, because of the two identical particles in the final state, *i.e.*

$$\text{rate}\,(E^+\to e^+\nu_e\nu_e) = 2^2\cdot\tfrac{1}{2}\cdot\text{rate}\,(E^+\to\mu^+\nu_\mu\nu_e)\,,$$

which is the result quoted above.

Fig. 6.15b: Same as Fig. 6.15a, concerning the *HL* decay rates for the purely leptonic channels [45].

7 Summary and Conclusions

Let me summarize this report and conclude.

I have described the foundations of Heavy Lepton searches where the key idea was the existence of a new Heavy Lepton carrying its own leptonic number. The time sequence was as follows.

The period 1960-1968 is based on a series of published papers describing the experimental work at CERN dedicated to the search for time-like photons able to produce Heavy Lepton pairs carrying a new leptonic number and thus producing the $(e^{\pm}\mu^{\mp})$ signature. This was possible thanks to a powerful set-up able to simultaneously detect $(e^{\pm}e^{\mp})$, $(\mu^{\pm}\mu^{\mp})$ and $(e^{\pm}\mu^{\mp})$ pairs in hadronic processes. The technologically innovative key-point of this work was the invention of the "pre-shower" technique published in 1963. Notice that a large solid-angle detector able to observe $(e^{\pm}\mu^{\mp})$ pairs produced in hadronic interactions was fully operative at CERN already in 1964.

From 1963 to 1970 the technology was transferred from CERN to Frascati. In 1967 the BCF group presented its proposal to INFN. All the calibration work (TOF, heavy-plate spark chambers, π/e and π/μ) was performed at CERN with known beams of (e, μ, π) at the correct energies simulating ADONE final states. Without this extensive series of experimental studies at CERN it would have been impossible to search for a new sequential Heavy Lepton in Frascati. The experimental set-up mounted around the ADONE interaction region was working as a swiss-clock and the quality of the (e^+e^-) and $(\mu^+\mu^-)$ final states reported in Figures 5.7 and 5.8 is indeed an example. The selection power of the Frascati set-up was so good that we could determine as by-product of our experiment the EM form factor of the pseudoscalar mesons (π and K) in the time-like range allowed by the ADONE energies. Our set-up was in fact conceived to distinguish clearly between all known particles: electrons, muons, pions and kaons.

The time interval 1967-1970 is characterized by the INFN proposal and the first results.

The period 1971-1975 represents the crucial transition: the *HL* and the acoplanar $(e\mu)$ method, from Frascati to SLAC.

Let me now conclude by listing the following basic steps:

- the idea of a new lepton heavier than the known ones (e, μ) and carrying its own leptonic number;
- the choice of the best production process: $e^+e^- \to HL^+HL^-$;
- the invention of the technology to detect its existence: the acoplanar ($e^\pm\mu^\mp$) method;
- the implementation of the large solid angle detector needed to establish the first upper limit on the HL mass;
- the proof that the acoplanar ($e^\pm\mu^\mp$) method worked as expected in the design proposal;
- the promotion for the HL search at energies higher than ADONE.

The above points are the original contributions during more than a decade (1960-1975) of the Bologna-CERN-Frascati (BCF) group to the discovery of the Heavy Lepton. Looking back, it gives me great pleasure to know that each step in this long search did play an important role in reaching the final goal.

8 References

[1] *Evidence for anomalous lepton production in e^+–e^- annihilation*
M.L. Perl et al.
Physical Review Letters 35, 1489 (1975).

[2] *A proposal to search for leptonic quarks and heavy leptons produced by ADONE*
M. Bernardini, D. Bollini, E. Fiorentino, F. Mainardi, T. Massam, L. Monari, F. Palmonari and A. Zichichi.
INFN/AE-67/3, 20 March 1967.

[3] *Measurement of the anomalous magnetic moment of the muon*
G. Charpak, F.J. Farley, R.L. Garwin, Th. Muller, J.C. Sens, V.L. Telegdi and A. Zichichi.
Physical Review Letters 6, 128 (1961).

[4] *A telescope to identify electrons in the presence of pion background*
T. Massam, Th. Muller and A. Zichichi.
CERN 63-25, 27 June 1963.

[5] *A new electron detector with high rejection power against pions*
T. Massam, Th. Muller, M. Schneegans and A. Zichichi.
Nuovo Cimento 39, 464 (1965).

