Proceedings of the 6th International Symposium on Electron and Photon Interactions at High Energies

Editors: H. Rollnik and W. Pfeil

PROCEEDINGS

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PREFACE

The 1973 "Symposium on Electron and Photon Interactions at High Energies" was the sixth in this series and was held ten years after they began February 1963 in Boston. At the present meeting the scope was enlarged by including high energy neutrino physics, thereby reflecting the fascinating developments towards a unification of electromagnetic and weak interactions and the importance of experiments with high energy neutrinos in this context. Therefore this meeting would be more appropriately termed "Symposium on Lepton and Photon Physics at High Energies". Only for reasons of continuity, the Organizing Committee decided to keep the old title this time.

Apart from a working session on the technical aspects of the neutrino experiments, this Symposium, as its forerunners, consisted exclusively of plenary sessions. These Proceedings contain the full text of the plenary talks and discussions. Abstracts of all submitted papers are also included.

The Organizing Committee would like to thank all of the speakers for their cooperation in preparing these Proceedings and all scientific secretaries for their help before, during and after the Symposium.

H. Rollnik

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INT. SYMP. ON ELECTRON AND PHOTON INTERACTIONS AT HIGH ENERGIES 1973 – NORTH-HOLLAND

RECENT EXPERIMENTAL RESULTS

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1 Introduction

Electron–Positron Colliding Beam Physics is a very young field. AdA, constructed at Frascati, was the first storage ring to be filled with electrons and positrons. In 1964, Bernardini et al. [1] reported the definite proof of electron–positron collisions in AdA through the detection of single Bremsstrahlung of one beam on the other. This observation was made at Orsay where the linear accelerator provided electron and positron beams of sufficient intensity for this observation. I hope very much that AdA is being preserved for a place of honor in a future Museum of Particle Accelerators!

The 1967 meeting at Stanford was the first Electron–Photon Symposium to hear particle physics results from e^+e^- collisions in VEPP-2 (Novosibirsk) and in ACO (Orsay) [2]. By the time of the 1969 Liverpool Symposium, these two laboratories had made exciting measurements of the properties of the ρ, ω and ϕ mesons, and had verified the validity of quantum electrodynamics at high values of q^2 both in the space- and time-like region [3]. The 1971 Cornell Symposium was the first to hear from ADONE whose completion expanded the region of available center-of-mass energy $\sqrt{s} = 2E$ to 2.4 GeV. (E is the individual beam energy). 5 different experimental groups reported very important results on the verification of quantum electrodynamics and the production of hadrons. In particular the production of multihadron events was found to be surprisingly large [4]. Since 1971 ADONE has raised its beam energy to reach a value of $\sqrt{s} = 3$ GeV. CEA has carried out experiments at center-of-mass energies of 4 and 5 GeV, and the first of the new generation of storage rings, SPEAR, has started operation with substantially higher luminosity than any of the previous systems. DORIS will soon join SPEAR as the second member of this new generation; both systems are designed to reach values of $\sqrt{s} = 6$–7 GeV and after some improvements will reach $\sqrt{s}$ values of up to 9 GeV! Fig. 1 is an attempt to summarize the energy range and the peak luminosity of colliding beam systems present, past and future!

All but two of the papers submitted to this Conference come from ADONE and CEA: as we will see these results add considerably to our knowledge of the physics of e^+e^- collisions, particularly in the high-energy region. The results on hadron production especially whet our appetite for future results with the new higher luminosity colliding beam systems.

A new generation of detectors is also coming into operation. Up to now all results have been obtained with non-magnetic detectors for reasons of simplicity and expected physics. Now that the production of hadrons in e^+e^- collisions is coming to the forefront, magnetic detectors are required, and the first ones have recently started operation at ADONE and SPEAR, with another one nearing completion at ACO.

