

TESTS OF QED WITH MULTI-PHOTONIC FINAL STATES

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In the Standard Model the process $e^+e^- \rightarrow \gamma\gamma(\gamma)$ is fully described by QED. Measurements of the differential cross-sections from the four LEP experiments are compared to the QED expectation and limits are set on parameters describing physics beyond the Standard Model. Three-photon events are used for a direct search for a photonically decaying resonance produced together with a photon.

1 Introduction

The process $e^+e^- \rightarrow \gamma\gamma(\gamma)$, called multi-photon production, is one of the few processes in high energy e^+e^- scattering which can be described by QED only. Since the only free parameter $\alpha(0)$ is precisely measured^a the Standard Model expectation is well known. Any deviation would hint at some new physics. In general such effects can be described by cut-off parameters or in the framework of effective Lagrangian theory. Effects can for example be caused by the t-channel exchange of excited electrons or the s-channel exchange of gravitons in models with extra dimensions. Events with three photons in the final state are used to search directly for a photonically decaying resonance which is produced together with a photon. Results will be presented from the four LEP experiments based on the full LEP2 statistics, including data taken in 2000.^b

2 Theory

The Born-level differential cross-section for the process $e^+e^- \rightarrow \gamma\gamma$ in the relativistic limit of lowest order QED is given by¹

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Born}} = \frac{\alpha^2}{s} \frac{1 + \cos^2\theta}{1 - \cos^2\theta}, \quad (1)$$

where s denotes the square of the centre-of-mass energy and θ is the scattering angle. Since the two photons are identical particles, the event angle is defined by convention such that $\cos\theta$ is positive.

^aSince the photons are in the final state the relevant momentum transfer for the fine-structure constant is the mass of the photon which is zero.

^bALEPH results from data taken in 2000 are not yet available.

Possible deviations from the QED cross-section can be parametrised in terms of cut-off parameters Λ_{\pm} which correspond to an additional exponential term to the Coulomb field ² as given in Eq. 2. Alternatively, in terms of effective Lagrangian theory, ³ the cross-section depends on the mass scales (e.g. Λ') for $ee\gamma\gamma$ contact interactions or non-standard $e^+e^-\gamma$ couplings. The resulting cross-sections are of two general types, either an angular independent offset to the cross-section or similar to the form given by Eq. 2.

$$\left(\frac{d\sigma}{d\Omega}\right)_{\Lambda_{\pm}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Born}} \pm \frac{\alpha^2 s}{2\Lambda_{\pm}^4}(1 + \cos^2\theta) \quad (2)$$

Recent theories have pointed out that the graviton might propagate in a higher-dimensional space where additional dimensions are compactified while other Standard Model particles are confined to the usual 3+1 space-time dimensions. The resulting large number of Kaluza-Klein excitations could be exchanged in the s-channel of $e^+e^- \rightarrow \gamma\gamma$ scattering. This leads to a differential cross-section ⁴ depending on the mass scale M_S which should be of order of the electroweak scale ($\mathcal{O}(10^{2-3}\text{GeV})$) and a parameter λ which is of $\mathcal{O}(1)$. Ignoring $\mathcal{O}(M_S^{-8})$ terms $M_S^{-4} = \alpha\pi\Lambda_{\pm}^{-4}$ for $\lambda = \mp 1$.

The existence of an excited electron e^* with an $e^*e\gamma$ coupling would contribute to the photon production process via t -channel exchange. The resulting cross-section depends on the e^* mass M_{e^*} and the coupling constant κ of the $e^*e\gamma$ vertex relative to the $ee\gamma$ vertex. ⁵ For large masses $M_{e^*} \approx \sqrt{\kappa}\Lambda_+$.

3 Radiative corrections

All cross-sections discussed above are calculated to $\mathcal{O}(\alpha^2)$. For higher order QED predictions an exact $\mathcal{O}(\alpha^3)$ Monte Carlo ⁶ and a Monte Carlo ⁷ for $e^+e^- \rightarrow \gamma\gamma\gamma\gamma$ in the relativistic limit are available, but no full $\mathcal{O}(\alpha^4)$ calculation. To keep theoretical uncertainties from higher orders below 1% it is essential to minimise third order corrections. This can be achieved via a proper choice of the scattering angle. Whereas in lowest order there are exactly two photons with the same scattering angle ($|\cos\theta_1| = |\cos\theta_2|$) for a measured event the two highest energy photons are in general not back-to-back ($|\cos\theta_1| \neq |\cos\theta_2|$). This leads to various possibilities for the definition of the scattering angle of the event.

