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TWO PHOTON PHYSICS AT LEP [a]

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LEP offers an excellent opportunity to measure two photon processes over a large kinematical range and thus study the complex nature of the photon. This article reviews the experimental status of "Two Photon Physics" at LEP. The recent results on resonances, multi-hadron production and photon structure functions are discussed.

1 Introduction

Over the past decade two photon physics has proven to be a very productive source of information about QED, QCD and hadron spectroscopy. The Feynman diagram responsible for a two photon collision process at LEP is shown in Figure 1, where the highly energy incident electrons and positrons split off virtual photons and the scattered electrons take most of the energy. These two photons then can annihilate to form a state X with mass $W_{\gamma\gamma}$. The momentum transfer to the photons depends on the angle and energy of the scattered leptons. When neither of the scattered leptons is detected (untagged events), the virtual photons are referred to as nearly real. This class of events allows several tests of QCD by studying hadronic resonances, the inclusive hadron cross section and jet production rates. If there is detection of one of the scattered leptons (single tagged events), it is possible to probe the photon "target" and study the structure function of the photon. In the following sections, a qualitative review is given of the $\gamma\gamma$ results obtained at LEP, with special attention to recent results.

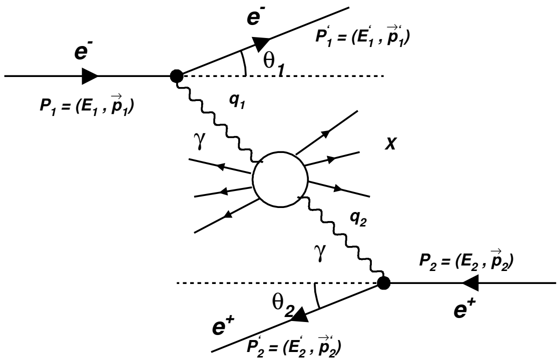


Figure 1: $\gamma\gamma$ collision in e^+e^- scattering

[a] Invited talk at Recontres de Moriond, March ' 98

2 Resonance production

Two photon formation of C-even meson resonances provides valuable information on the internal structure of mesons. In particular it is interesting to look for resonances whose $\gamma\gamma$ couplings are much smaller than quark-model predictions: e.g. glue-ball or hybrid quark-gluon states. One can also produce resonances in two-photon events in which one photon is far off mass shell. The interest in this case is twofold. First, the meson transition form factor can be measured and secondly spin-1 states can be produced.

Table 1: List of resonances studied by the L3 Collaboration

Resonance	Final state	J^{PC}	$\Gamma_{\gamma\gamma}$(keV)
$\eta^{'}$ (958)	$\pi^+\pi^-\gamma$	0^{-+}	$4.17 \pm 0.10 \pm 0.27$ [1]
a_2 (1320)	$\pi^+\pi^-\pi^0$	2^{++}	$0.98 \pm 0.05 \pm 0.09$ [2]
$a_2^{'}$ (1750)	$\pi^+\pi^-\pi^0$	2^{++}	$0.29 \pm 0.04 \pm 0.02/(BR)$ [2]
$f_2^{'}$ (1525)	$K_s^0K_s^0$	2^{++}	$0.09 \pm 0.02 \pm 0.02/(BR)$ [3]
η_c (2980)	12 Channels	0^{-+}	$8.0 \pm 2.3 \pm 2.4$ [4]
χ_{c2}(3555)	$J/\psi\gamma$	2^{++}	$0.97 \pm 0.40 \pm 0.36$ [5]

At LEP, the L3 experiment has explored many exclusive channels. The resonances studied are shown in Table 1. Two recent results are discussed in the following sections.

2.1 $\eta^{'}$ Transition Form factor

Using LEP I data with a total luminosity of 129 pb^{-1} , the $\eta^{'}$ is detected[1] in its decay $\eta^{'} \to \gamma\rho^o$, where $\rho^o \to \pi^+\pi^-$. Figure 2 (a) shows the $\pi^+\pi^-\gamma$ invariant mass produced by quasi-real