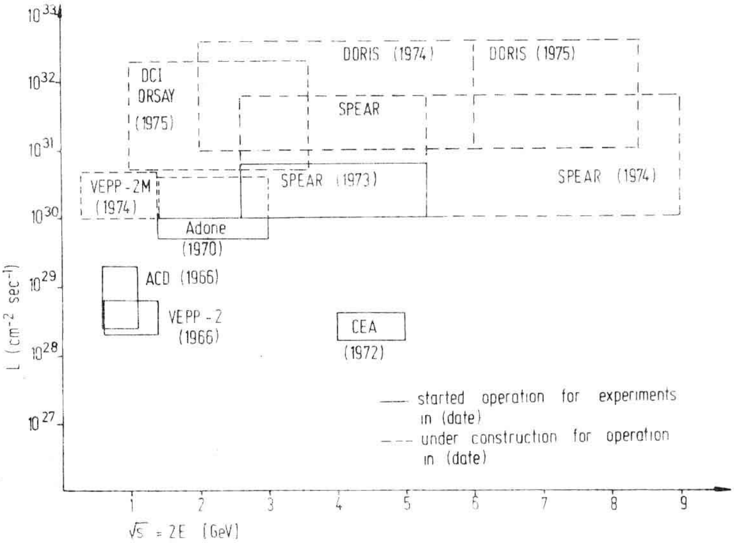


Fig. 1. The indicated luminosities are approximate. No attempt has been made to include the energy dependence of luminosity, and the indicated peak luminosities are not necessarily available over the whole region of operation. Average luminosities are usually a factor of 3–5 lower. VEPP-3 and VEPP-4 are not included because of lack of recent information.

In this talk I will summarize the new experimental results that have become available since the 1971 Cornell Conference; I will particularly stress those results submitted to this conference and those published since the 1972 Particle Physics Conference in Chicago. I clearly cannot do justice to all of the experiments and I apologize to those who feel that they have been slighted more than a tolerable amount.

2 Quantum electrodynamic processes

The three reactions of order α^2 for the study of the validity of QED with e^+e^- colliding beams are:

$$e^+ + e^- \rightarrow e^+ + e^-, \tag{1}$$

$$e^+ + e^- \rightarrow \gamma + \gamma, \tag{2}$$

$$e^+ + e^- \rightarrow \mu^+ + \mu^-. \tag{3}$$

The QED calculations for these processes are based on the assumption that (1) leptons behave like point-like Dirac particles; (2) Maxwell's equations are valid, the photon propagator is simply given by $1/q^2$; (3) diagrams of the order α^2 dominate in the calculations, and contributions from higher order diagrams can be taken care of by the usual methods of radiative corrections. The validity of these assumptions has been tested with increasing accuracy and over an increasingly large energy region in experiments reported at this Symposium from Frascati and CEA: let me say right away that no deviations have been found! I will not discuss reaction (3) since no new results have become available since last year's Chicago Conference.

Reactions (2) and (3) contain no e^+ or e^- in the final state and are thus "annihilation reactions"; they do not occur in e^-e^- collisions. As will be discussed below, the Bhabha scattering reaction (1) involves an additional annihilation diagram not present in the e^-e^- elastic scattering. Reaction (3) is the only one of the three to uniquely involve a time-like photon.

Interesting results on the validity of QED and on the search for heavy leptons are reported at this symposium from studies of the α^3 order Bremsstrahlung reaction:

$$e^+ + e^- \rightarrow e^+ + e^- + \gamma, \tag{4}$$

Three QED reactions of order α^4 have been studied in e^+e^- colliding beam systems:

$$e^+ + e^- \rightarrow e^+ + e^- + \gamma + \gamma, \tag{5}$$

$$e^+ + e^- \rightarrow e^+ + e^- + e^+ + e^-, \tag{6}$$

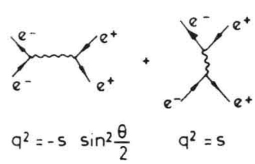
$$e^+ + e^- \rightarrow e^+ + e^- + \mu^+ + \mu^-. \tag{7}$$

The double Bremsstrahlung reaction (5) was first studied at Novosibirsk [5] and has since served as a convenient luminosity monitor for medium luminosity experiments. New interesting results are reported at this symposium for reactions (6) and (7) from experiments at Frascati in which the inelastically scattered electron and positron are detected.