The simplest quantity is the average $\cos\theta_{\text{av}} = (|\cos\theta_1| + |\cos\theta_2|)/2$ which leads to corrections of up to 30% at angles of $\cos\theta_{\text{av}} \approx 0$. These large corrections arise since the average does not change if one photon flips from one hemisphere to the other. This problem can be avoided using the

difference $\cos \theta_{\text{dif}} = (|\cos \theta_1 - \cos \theta_2|)/2$, which shows otherwise the same behaviour with corrections up to 10 (15)% for large values of $\cos \theta_{\text{dif}} > 0.88$ (0.95). A physics motivated definition is the angle in the centre-of-mass system of the two highest energy photons $\cos \theta^* = |\sin \frac{\theta_1 - \theta_2}{2}| / (\sin \frac{\theta_1 + \theta_2}{2})$. This definition leads to the smallest corrections of 3-7% within the studied angular range of $\cos \theta^* < 0.97$ and is therefore chosen for the analyses.

4 Selection

The selection of multi-photonic events relies on the photon detection in the electromagnetic calorimeter ECAL. The ECAL signature however is the same for $\gamma\gamma(\gamma)$ and $e^+e^-(\gamma)$ events. Since the Bhabha cross-section is huge this background must be suppressed by 4-5 orders of magnitude. To reject Bhabhas the tracking detectors are used to distinguish electrons from photons. This can be difficult at small scattering angles where the electrons do not travel the full extent of the tracking chamber and two particles can easily be reconstructed as one track. Also photon conversions at a small distance to the interaction point, i.e. before the first active detector layer are hard to separate. Since the conversion rate depends on the material in the detector the optimal angular range for the selection strongly depends on the experiment. The acceptance ranges given in Tab. 1 reflect also the different angular coverage of the ECAL. A very dangerous background is caused by low s' Bhabhas, with an invariant photon mass just above the threshold of 1 MeV. They have the same signature as a photonic event with early conversion and are badly simulated, since most Bhabha Monte Carlos impose much higher cuts on s' .

Table 1. Acceptance range and efficiency ϵ within this acceptance range of the four experiments. The efficiency might depend slightly on \sqrt{s} . The assumed systematic error on the efficiency $\delta\epsilon$ and the radiative corrections $\delta\rho$ are also given. Preliminary L3 results do not include systematic errors. Other systematic errors are small.

	$\cos \theta$ range	ϵ	$\delta\epsilon$	$\delta\rho$
ALEPH	[0, 0.95]	83%	1.3%	1.0%
DELPHI	$[0.035, 0.731] \cup [0.819, 0.906]$	76%	2.5%	0.5%
L3	[0, 0.961]	64%	1.2%/–	–
OPAL	[0, 0.90]	92%	1.0%	1.0%

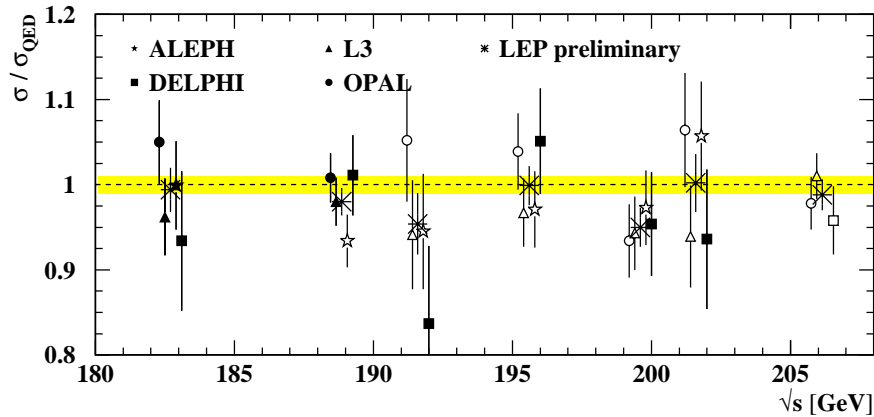


Figure 1. Measured total cross-section relative to the QED expectation. The values of single experiments are shown displaced in \sqrt{s} for clarity. Filled symbols represent final results, open symbols are preliminary. The error on preliminary L3 cross-sections is statistical only. The theoretical error of 1% is shown as shaded band and is not included in the experimental errors.

