PHOTON RADIATION IN LEPTONIC REACTIONS AT LEP*

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Studies of photon radiation in leptonic reactions recorded with the four LEP experiments are presented. The predictions of the Monte-Carlo programs for photon spectra and angular distributions show excellent agreement with data. Events with photon radiation in the initial state provide information about lepton-pair production at reduced centre-of-mass energies. A large number of the events recorded at nominal centre-of-mass energies well above the Z resonance are due to the "radiative return to the Z". Separating these events from the "genuine high energy events" allows to measure fermion-pair production at $130\,\mathrm{GeV} < \sqrt{s} < 140\,\mathrm{GeV}$. The measurement of photon radiation in the reactions $e^+e^- \to \mu^+\mu^-\gamma$ and $e^+e^- \to \nu\bar{\nu}\gamma$ puts limits on the existence of anomalous $Z\gamma$ couplings.

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1. Introduction

During the LEP1 program the four experiments at LEP have collected data in the vicinity of the Z resonance. The large number of recorded Z decays, corresponding to an integrated luminosity of $150\,\mathrm{p}b^{-1}$ per experiment, was used to extract fundamental electroweak parameters like the mass and the width of the Z boson. The high energy of the particles makes radiative corrections due to photon radiation very important. In addition, the pure weak corrections, which provide informations about unknown particles, can only be measured, if the much larger QED corrections are perfectly understood. It is therefore desirable to compare the measured photon radiation with the prediction of the Monte-Carlo programs.

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2. Comparison of photon radiation with QED prediction

Firstly, I will present a comparison between the measured photon radiation in leptonic Z decays and the theoretical prediction. For this purpose data recorded with the L3 detector at LEP in the years 1991 to 1994 are analysed. They correspond to an integrated luminosity of 106 pb^{-1}. Events of the reaction $e^+e^- \to \mu^+\mu^-(\gamma)$ are studied, because they allow a clear distinction between photons and leptons in the detector. The Monte-Carlo program KORALZ [1] will be used for the theoretical prediction. To simulate photon radiation the KORALZ generator uses the program YFS3, which generates hard photons up to $\mathcal{O}(\alpha^2)$ in initial and final state.

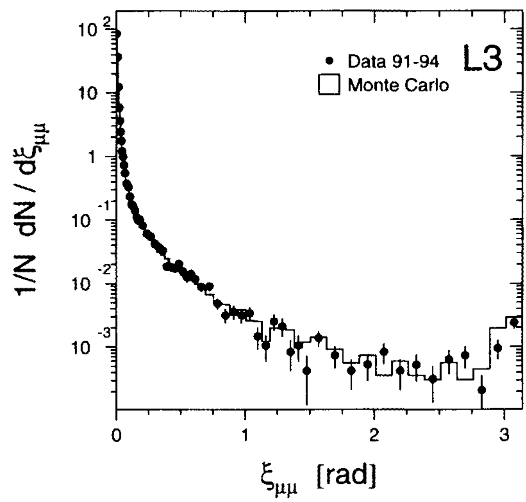

Fig. 1. Acolinearity, $\xi_{\mu\mu}$, of the muon pair. Muon-pair events recorded by the L3 detector are compared to the prediction of the Monte-Carlo program KORALZ.

For the reaction $e^+e^- \to \mu^+\mu^-(\gamma)$ the angle in space between the two muons is expected to be π, if there is no photon radiation in the event. The acolinearity, $\xi_{\mu\mu}$, of the muon pair, defined as the difference of this angle from π, is shown in Fig. 1. The events with little photon radiation are in the region $\xi_{\mu\mu} \approx 0$. The maximum possible acolinearity, $\xi_{\mu\mu} \approx \pi$, is due to events, where the two muons are going in the same direction and a photon with beam energy is recoiling against the muon pair. Perfect agreement between data and theory in the full range of the acolinearity distribution is established. The measurement covers cross sections differing by about five orders of magnitude.