In reactions (4)–(7) the final state contains the initial state leptons plus one or more particles or photons. These reactions occur both in e^+e^- and in e^-e^- collisions. The name "electroproduction" is traditionally used to describe the production of particles by electrons (or positrons) inelastically scattered from a target; reactions (4)–(7) are examples of electroproduction in contrast to reactions (2) and (3) which are annihilation reactions and only occur in e^+e^- collisions.

2.1 *Bhabha scattering $e^+e^- \rightarrow e^+e^-$*

The elastic scattering process $e^+e^- \rightarrow e^+e^-$ is described by two Feynman diagrams:



For experiments which do not measure the charge of the lepton (the only ones reported to date) the annihilation diagram (on the right) plays its most significant role at the scattering angle of $\theta = 90°$. All the experiments detect electrons and positrons scattered into a solid angle centered around $\theta = 90°$.

At Frascati the luminosity is measured using small angle Bhabha scattering; at CEA the double Bremsstrahlung process is used for this purpose. Both monitors detect events dominated by low q^2 space-like processes where it is reasonable to assume that QED is valid [6].

The most accurate experiment spanning the region of $\sqrt{s} = 1.2$–3.0 GeV has been carried out at Frascati by the BCF group [7]. Their results are based on 12,827 events scattered into the region $45° < \theta < 135°$ and distributed among 11 values of $\sqrt{s}$. The authors fit their beautiful results shown in fig. 2 with the expression:

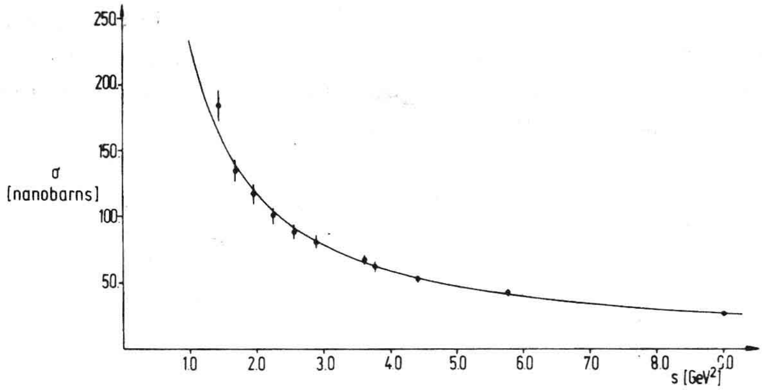


Fig. 2. The cross section for Bhabha scattering into the angular region $45° < \theta < 135°$ as a function of s as measured by the BCF group at ADONE [7]. The solid curve is calculated from QED with first order radiative corrections.

$$\sigma = As^n \tag{8}$$

and report:

$$A_{exp}/A_{QED} = 1.00 \pm 0.02, \qquad n = -(0.99 \pm 0.02). \tag{8'}$$

The theoretical calculations include first order radiative corrections.

In fact the event sample is large enough to permit significant checks of the radiative corrections with the experimental data and thus checks QED to the order of α^3 [reaction (4)]. Of special interest is the distribution in the acoplanarity angle ϕ which is defined as the angle between two planes, each of which contains the electron or positron and the beam axis. The often-used peaking approximation assumes that the ϕ distribution is a δ function at $\phi = 0$; in fact the BCF group finds 429 e^+e^- events that have $|\phi| > 5°$ [8]. This number is in excellent agreement with theoretical predictions based on the work of Kessler and collaborators [9] both in terms of s dependence and of absolute numbers as shown in fig. 3 (which is restricted to the fraction of events with $|\phi| > 10°$).