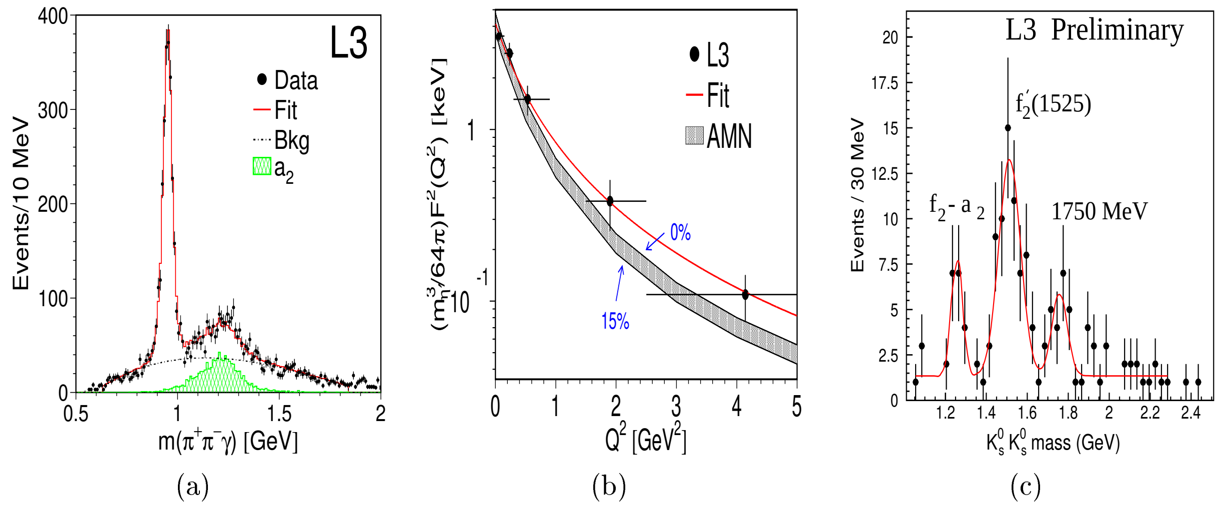


Figure 2: (a) The $\eta^{'}$ invariant mass spectrum , (b) the $\eta^{'}$ form factor, fitted with a VDM pole form and (c) the $K_s^0K_s^0$ mass spectrum.

photons. The spectrum is fitted with a Gaussian for the signal and a second order polynomial for the background allowing for the a_2 contribution, 2123 ± 53 events are found. The two photon partial width of the $\eta^{'}$ is extracted to be $\Gamma_{\gamma\gamma} = 4.17 \pm 0.10 \pm 0.21$ keV.

For the measurement of the $\eta^{'}$ transition form factor events are selected in different Q^2 bins, where the Q^2(see figure 1 ,where $Q_i^2 = -q_i^2$) four momentum transfer is measured by the luminosity dectector($0.9 < Q^2 < 10$ GeV^2) or deduced from the transverse momentum of the final state ($Q^2 \approx |p_t|^2$,$0.015 < Q^2 < 0.9$ GeV^2). For each Q^2 interval the cross section and the Form factor $F^2(Q^2)$ are measured. Figure 2(b) shows the five $F^2(Q^2)$ points; performing a fit with a form factor parametrization, according to the VDM (Vector Dominance Model) as

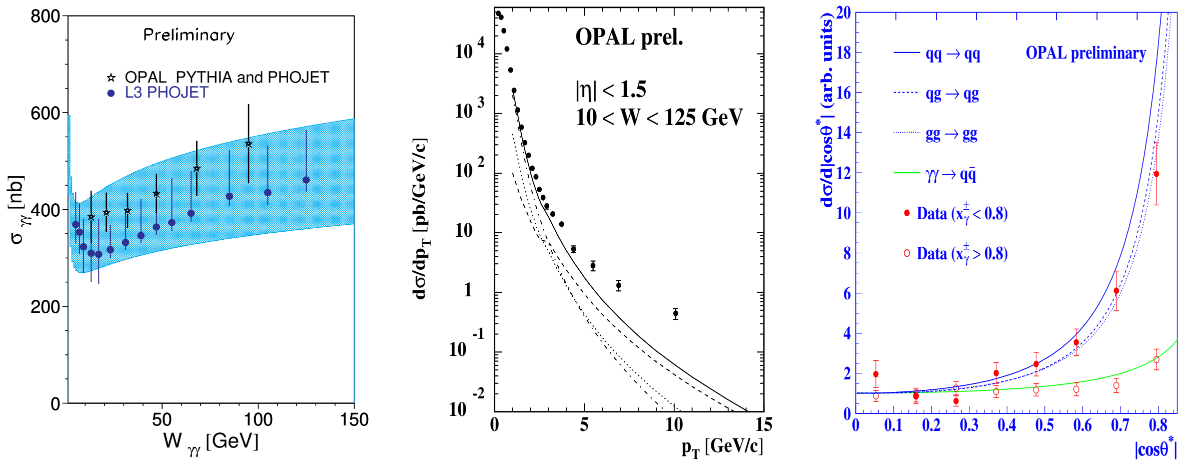
$F^2(Q^2) = \left(\frac{1}{1+Q^2/\Lambda^2}\right)^2$ the value $\Lambda = 900 \pm 51$ MeV is obtained consistent with VDM prediction of $\Lambda = 870$ MeV. Also shown is a comparison with QCD predictions [6]. The measurement favours a low gluonium content. More precise QCD calculations and a large data sample are needed to draw firm conclusion on the gluonium content of the η'.