The photons found in the muon-pair events are ordered according to their energy, and the energies of the first and second photon, E_1 and E_2, are normalised to the beam energy:

$$k_i = \frac{E_i}{E_{\text{beam}}} \, . \tag{1}$$

The resulting photon spectra are plotted in Fig. 2. For both, the total rate and the energy spectrum of the photons, data and Monte Carlo agree very well.

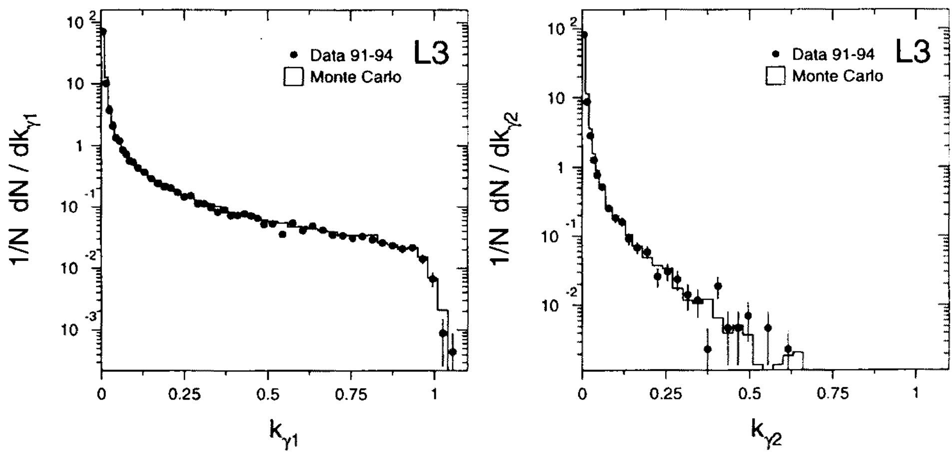

Fig. 2. Photon energies normalised to the beam energy. Muon-pair events recorded by the L3 detector are compared to the prediction of the Monte-Carlo program KORALZ.

The distributions show that the simulation of photon radiation works very well. The studies demonstrate the excellent quality of the QED radiative corrections, which are dominated by bremsstrahlung effects.

3. Study of initial-state radiation

Initial-state radiation is highly suppressed on the Z resonance. This is due to the fact that the radiation of a photon in the initial state reduces the effective centre-of-mass energy of the fermion-pair production and the event takes place at a smaller cross section. Nevertheless, using the large amount of data recorded at centre-of-mass energies in the vicinity of the Z peak, one still selects many events with hard initial-state photon radiation. They can be used to measure fermion-pair production at reduced centre-of-mass energies.

Photons are emitted predominantly collinear to the direction of the radiating particles. Initial-state photons go mainly along the direction of the

e^+e^- beams, while final-state photons cover the full solid angle. A separation of the different types of radiation is therefore possible. For three-particle final states the particle momenta follow from the measured directions using energy and momentum conservation. Assuming that the undetected initial-state photon is radiated along the beam line, its energy, E_γ is given by the polar angles, θ_1 and θ_2, of the outgoing fermions:

$$E_\gamma = \sqrt{s}\frac{|\sin(\theta_1+\theta_2)|}{\sin\theta_1+\sin\theta_2+|\sin(\theta_1+\theta_2)|} \; . \tag{2}$$

From the energy of the initial-state photon one finds for the effective centre-of-mass energy squared, s':

$$s' = s\left(1-2\frac{E_\gamma}{\sqrt{s}}\right) \; . \tag{3}$$

To measure the lepton-pair production at lower energies the four LEP collaborations [2–5] use events of the reaction $e^+e^- \to \mu^+\mu^-(\gamma)$. This process allows a clear separation between photons and outgoing leptons and hence gives a good rejection of the final-state bremsstrahlung events. Moreover, the polar angles of the two leptons can be measured with good precision, which is necessary for the determination of $\sqrt{s'}$. In the case of the L3 detector the resolution of $\sqrt{s'}$ is about 0.4 GeV.