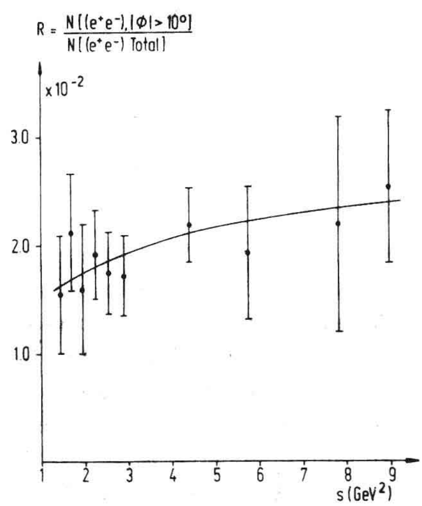


Fig. 3. The s dependence of the ratio of the number of events with acoplanarity angle larger than 10° to the total number of Bhabha scattering events observed by the BCF group [7]. The solid curve is calculated from QED.

The authors point out that acoplanar pairs of e^+e^- could also be produced by heavy leptons through the decays

$$e^{*+} \rightarrow e^+ + \nu_e + \bar{\nu}_{e^*}, \qquad e^{*-} \rightarrow e^- + \bar{\nu}_e + \nu_{e^*}. \tag{9}$$

Since all acoplanar events are well accounted for by QED there is no evidence for such heavy leptons in this experiment.

Conversi et al. [10] report the results of an experiment of Bhabha scattering at $\sqrt{s} = 2.8$ GeV which includes 2541 events scattered into the region $53° < \theta < 23°$. They report

$$R \equiv \sigma_{exp}/\sigma_{QED} = 0.98 \pm 0.04, \qquad \sqrt{s} = 2.8 \text{ GeV}. \tag{10}$$

This is the highest statistics experiment to date at such high an energy. This result is shown in fig. 4 which also includes other recent results.

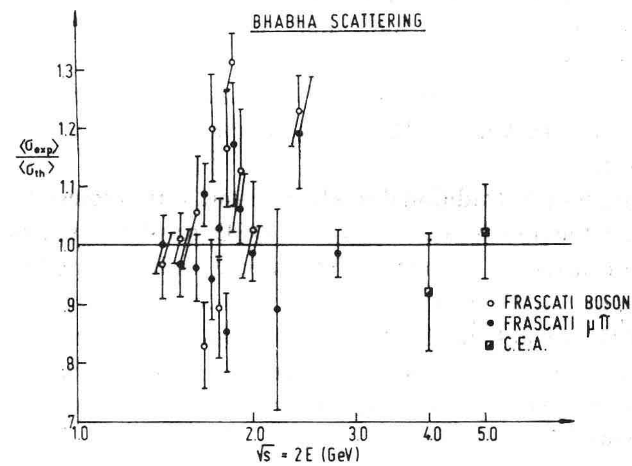


Fig. 4. Summary plot of the checks of QED in Bhabha scattering as a function of center-of-mass energy. The results of the BCF group [7] could not be included since their detailed results at different energies are not reported in their paper. This figure is taken from [11] which lists sources.

The highest energy results on Bhabha scattering available to date are reported from CEA at a value of $\sqrt{s} = 5.0$ GeV [11] based on 227 events in the region $50° < \theta < 130°$. The authors report

$$R \equiv \sigma_{exp}/\sigma_{QED} = 1.03 \pm 0.08, \qquad \sqrt{s} = 5.0 \text{ GeV}. \tag{11}$$

The evaluation of the luminosity on which this result is based represents an improvement of the method used in the earlier CEA experiment at $\sqrt{s} = 4.0$ GeV [12]. When the improved method is applied to the earlier experiment, the ratio is raised from the published value of $R = 0.88 \pm 0.10$ to the revised value of

$$R \equiv \sigma_{exp}/\sigma_{QED} = 0.92 \pm 0.10. \tag{12}$$

Fig. 5 shows the excellent detailed agreement of the angular distribution at $\sqrt{s} = 5.0$ GeV with the theory.