[6] *Un grand détecteur E.M. à haute rejection des pions*
D. Bollini, A. Buhler-Broglin, P. Dalpiaz, T. Massam, F. Navach, F.L. Navarria, M.A. Schneegans and A. Zichichi.
Revue de Physique Appliquée 4, 108 (1969).

[7] *A large electromagnetic shower detector with high rejection power against pions*
M. Basile, J. Berbiers, D. Bollini, A. Buhler-Broglin, P. Dalpiaz, P.L. Frabetti, T. Massam, F. Navach, F.L. Navarria, M.A. Schneegans and A. Zichichi.
*Nuclear Instruments and Methods **101**, 433 (1972).*

[8] *Range measurements for muons in the GeV region*
A. Buhler, T. Massam, Th. Muller and A. Zichichi.
CERN Report 64-31, 24 June 1964.

[9] *Range measurements for muons in the GeV region*
A. Buhler, T. Massam, Th. Muller and A. Zichichi.
*Nuovo Cimento **35**, 759 (1965).*

[10] *A large-acceptance and high-efficiency neutron detector for missing-mass studies*
D. Bollini, A. Buhler-Broglin, P. Dalpiaz, T. Massam, F. Navach, F.L. Navarria, M.A. Schneegans, F. Zetti and A. Zichichi.
*Nuovo Cimento **61A**, 125 (1969).*

[11] *Search for the timelike structure of the proton*
M. Conversi, T. Massam, Th. Muller and A. Zichichi.
*Physics Letters **5**, 195 (1963).*

[12] *An experiment on the timelike electromagnetic structure of the proton*
M. Conversi, T. Massam, Th. Muller and A. Zichichi.
Proceedings of the International Conference on "Elementary Particles", Siena, Italy, 30 September-5 October 1963 (Soc. Ital. di Fisica, Bologna, 1964), Vol. I, 488.

[13] *Proton antiproton annihilation into muon pair*
M. Conversi, T. Massam, Th. Muller, M. Schneegans and A. Zichichi.
Proceedings of the International Conference on "High-Energy Physics", Dubna, USSR, 5-15 August 1964 (Atomizdat, Moscow, 1966), Vol. I, 857.

[14] *The leptonic annihilation modes of the proton-antiproton system at 6.8 $(GeV/c)^2$ timelike four-momentum transfer*
M. Conversi, T. Massam, Th. Muller and A. Zichichi.
*Nuovo Cimento **40**, 690 (1965).*

[15] *Observation of the rare decay mode of the ϕ-meson: $\phi \to e^+e^-$*
D. Bollini, A. Buhler-Broglin, P. Dalpiaz, T. Massam, F. Navach, F.L. Navarria, M.A. Schneegans and A. Zichichi.
*Nuovo Cimento **56A**, 1173 (1968).*

[16] *The decay mode $\omega \rightarrow e^+e^-$ and a direct determination of the ω–ϕ mixing angle*
D. Bollini, A. Buhler-Broglin, P. Dalpiaz, T. Massam, F. Navach, F.L. Navarria, M.A. Schneegans and A. Zichichi.
Nuovo Cimento 57A, 404 (1968).

[17] *The basic SU_3 mixing: $\omega_8 \leftrightarrow \omega_1$*
A. Zichichi.
"Evolution of Particle Physics" (Academic Press Inc., New York-London, 1970), 299.

[18] *Validity of the leptonic selection rules for the ($\mu e \gamma$) vertex at high four-momentun transfers*
V. Alles-Borelli, M. Bernardini, D. Bollini, P.L. Brunini, T. Massam, L. Monari, F. Palmonari and A. Zichichi.
Nuovo Cimento Letters ***4****, 1151 (1970).*

[19] *Limits on the electromagnetic production of heavy leptons*
V. Alles-Borelli, M. Bernardini, D. Bollini, P.L. Brunini, T. Massam, L. Monari, F. Palmonari and A. Zichichi.
Nuovo Cimento Letters ***4****, 1156 (1970).*

[20] *Study of charged final states produced in e^+e^- interactions*
V. Alles-Borelli, M. Bernardini, D. Bollini, P.L. Brunini, E. Fiorentino, T. Massam, L. Monari, F. Palmonari and A. Zichichi.
Proceedings of the VIII Course of the "Ettore Majorana" International School of Subnuclear Physics, Erice, Italy, 1970: "Elementary Processes at High Energy" (Academy Press Inc. New York-London, 1971), 790.