2.2 $K_s^0 K_s^0$ Resonances

The resonance formation process $\gamma\gamma \to R \to \mathrm{K}_s^0\mathrm{K}_s^0 \to \pi^+\pi^-\pi^+\pi^-$ has been studied [3] with the L3 detector. Events with four charged tracks, charge balance and no photons are selected. There must be two $\pi^+\pi^-$ pairs forming a secondary vertex at a distance larger than 3 mm from the beam axis and with the angle between the flight direction of each K_s^0 candidate and the total transverse momentum vector of the two outgoing tracks smaller than 0.3 rad. The $\mathrm{K}_s^0\mathrm{K}_s^0$ mass spectrum fig. 2(c), shows clear evidence for the formation of the $f_2'(1525)$ tensor meson. Around 1300 MeV, $f_2 - a_2$ destructive interference is observed consistent with theoretical predictions [8]. In addition, there is an enhancement of $\approx$3 standard deviations around 1750 MeV which is possibly due to the formation of a radially excited state of the f_2', also consistent with theoretical predictions [7]. The measured two photon partial width of f_2' is shown in Table 1. The angular distribution of f_2' in the two-photon centre-of-mass system favours helicity-2 formation over helicity-0, which is consistent with theoretical predictions [9].

3 Multi-Hadron and Dijet Production

At high energies, the two photon process $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-\,hadrons$ is a copious source of hadron production. In this reaction the photons either interact as a point-like particle or undergo quantum fluctuation into a vector meson opening up all the possibilities of hadronic interactions. These interactions can be described in terms of Regge poles [10,11], (Pomeron or Reggeon exchange). A measurement of the total hadronic cross section as a function of $\sqrt{s}$, improves our understanding of the hadronic nature of the photon. At LEP, using the high energy runs above the Z peak, L3 and OPAL have measured the cross section [12,13] $\sigma(\gamma\gamma \to hadrons)$ in the range $10 \leq W_{\gamma\gamma} \leq 145$ GeV as shown in the Figure 3(a). The systematic errors are dominated by the different detector efficiencies of Monte Carlo models used to unfold the data. The two experiments differ by 24% in normalisation but have a same behaviour as a function of $W_{\gamma\gamma}$.



(a) (b) (c)

Figure 3: (a) The measured cross-section $\sigma(\gamma\gamma \to hadrons)$ as a function of $W_{\gamma\gamma}$; (b) differential cross section as function of p_T of inclusive charged hadrons and (c) measured angular distributions in direct and resolved events.

For the first time values of $W_{\gamma\gamma}$ above 10 GeV are explored. The increase in the cross section with energy is characteristic of Pomeron exchange. The energy dependence of $\sigma(\gamma\gamma \rightarrow hadrons)$ cross section can be parameterised by universal Regge [15] behaviour of total cross section. If the slope of the Pomeron contribution is left as a free parameter a value of $\epsilon = 0.16 \pm 0.02 \pm 0.03$ is obtained. Also shown in the figure 3(a) is the $\sigma_{\gamma\gamma}$ prediction from γp and pp cross section assuming Gribov factorisation [14]. The large uncertainty in the theoretical predictions will be under control with future measurements from LEP.