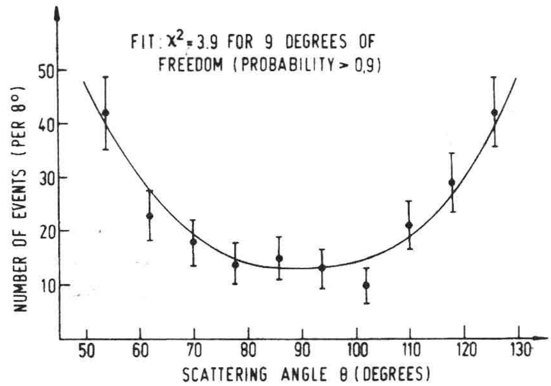


Fig. 5. The angular distribution of Bhabha scattering at $\sqrt{s} = 5.0$ GeV (from ref. [11]).

We conclude that all of the available experiments on high energy Bhabha scattering are in excellent agreement with QED within an accuracy at individual energies of 3–5% up to $\sqrt{s} = 3$ GeV and within 8–10% up to $\sqrt{s} = 5$ GeV.

In order to interpret these limits on the validity of QED in Bhabha scattering, it is of course necessary to use theoretical models for the breaking of QED. This summary of experiments could stop with the numbers that have been given.

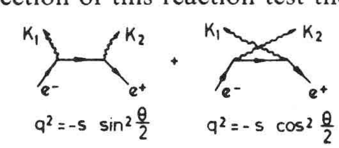
However it is useful to discuss one traditional model and one very interesting model for breaking QED. In the traditional model the possible deviation from QED is assigned to a heavy photon of mass Λ with either positive (Λ_+) or negative (Λ_-) metric. This model leads to a modification of the photon propagation by a factor of $F(q^2) = 1 \pm q^2/(q^2 - \Lambda_\pm^2)$. I am not sure of the theoretical foundation of this model, but it does have the advantage of predicting a deviation which increases with increasing s and this serves to increase the relative importance of higher energy, larger error experiments compared to lower energy, smaller error experiments! The high energy CEA experiment sets limits of $\Lambda_- > 10.6$ GeV and $\Lambda_+ > 10.0$ GeV with 95% confidence.

A very interesting model developed by Conversi et al. [10] ascribes any deviation from QED to the possible existence of a scalar boson ϕ (mass m_ϕ) of the kind introduced in the recent attempts to give a unified theory of weak and electromagnetic interactions. By incorporating the Giorgi–Glashow model (which includes a charged intermediate boson of mass m_w) and using the present experimental value of $(g-2)$ for the muon, these authors report the following limits on the values of m_ϕ for fixed values of m_w from the results of their $\sqrt{s} = 2.8$ GeV experiment [10]:

$m_\phi > 10$ GeV ($m_w = 10$ GeV); $m_\phi > 6.5$ GeV ($m_w = 15$ GeV);
$m_\phi > 4.5$ GeV ($m_w = 20$ GeV).

2.2 *Two photon annihilation*

The second QED reaction (2) has two Feynman amplitudes with virtual electron states as shown. Experiments measuring the cross section of this reaction test the electron propagator.



Measurements of the annihilation into two photons have been published by a group in Novosibirsk [13] (58 events at $\sqrt{s}$ = 1.0 GeV) and a group at Frascati [14] (107 events distributed in the interval $\sqrt{s}$ = 1.4–2.4 GeV). To these can now be added a CEA result [15] based on 34 events at the single energy of $\sqrt{s}$ = 4.0 GeV

$$R \equiv \sigma_{\rm exp}/\sigma_{\rm QED} = 1.09^{+0.23}_{-0.21}. \tag{13}$$

(The improved luminosity evaluation [11] has been applied to the published value of 1.05).