5 Cross-section results

The total and differential cross-sections are measured within the angular ranges given in Tab. 1. Figure 1 shows the total cross-sections normalised to the QED expectation for all four LEP experiments^{8,9,10,11} and their combination. Apart from the common theoretical uncertainty the correlated systematic error between experiments is negligible. In general there is a very good agreement. The average over all energies and experiments yields $0.980 \pm 0.008 \pm 0.007$ where the first error is statistical and the second systematic. This is two standard deviations low, not accounting for the assumed theoretical error of 1% which is of the same size as the experimental error.

The angular distributions are compared to the differential cross-sections predicted by various models. No significant deviation from QED was found and limits given in Tab. 2 are derived. For all experiments the limit on Λ_+ is larger than the limit on Λ_- . This effect is not significant yet it implies that the observed cross-section in the central region of the detectors is smaller than expected. Small scattering angles are less sensitive to these limits though their number of events is largest.

Table 2. Limits derived from fits to the angular distribution: the cut-off parameter Λ_{\pm} , the mass scale for $e\gamma\gamma$ contact interaction Λ' , the mass of an excited electron M_{e^*} and the mass scale for extra dimensions M_S for $\lambda = \pm 1$.

[GeV]	Λ_+	Λ_-	Λ'	M_{e^*}	M_S $\lambda=+1$	M_S $\lambda=-1$
ALEPH	319	317	705	337	810	820
DELPHI	354	324	–	339	832	911
L3	385	325	810	325	835	990
OPAL	344	325	763	354	833	887

6 Resonance production

Three photon final states can originate from a photonically decaying resonance $X \rightarrow \gamma\gamma$, which is produced together with a photon via $e^+e^- \rightarrow X\gamma$. Fig. 2 shows the invariant mass of photon pairs in events with exactly three photons. Within the small statistics the mass distribution is in good agreement with the expectation from the QED process.

If the Higgs is assumed to be this resonance X the Standard Model coupling of $H \rightarrow \gamma\gamma$ via loops of charged, massive particles is too small to lead to an observable effect. For the Standard Model Higgs the maximum of the branching ratio for $H \rightarrow \gamma\gamma$ is $2.6 \cdot 10^{-3}$ at a Higgs mass of about 125 GeV and a total Higgs width of ~ 4 MeV. For larger Higgs masses the branching ratio decreases due to the increasing $H \rightarrow W^+W^-$ contribution. However, for limits on anomalous couplings in the case of fermiophobic Higgs models the three photon final state gives information which is complementary to $e^+e^- \rightarrow HZ$ with $H \rightarrow \gamma\gamma$ or $e^+e^- \rightarrow H\gamma$ with $H \rightarrow b\bar{b}$.

Anomalous $H \rightarrow \gamma\gamma$ couplings can be described by ¹²

$$\mathcal{L}_{\text{eff}}^{H\gamma\gamma} = -\frac{gM_W \sin^2 \theta_W}{\Lambda^2} \frac{1}{2} (f_{BB} + f_{WW} - f_{BW}) H A_{\mu\nu} A^{\mu\nu}, \quad (3)$$

where Λ is the energy scale and the three possible couplings are f_{BB} , f_{WW} and f_{BW} . Limits on γZ interaction set strong constraints on f_{BW} ¹³ which is therefore set to zero. The two other parameters are in general assumed to be identical $f_{BB} = f_{WW} \equiv F$.

In Fig. 3 the limit ¹⁴ on F/Λ^2 is shown from $H \rightarrow \gamma\gamma$ decay for the two processes $e^+e^- \rightarrow H\gamma$ and $e^+e^- \rightarrow HZ$, with $Z \rightarrow q\bar{q}$ and $\nu\bar{\nu}$. Although HZ production has the higher sensitivity for F/Λ^2 at low Higgs masses, $H\gamma$ production provides strong limits up to $M_H \sim 170$ GeV.