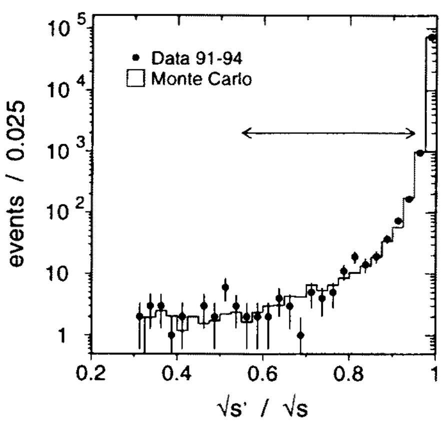

Fig. 3. The measured $\sqrt{s'}$ distribution for muon-pair events recorded by the L3 detector at $\sqrt{s} = m_Z$ [4].

The $\sqrt{s'}$ distribution measured at L3 [4] is shown in Fig. 3. Good agreement between data and Monte-Carlo prediction is observed. The cross sections at reduced centre-of-mass energies are determined by comparing the background corrected number of selected events in data with the Monte-Carlo prediction. The measured cross sections cover the energy range between the inclusive measurements at TRISTAN ($\sqrt{s} \approx 60\,\text{GeV}$) and at LEP1 ($\sqrt{s} \approx 90\,\text{GeV}$). The results of the four LEP experiments are shown in Fig. 4 together with the inclusive measurements at PEP, PETRA, TRISTAN and LEP, which have been corrected for the effect of initial-state photon radiation.

The forward-backward asymmetry is defined through the cross sections in forward direction, $\sigma_\text{f} = \sigma(\cos\theta^* > 0)$, and in backward direction, $\sigma_\text{b} = \sigma(\cos\theta^* < 0)$:

$$A_{fb} = \frac{\sigma_\text{f} - \sigma_\text{b}}{\sigma_\text{f} + \sigma_\text{b}} \,. \tag{4}$$

The angle θ^* is the production angle of the μ^- in the centre-of-mass system of the muon pair:

$$\cos\theta^* = \frac{\sin(\theta_{\mu^+} - \theta_{\mu^-})}{\sin\theta_{\mu^+} + \sin\theta_{\mu^-}} \,, \tag{5}$$

where θ_μ is the polar angle in the laboratory frame.

The results of the asymmetry measurements at the four LEP experiments are shown in Fig. 4. Also included are the inclusive measurements at PEP, PETRA, TRISTAN and LEP, which have been corrected for the effect of initial-state photon radiation.

4. Fermion-pair production above the Z

At the end of the data taking period of 1995 LEP delivered data corresponding to an integrated luminosity of 5 pb^{-1} per experiment at centre-of-mass energies between 130 GeV and 140 GeV. All four experiments reported on the measurements of the reactions:

$$e^+e^- \to hadrons(\gamma) \qquad e^+e^- \to \mu^+\mu^-(\gamma) \qquad e^+e^- \to \tau^+\tau^-(\gamma)$$
$$e^+e^- \to e^+e^-(\gamma) \qquad e^+e^- \to \nu\bar{\nu}(\gamma)$$

They measured cross sections for all reactions and forward-backward asymmetries for the charged lepton final states [6–9]. For a large fraction of the selected events, initial-state photons reduce the effective centre-of-mass energy, $\sqrt{s'}$, of the fermion-pair production to values close to the Z mass. A cut on $\sqrt{s'}$ allows to remove the "radiative return to the Z" and to measure exclusive cross sections and asymmetries for "genuine high energy events".

The effective centre-of-mass energy of the fermion pair is derived as follows. If an isolated photon is identified in the detector it is assumed to be radiated from the initial-state and Eq. (3) is used to calculate $\sqrt{s'}$. Otherwise the photon energy is calculated from the polar angles of the outgoing fermions, θ_1 and θ_2, using Eq. (3). In the case of the reaction $e^+e^- \rightarrow hadrons(\gamma)$ a jet finding algorithm is used to cluster the detected particles into two jets with polar angles θ_1 and θ_2.

Fig. 4 shows the $\sqrt{s'}$ distribution for the hadron and charged lepton final states as measured by the OPAL collaboration [7]. The position of the arrow indicates the separation between "genuine high energy events" and "return to the Z".