All of the measurements agree with QED as shown in fig. 6; the three experiments use different methods of measuring the luminosity, with low q^2 processes dominating in all three.

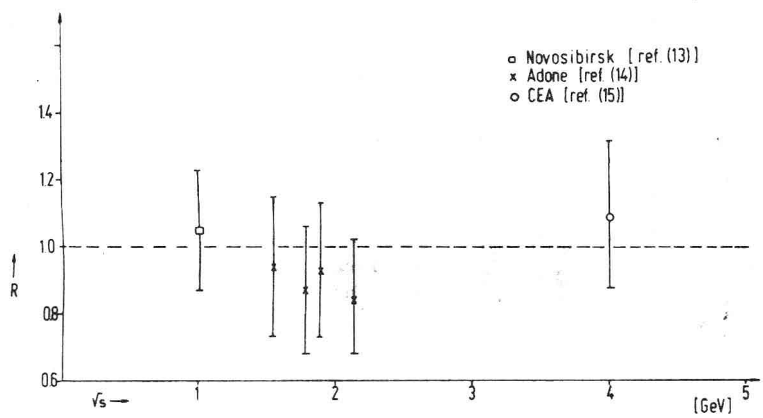


Fig. 6. Summary plot of the checks of QED in the reaction $e^+e^- \to \gamma\gamma$.

2.3 Experimental intermezzo

These studies of QED reactions have been carried out with non-magnetic detectors involving scintillation counters, spark chambers (optical or wire on-line), radiators and absorbers. Electrons and photons are identified through electromagnetic shower production, muons through range and absence of nuclear interactions, hadrons through range, absence of electromagnetic showers, and presence of nuclear interactions. A typical and most recent example is BOLD [12], the detector used at CEA, which is shown in fig. 7. The various detectors differ mainly in the solid angle covered and the arrangement of radiators, counters and spark chambers which are tuned for the observation of a given particle at a given energy.

Beron et al. [16] have recently completed the first SPEAR experiment at $\sqrt{s}$ = 5.2 GeV with a somewhat different detector shown in fig. 8. The energy of the electromagnetic showers is measured with high precision in large NaI counters at a cost in solid angle, a cost which can be afforded at SPEAR! It is important to note that with peak luminosities of $\sim 6 \times 10^{30}$ cm^{-2} sec^{-1}, no special problems have been encountered with background in the proportional chambers or the 75 cm diameter, 50 cm thick NaI crystals placed close to the beam pipe at θ = 90°. It is amusing to note that in a 35 day run ($\frac{1}{2}$ that of the second CEA run) an integrated luminosity of 2.7×10^{36} cm^{-2} (200 times that of the CEA run) was used to acquire 10–15 times the number of events of the CEA experiment! We look forward to the results from this experiment!