[21] *Experimental check of crossing symmetry in the electromagnetic interaction of leptons*
V. Alles-Borelli, M. Bernardini, D. Bollini, P.L. Brunini, E. Fiorentino, T. Massam, L. Monari, F. Palmonari and A. Zichichi.
Nuovo Cimento Letters ***2****, 376 (1971).*

[22] *Experimental proof of the inadequacy of the peaking approximation in radiative corrections*
V. Alles-Borelli, M. Bernardini, D. Bollini, P.L. Brunini, E. Fiorentino, T. Massam, L. Monari, F. Palmonari and A. Zichichi.
Physics Letters ***36B****, 149 (1971).*

[23] *A check of quantum electrodynamics and of electron-muon equivalence*
V. Alles-Borelli, M. Bernardini, D. Bollini, P.L. Brunini, E. Fiorentino, T. Massam, L. Monari, F. Palmonari and A. Zichichi.
Nuovo Cimento 7A, 330 (1972).

[24] *Direct check of QED in e^+e^- interactions at high q^2 values*
V. Alles-Borelli, M. Bernardini, D. Bollini, P.L. Brunini, E. Fiorentino, T. Massam, L. Monari, F. Palmonari and A. Zichichi.
*Nuovo Cimento **7A**, 345 (1972).*

[25] *Acoplanar (e^+e^-) pairs and radiative corrections*
M. Bernardini, D. Bollini, P.L. Brunini, E. Fiorentino, T. Massam, L. Monari, F. Palmonari, F. Rimondi and A. Zichichi.
*Physics Letters **45B**, 169 (1973).*

[26] *Accurate measurement of the energy dependence of the process $e^+ + e^- \rightarrow e^\pm + e^\mp$, in the s-range 1.44-9.0 GeV^2*
M. Bernardini, D. Bollini, P.L. Brunini, E. Fiorentino, T. Massam, L. Monari, F. Palmonari, F. Rimondi and A. Zichichi.
*Physics Letters **45B**, 510 (1973).*

[27] *Limits on the mass of heavy leptons*
M. Bernardini, D. Bollini, P.L. Brunini, E. Fiorentino, T. Massam, L. Monari, F. Palmonari, F. Rimondi and A. Zichichi.
*Nuovo Cimento **17A**, 383 (1973).*

[28] *A detailed study of exclusive and inclusive (e^+e^-)-induced processes in the energy range 1.2-3.0 GeV*
M. Bernardini, D. Bollini, P.L. Brunini, T. Massam, L. Monari, F. Palmonari, F. Rimondi and A. Zichichi.
Proceedings of the 17th International Conference on "High-Energy Physics", London, UK, 1-10 July 1974 (Rutherford Lab., Chilton, 1974), IV-6.

[29] *An experimental study of acoplanar $(\mu^\pm\mu^\mp)$ pairs produced in (e^+e^-) annihilation*
D. Bollini, P. Giusti, T. Massam, L. Monari, F. Palmonari, G. Valenti and A. Zichichi.
*Nuovo Cimento Letters **13**, 380 (1975).*

[30] *Measurements of $\sigma(e^+e^- \rightarrow \mu^\pm\mu^\mp)$ in the energy range 1.2-3.0 GeV*
V. Alles-Borelli, M. Bernardini, D. Bollini, P. Giusti, T. Massam, L. Monari, F. Palmonari, G. Valenti and A. Zichichi.
*Physics Letters **59B**, 201 (1975).*

[31] *Proof of hadron production in e^+e^- interactions*
V. Alles-Borelli, M. Bernardini, D. Bollini, P.L. Brunini, F. Fiorentino, T. Massam, L. Monari, F. Palmonari, G. Valenti and A. Zichichi.
Proceedings of the International Conference on "Meson Resonances and Related Electromagnetic Phenomena" Bologna, Italy, 14-16 April 1971 (Editrice Compositori, Bologna, 1972), 489.