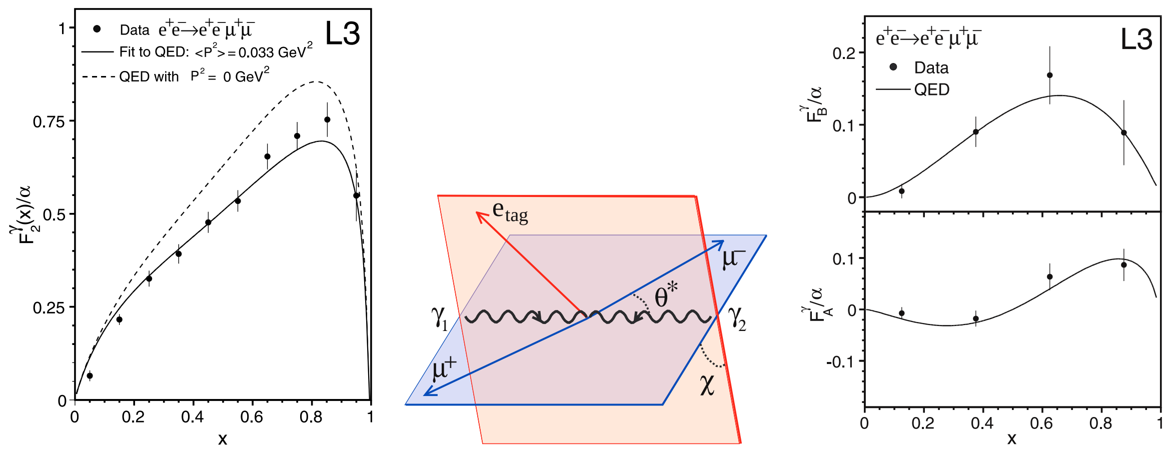
Figure 3 (b) shows a preliminary OPAL measurement of differential cross-section as a function of transverse momentum [16] for charged hadrons produced by the two quasi-real photons. The results are compared to NLO perturbative QCD calculations [17]. For lower values of W, more charged hadrons than predicted are found at large p_T.

OPAL has performed a very nice measurement, using dijet production in two-photon collisions at $\sqrt{s} = 161$ and 172 GeV. They have demonstrated in their preliminary results [18] that it is possible to distinguish between direct and resolved processes in the dijet events. Figure 3 (c) shows the measured distribution of the parton scattering angle θ^* for direct and double-resolved, compared to the relevant QCD matrix element calculations [19]. One observes a clear distinction between the direct process ($x_\gamma > 0.8$) and the resolved one ($x_\gamma < 0.8$), where the strong rise in *cos*θ^* distribution near cosθ^*=1 is due to a large double-resolved contribution, as expected from QCD.

4 Leptonic Structure Function

The leptonic structure function has been measured by all LEP experiments [20,21,22,23]. The measurement provides not only a QED test but is also an experimental check for the procedures used in the study of the hadronic photon structure functions.

A recent result from L3, with a large sample of data, shows that it is possible to measure the effect of non-zero target photon virtuality as shown in figure 4 (a). The analysis is performed using the $e^+e^- \rightarrow \mu^+\mu^-$ sample, for a range of Q^2 ($1.4 < Q^2 < 7.6$ GeV^2). The fit to F_2^γ corresponds to target photon virtuality of 0.33 ± 0.005 GeV^2, in good agreement with QED predictions, if initial state radiative corrections are included.



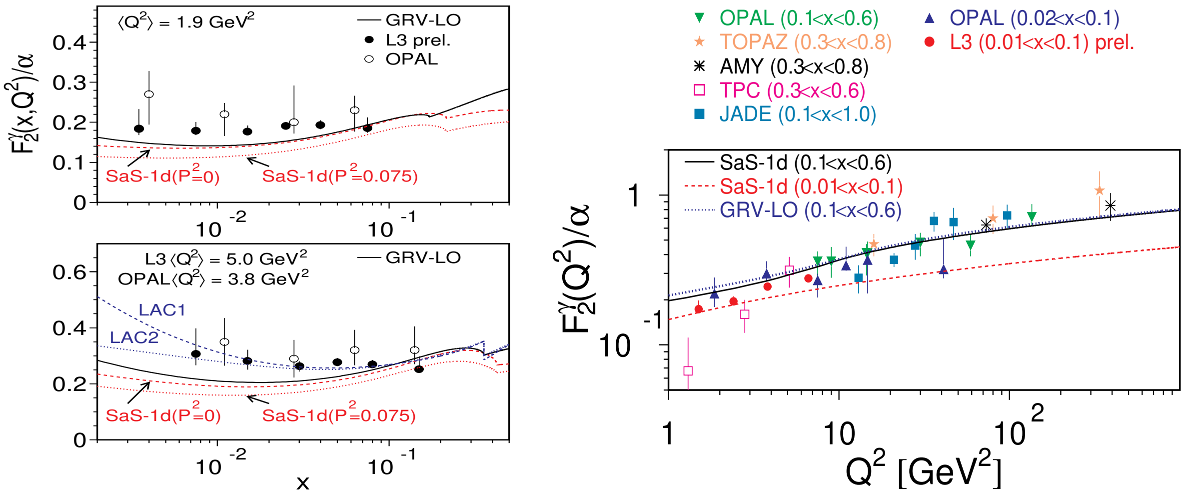
(a) (b) (c)