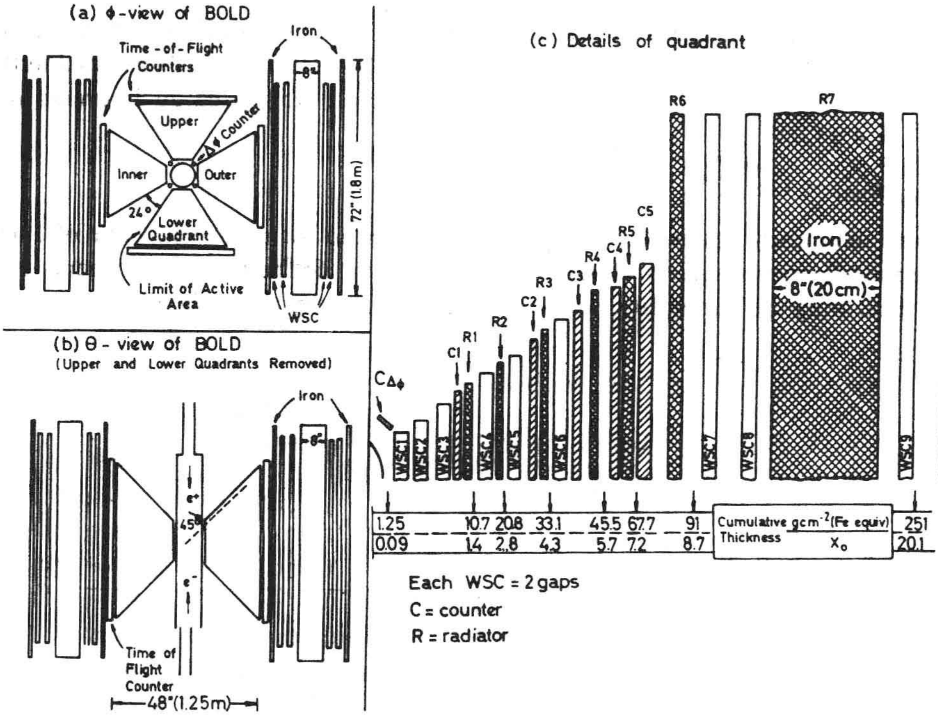


Fig. 7. The non-magnetic detector BOLD (from ref. [11]).

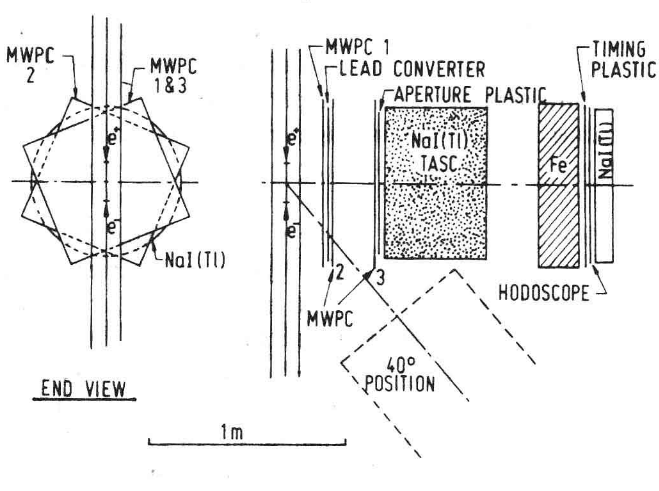
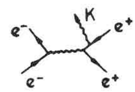


Fig. 8. The experimental arrangement used by the HEPL group at SPEAR to check QED (from ref. [16]).

2.4 Large angle Bremsstrahlung

Reaction (4) involves two photons as shown in one of the eight lowest order Feynman diagrams that contribute to this process [17]:



We have already discussed one study of this reaction under the topic of radiative corrections to Bhabha scattering (section 1).

Bacci et al. [18] report new results with 118 large angle (> 15°) events in the energy range $\sqrt{s}$ = 1.4–3.0 GeV. The results, shown in fig. 9, are in excellent agreement with QED (the maximum at 1.6

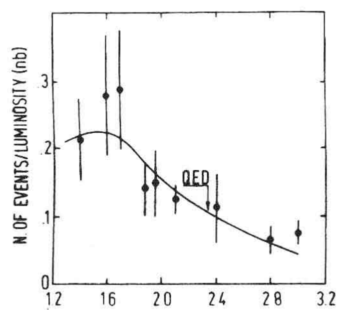


Fig. 9. The distribution in the mass of the (γe) system in the reaction $e^+ + e^- \rightarrow e^+ + e^- + \gamma$ as observed at Frascati [18]. The solid curve is calculated from QED: the shape is primarily determined by the apparatus geometry. A heavy lepton e* decaying by the (eγ) channel would appear as a spike.