[32] *e^+e^- annihilation into two hadrons in the energy interval 1400-2400 MeV*
V. Alles-Borelli, M. Bernardini, D. Bollini, P.L. Brunini, F. Fiorentino, T. Massam, L. Monari, F. Palmonari, F. Rimondi and A. Zichichi.
Physics Letters ***40B****, 433 (1972).*

[33] *Proof of comparable K-pair and π-pair production from time-like photons of 1.5, 1.6 and 1.7 GeV, and determination of the K-meson electromagnetic form factor*
M. Bernardini, D. Bollini, P.L. Brunini, F. Fiorentino, T. Massam, L. Monari, F. Palmonari, F. Rimondi and A. Zichichi.
Physics Letters ***44B****, 393 (1973).*

[34] *The time-like electromagnetic form factors of the charged pseudoscalar mesons from 1.44 to 9.0 GeV^2*
M. Bernardini, D. Bollini, P.L. Brunini, F. Fiorentino, T. Massam, L. Monari, F. Palmonari, F. Rimondi and A. Zichichi.
Physics Letters ***46B****, 261 (1973).*

[35] *The energy dependence of $\sigma(e^+e^- \to$ hadrons) in the total centre-of-mass energy 1.2 to 3.0 GeV*
M. Bernardini, D. Bollini, P.L. Brunini, F. Fiorentino, T. Massam, L. Monari, F. Palmonari, F. Rimondi and A. Zichichi.
Physics Letters ***51B****, 200 (1974).*

[36] *Cross-section measurements for the exclusive reaction $e^+e^- \to 4\pi^\pm$ in the energy range 1.2-3.0 GeV*
M. Bernardini, D. Bollini, P.L. Brunini, F. Fiorentino, T. Massam, L. Monari, F. Palmonari, F. Rimondi and A. Zichichi.
Physics Letters ***53B****, 384 (1974).*

[37] *A study of the hadronic angular distribution in (e^+e^-) processes from 1.2 to 3.0 GeV*
M. Bernardini, D. Bollini, P.L. Brunini, F. Fiorentino, T. Massam, L. Monari, F. Palmonari, F. Rimondi and A. Zichichi.
Nuovo Cimento ***26A****, 163 (1975).*

[38] *The pion electromagnetic form factor in the time like range (1.44-9.0) $(GeV)^2$*
D. Bollini, P. Giusti, T. Massam, L. Monari, F. Palmonari, G. Valenti and A. Zichichi.
Nuovo Cimento Letters ***14****, 418 (1975).*

[39] *The present knowledge of $|F\pi|$ and the value of a low-energy (e^+e^-) storage ring*
M. Basile, D. Bollini, G. Cara Romeo, L. Cifarelli, P. Giusti, T. Massam, L. Monari, F. Palmonari, M. Placidi, G. Valenti and A. Zichichi.
Nuovo Cimento ***34A****, 1 (1976).*

[40] *The heartbeat of the proton*
V.F. Weisskopf.
in "*Lepton Physics at CERN and Frascati*", Ed. N. Cabibbo, World Scientific Series in 20th Century Physics (World Scientific, Singapore, 1994), 41.

[41] *Heavy electrons and muons*
F.E. Low.
Physical Review Letters ***14****, 328 (1965).*

[42] *Search for new particles produced by high-energy protons*
A. Barna, J. Cox, F. Martin, M.L. Perl, T.H. Tan, W.T. Toner, T.F. Zipf and E.H. Bellamy.
Physical Review ***173****, 1391 (1968).*

[43] For a review of the theoretically required heavy leptons with their production and decay properties, see for instance:
Spontaneously broken gauge theories of weak interactions and heavy leptons
J.D. Bjorken and Ch. Llewellyn Smith.
Physical Review ***7D****, 887 (1973).*

[44] *How does the muon differ from the electron?*
M.L. Perl.
Physics Today, July 1971, 34.

[45] *Why (e^+e^-) physics is fascinating*
A. Zichichi.
Nuovo Cimento Rev. ***4****, 498 (1974)*, based on the contribution to many conferences, in particular: the EPS Conference of Wiesbaden, 3-6 October 1972; and also the IV International Symposium on Multiparticle Hadrodynamics, Pavia, 31 August-4 September 1973; the XVI International Conference on High-Energy Physics, Batavia, Ill., 1972; the Informal Meeting on Recent Developments in High-Energy Physics, Frascati, 26-31 March 1973; the International Discussion Meeting on (e^+e^-) Annihilation, Bielefeld, 19-21 September 1973.