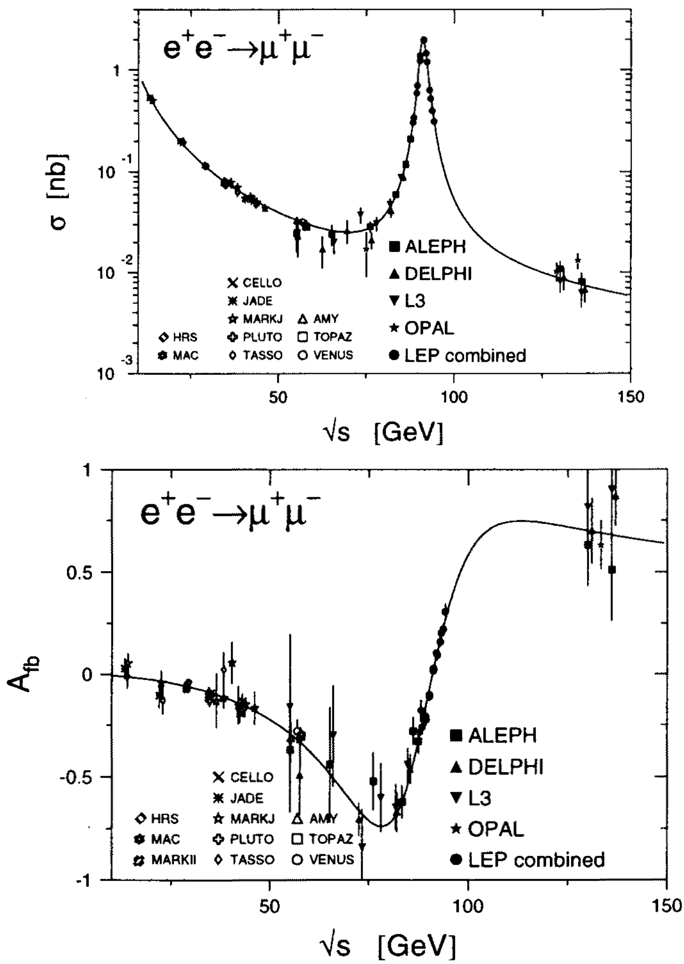

Fig. 4. Cross sections and forward-backward asymmetries of muon-pair production. Between 50 GeV and 87 GeV the results from the ISR analyses [3–5] are shown. The points between 130 GeV and 140 GeV are measured after removing the Z decays [6–9]. The inclusive measurements at PEP, PETRA, TRISTAN and LEP are also included.

Since the quark coupling to the Z is relatively large, most of the hadronic events appear to be pure Z decays. In the case of Bhabha scattering the events mostly take place at the nominal centre-of-mass energy. This is due to the dominance of the t-channel cross section, which is independent of the Z and still large at high centre-of-mass energies. For muon pairs and tau pairs one observes the same $\sqrt{s'}$ distribution with about equal numbers of events from high energies and from Z decays.

Selecting only events above a certain $\sqrt{s'}$ value allows to measure the fermion-pair production at 130 GeV $< \sqrt{s} <$ 140 GeV. The results of the cross-section and asymmetry measurements are shown in Fig. 5.