GeV is due to the particular set-up used). In the experiment the angles of the three product particles are measured. It is thus possible to calculate the energy of the particles and the invariant mass of the (e, γ) system. The observed invariant mass distribution is in very good agreement with QED predictions which sets an upper limit to the production of a heavy lepton e*, which decays into an $e^{\pm}$ and a photon:

$$e^+ + e^- \rightarrow e^{\pm} + e^{*\mp} \qquad (14)$$
$$\hookrightarrow e^{\mp} + \gamma .$$

Fig. 10 shows the upper limits that have been obtained for λ, the (e*eγ) coupling constant, as a function of the heavy lepton mass m^*.

2.5 Lepton production in processes of order α^4

2.5.1 Characteristic features

It is now well known that the cross sections of the fourth order reactions (6) and (7) can reach values competitive with the corresponding lower order annihilation reactions. This is because the latter vary with energy as s^{-1} while the former vary as $\rightarrow \ln s$; a cross-over therefore occurs which turns out to be at a few GeV [21]. The importance of these processes in colliding beam physics was rediscovered

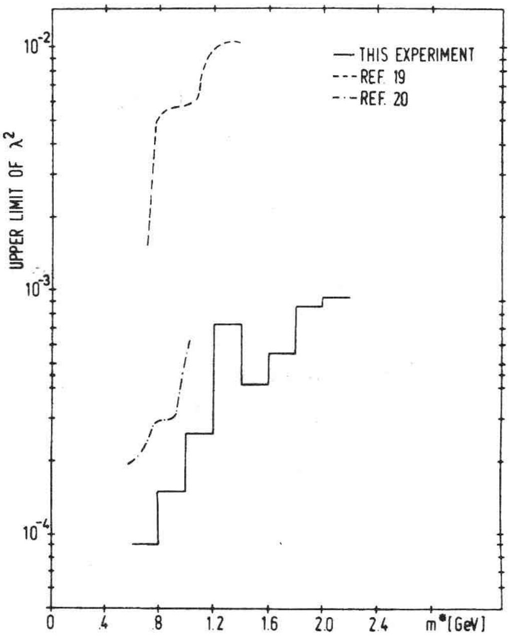


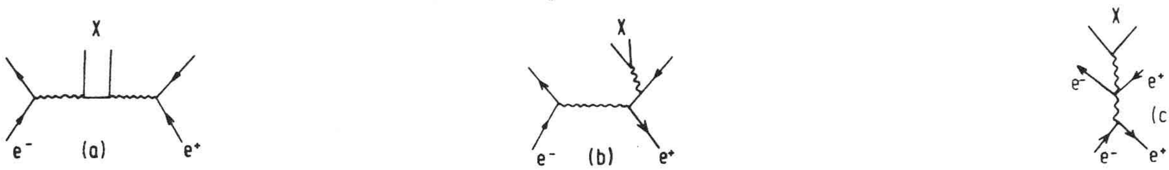
Fig. 10. The limits set by the wide angle Bremsstrahlung experiment [18] on the coupling constant $\lambda(e^*e\gamma)$ as a function of the heavy lepton mass m^*.

theoretically after having been forgotten, and reaction (6) was unexpectedly observed at Novosibirsk [22]. A comprehensive review article [23] summarizes the theory of processes of this type.

Reactions (6) and (7) are examples of the general electroproduction reaction:

$$e^+ + e^- \rightarrow e^+ + e^- + X, \tag{15}$$

where X is any system of leptons or hadrons consistent with the usual conservation laws. Calculations of the cross sections involve three types of diagrams:



Although the cross sections corresponding to these two photon diagrams are depressed by a factor of q^2 with respect to cross sections corresponding to the one-photon annihilation graph, the very low q^2 possible for each of the two photons (and not possible for the one annihilation photon) can more than compensate for this factor and produce the ln s energy dependence.

By proper choice of the kinematic region of observed particles, it is possible to select events in which diagram (a) with low mass, nearly-real photons, dominates the observations. *If* such a choice is made (and the use of small angle e^- and e^+ "tagging" for this purpose will be discussed below), then the observations can be thought of as the result of the collision of two nearly-real photons resulting in the