Figure 4: (a) F_2^γ measured in the range $1.4 < Q^2 < 7.6$ GeV^2, (b) definition of the angles θ^* and χ in the $\gamma\gamma$ centre of mass frame and (c) measurement of the F_A and F_B structure of function.

Also shown in 4 (c), is the first measurement of the F_A and F_B structure functions , obtained by studying the azimuthal angle distribution of the μ^- in the $\gamma\gamma$ centre-of-mass system [25,26,27,28]. Assuming that the target photon direction is parallel to the beam axis, the polar angle θ^* of the μ^- and the azimuthal angle χ are defined as shown in Figure 4(b). Here χ is the angle between the plane defined by the μ^- direction and the $\gamma\gamma$ axis, and the scattering plane of the tagged electron. Both structure functions originate from the interference terms of the scattering amplitudes. The characteristic x dependence of the interference terms, as predicted by QED, is observed in the data as shown in figure 4 (c). In particular F_A is due to the interference between longitudinal-transverse and transverse-transverse photon amplitudes. With this measurement, L3 proves that the longitudinal leptonic photon helicity amplitude can be accessed by the study of azimuthal correlation and is significantly non-zero.

5 Hadronic structure function F_2^γ

The measurement of the hadronic structure function, F_2^γ has been performed at LEP in the range $0.0025 < x < 1$ and $1.2\ \mathrm{GeV}^2 < \mathrm{Q}^2 < 279\ \mathrm{GeV}^2$ [32,33,34,35]. The physical interest in the analysis of the hadronic photon structure function is twofold. Firstly, to measure the shape of F_2^γ, especially at small values of x, at fixed Q^2, where HERA experiments observe a strong rise of the proton structure function. Secondly the Q^2 evolution of F_2^γ is investigated. The F_2^γ measurements from L3 and OPAL are shown in Figure 5 (a) in the Q^2 interval from 1.2 to 9.0 GeV^2. The x range is $0.002 < x < 0.1$ at $\langle Q^2 \rangle = 1.9\ \mathrm{GeV}^2$ and $0.005 < x < 0.2$ at $\langle Q^2 \rangle = 5.0\ \mathrm{GeV}^2$. For the low values of x, the data are above the predictions of the GRV-LO [29] and SaS-1d [31] models, perhaps indicating a higher contribution of gluons in the photon structure function F_2^γ. The LAC [30] model can reproduce the x behaviour of F_2^γ at $\langle Q^2 \rangle = 5\ \mathrm{GeV}^2$ but it predicts too fast a rise of F_2^γ as function of $\ln Q^2$.



(a) (b)

Figure 5: (a) The measured F_2^γ at $\langle Q^2 \rangle = 1.9\ \mathrm{GeV}^2$ and $5.0\ \mathrm{GeV}^2$ and (b) evolution of F_2^γ as a function of Q^2 for different range of x values.

A compilation of the results for different experiments on the Q^2 evolution of F_2^γ in various ranges of x are shown in Figure 5 (b). The measured values of F_2^γ show clearly the linear growth with $\ln Q^2$ as expected by QCD. The predictions of the GRV-LO [29] and SaS-1d [31] models are also shown.

Outlook

Progress in the field of the two photon physics at LEP is significant, most notably are the multi-hadron production and photon structure functions. With the statistics of 500 pb^{-1} luminosity available at the end of LEP II data taking, we expect not only large improvements in the modelling of the hadronic component at small x values but also look forward for possible glueball states.

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