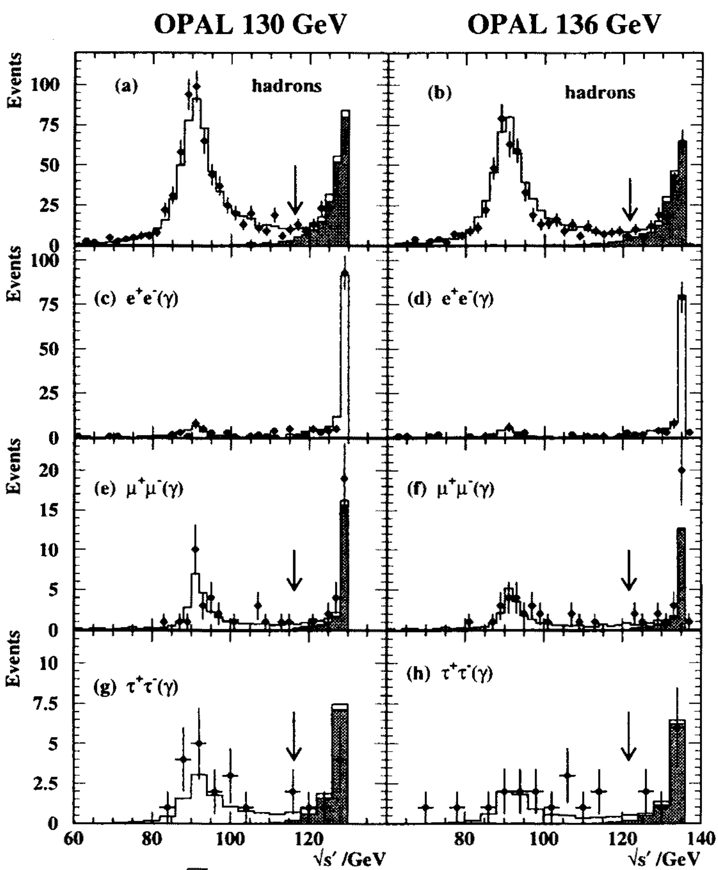

Fig. 5. Distributions of $\sqrt{s'}$ for hadron production, Bhabha scattering, muon-pair and tau-pair production measured by the OPAL collaboration [7]. The points show the data, the histograms the Monte-Carlo prediction. The shaded histograms represent the prediction for events with $s'/s > 0.8$.

5. Search for anomalous Zγ couplings

According to the Standard Model, tree-level Z$\gamma\gamma$ and ZZγ couplings do not exist. Quantum corrections effectivly induce such couplings, but their magnitudes are too small to have measurable consequences at any present or planned experiment. Thus, should 3-point Zγ couplings be observed, it would be a clear signal of New Physics. Z compositeness is one example of a New Physics scenario that could produce anomalous couplings of sufficient magnitude to be observable by present experiments at the LEP and TEVATRON colliders.

For an on-shell photon in the final state, the most general ZVγ ($V = $ Z$, \gamma$) vertex function which is invariant under Lorentz and electromagnetic gauge transformations may be written in terms of four form factors [10], h_i^V ($i = 1..4$). In terms of an effective Lagrangian, the contributions proportional to h_1^V and h_3^V are associated with dimension-6 operators and h_2^V and h_4^V are associated with dimension-8 operators. Consequently, the experimental sensitivity to the $h_{2,4}^V$ form factors grows faster with increasing centre-of-mass energy than does the sensitivity to $h_{1,3}^V$.

Following [10] the form factors are expressed as:

$$h_i^V(s) = \frac{h_{i0}^V}{(1 + s/\Lambda_V^2)^{n_i}} \qquad \text{with} \qquad n_1 = n_3 = 3, \quad n_2 = n_4 = 4\,. \tag{6}$$

This form-factor ansatz guarantees tree-level unitarity at asymptotically high energies for reasonable choices of n_i and Λ_V and as compositness may be responsible for anomalous couplings, it has the same form as those for nucleons, which are known to be composite systems.

Anomalous Zγ couplings would manifest themselves at LEP in the radiative production of fermion pairs. At LEP1 energies, the dominant amplitudes are those in which the electron and positron annihilate into a Z. Therefore the ZZγ vertex would produce events, where the Z radiates a hard photon and then decays into a fermion pair. The reaction $e^+e^- \to \nu\bar{\nu}(\gamma)$ is ideal to observe such events. Here the Standard Model background is small, because the neutrinos do not radiate photons and initial-state radiation is suppressed due to the Z resonance. The result of L3 from a search in this single-photon channel [11] is shown in Fig. 6. In addition the measurement of the CDF collaboration [12] at the TEVATRON collider is included. To obtain their limits they have studied radiative Z decays into charged leptons.