The partial width of $H \rightarrow \gamma\gamma$ is studied with the process $e^+e^- \rightarrow H\gamma$.

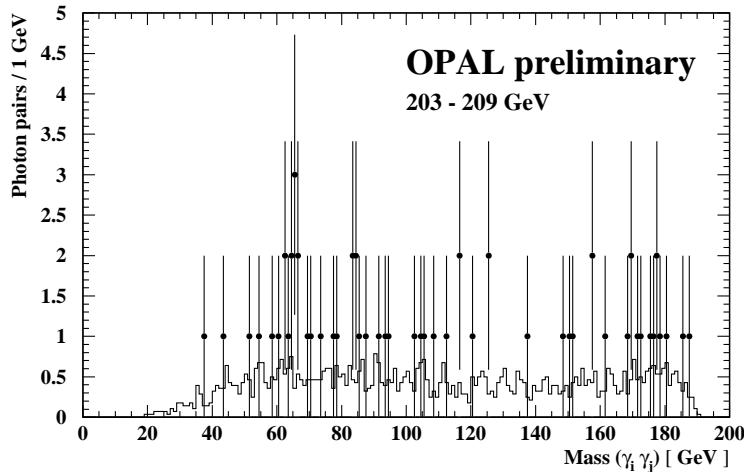


Figure 2. Invariant mass of photon pairs from events with three photons in the final state. There are three combinations per event. The points represent the data taken in 2000 by OPAL and the histogram the corresponding QED expectation. The mass resolution is about 0.5 GeV. The mass range is limited not only by the centre-of-mass energy but also by the imposed cut on the opening angle between photons.

Fig. 3 shows limits¹⁵ from three photon final states ($H \rightarrow \gamma\gamma$) which are stronger than those obtained from $b\bar{b}\gamma$ events ($H \rightarrow b\bar{b}$).

7 Conclusion

The process $e^+e^- \rightarrow \gamma\gamma(\gamma)$ provides high statistics data for the test of the Standard Model. Combining all four LEP experiments a precision of 1% for the total cross-section is reached. Since this process is dominated by QED a precise prediction is in principle possible. However, since calculations are available only up to next-to-leading order a theoretical error of about 1% has to be taken into account while searching for deviations from the Standard Model. The observed total cross-section is two standard deviations below the expectation not accounting for this theoretical error. Three photon final states are interesting for the search for photonically decaying resonances, which are produced along with a photon. The Standard Model prediction for the $H \rightarrow \gamma\gamma$ branching ratio is too small to lead to an observable cross-section at LEP hence limits on anomalous couplings are placed.

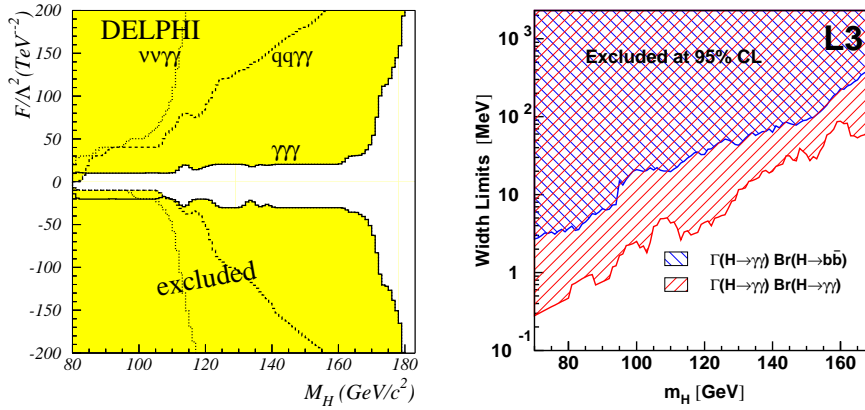


Figure 3. Limits on anomalous $H \rightarrow \gamma\gamma$ coupling depending on the Higgs mass. The DELPHI plot shows limits on F/Λ^2 derived from $H\gamma$ and HZ production. The L3 plot shows limits on the partial width $H \rightarrow \gamma\gamma$ from $e^+e^- \rightarrow H\gamma$ with $H \rightarrow b\bar{b}$ and $\gamma\gamma$. Data taken until 1999 were used.

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