Single-photon events recorded at the Z are not sensitiv to the Z$\gamma\gamma$ vertex, because the photon does not couple to the neutrinos. Therefore L3 has used the $\mu^+\mu^-\gamma$ final state to set limits on the existence of Z$\gamma\gamma$ couplings. In this analysis one has to apply additional cuts on the detected photons to

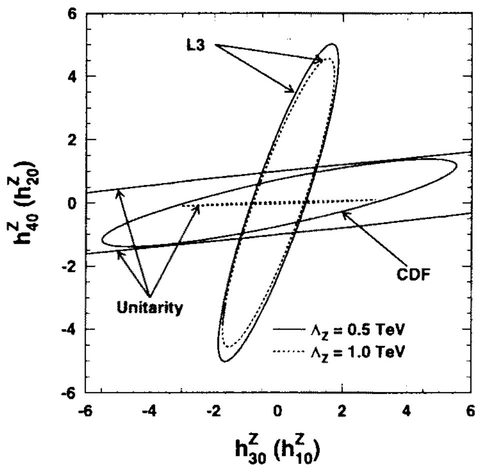

Fig. 6. Limits on anomalous ZZγ-couplings from L3 [11] and CDF [12] at 95% confidence level.

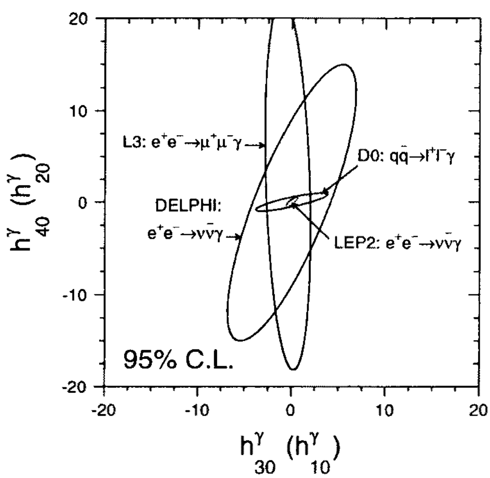

Fig. 7. Limits on anomalous Z$\gamma\gamma$-couplings from different collider experiments [13, 14] at 95% confidence level. The prospects of the LEP2 program [15] are also included.

enhance the visibility of anomalous couplings and to suppress the QED background coming mainly from final-state radiation. Especially a good angular separation of the photons from the beams and from the outgoing muons is required. A fit of the anomalous couplings to the energy spectrum of the photons gives the limits shown in Fig. 7.

The result of the D0 collaboration [13] at the TEVATRON collider using the radiative decay of Z bosons into leptons is also shown in Fig. 7. At energies above the Z resonance, the dominant sensitivity to $Z\gamma\gamma$ couplings at LEP comes again from the $\nu\bar{\nu}\gamma$ final state. DELPHI has used single-photon events [14] recorded at centre-of-mass energies between 130 GeV and 140 GeV and corresponding to an integrated luminosity of $5\,pb^{-1}$. Their limits on the $Z\gamma\gamma$ vertex do not reach the sensitvity of the other experiments yet. But the total luminosity of $500\,pb^{-1}$ per experiment expected at LEP2 will improve the limits significantly [15].

6. Conclusions

The studies of photon radiation in leptonic reactions at LEP show very good agreement between data and QED prediction.

Selecting events with initial-state photon radiation allows to measure the lepton-pair production at reduced centre-of-mass energies. Using the LEP data taken at the Z resonance one can measure the cross sections and forward-backward asymmetries of the muon-pair production at 50 GeV $< \sqrt{s} <$ 87 GeV. This analysis covers the energy range between the inclusive measurements at TRISTAN and LEP. The results agree very well with the Standard Model prediction.

The data taken between 130 GeV and 140 GeV can only be used to measure fermion-pair production at these energies after the "radiative return to the Z" and therefore all Z decays have been removed. The resulting cross sections and asymmetries are in good agreement with the Standard Model prediction.

The study of high energy photons in the reactions $e^+e^- \to \nu\bar{\nu}\gamma$ and $e^+e^- \to \mu^+\mu^-\gamma$ allows to search for anomalous $Z\gamma$ couplings. No indication for such couplings is found. The existing limits can be improved significantly by the measurements of the LEP2 program.

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