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PHOTON STRUCTURE AND GAMMA-GAMMA PHYSICS

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ABSTRACT

The LEP experiments are making real progress in understanding the structure of the photon, though the results do not yet give such clear demonstrations of QCD in action as the proton structure has done. Other new results are reported, including QED related effects and $\gamma\gamma \to$ *Resonances*, from LEP and from CLEO II.

1 Introduction

The photon is not a hadron – it has fundamental direct couplings to all charged particles - *except* when it has already turned into a hadron before it interacts, see Figure 1. This duality gives rise to a wide range of phenomena that test both the perturbative and non-perturbative parts of QCD. Current experiments at LEP and CLEO II at Cornell are improving our understanding of photon structure and the properties of gamma-gamma resonances.

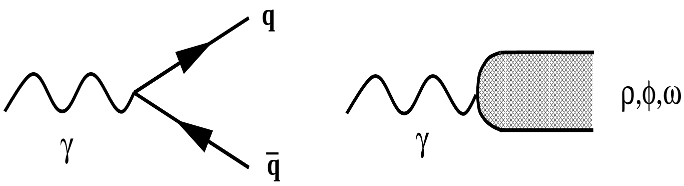


Figure 1: The dual nature of the photon.

Figure 2 shows the generic Feynman graph for all $\gamma\gamma$ processes at an e^+e^- collider. It is labelled to show one of the scattered beam leptons as a "tagged" and measured final state particle. The results which follow come from untagged events as well as this singly tagged case. If a scattered lepton is tagged then its four momentum transfer is usually well measured, and we define

$Q^2 = -q^2 = 2E_{beam}E_{tag}(1 - \cos\theta_{tag})$. If a scattered lepton is untagged then we know that its scattering angle was less than a few tens of milliradians and that $P^2 \simeq 0$.

The invariant mass $W_{\gamma\gamma}$ can sometimes be well measured – if all the final state particles are caught by the detector. But in multihadron final states some of the particles are often missed, which means that both $W_{\gamma\gamma}$ and the Bjorken scaling variable

$$x = \frac{Q^2}{Q^2 + P^2 + W_{\gamma\gamma}^2} \simeq \frac{Q^2}{Q^2 + W_{\gamma\gamma}^2}$$

will be badly measured, and biased. There is no alternative way of determining $W_{\gamma\gamma}$ from the initial state kinematics, as can be done for $W_{\gamma p}$ in electron-proton scattering at HERA, because both virtual γs are drawn from broad bremsstrahlung-like spectra.

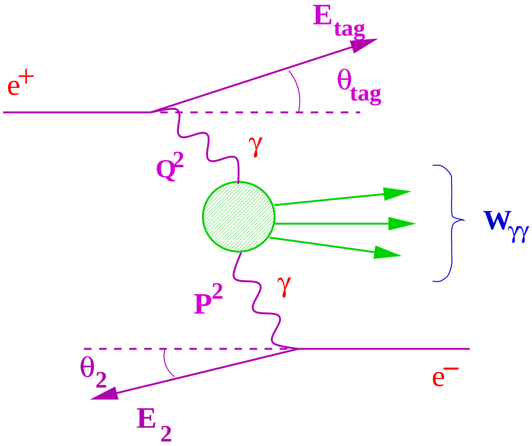


Figure 2: Singly tagged $\gamma\gamma$ event.

Virtual photon beams bring two other disadvantages:
i) the bulk of the $\gamma\gamma$ cross section is at very low values of $W_{\gamma\gamma}$ [1)] so the effective luminosity for high energy processes is much less than at HERA.
ii) the longitudinal momenta of the two colliding photons are usually unequal, giving a strong boost along the beam direction to the final state and accentuating the loss of particles from the well-measured region.

The prospect of eventually producing "narrow band" beams of real photons by Compton backscattering at a future linear collider has been extensively discussed elsewhere [2)]. Such a facility would raise the effective luminosity for interesting hard processes to at least the level of the γp luminosity at HERA, with a significant part of the spectrum within 10% of the peak value of $\sqrt{s_{\gamma\gamma}}$. As well as allowing much of the physics discussed in the rest of this review to be done with better precision, a high energy "Compton Collider" could give important access to properties of Higgs and SUSY particles which could not be seen in other ways and would extend the range of constraints on the triple-gauge-boson couplings. A low energy Compton Collider would be a unique facility for the study of meson resonances, certainly up to around the η_c, may even allow a chance to see the η_b [3)].

2 Photon Structure

The differential cross section for singly tagged processes is [1)]

$$\frac{d^2\sigma(e\gamma \to ex)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left\{\left(1 + (1-y)^2\right) F_2^\gamma(x, Q^2) - y^2 F_L^\gamma(x, Q^2)\right\}.$$

This has been integrated over the azimuthal angle of the unseen scattered lepton. The second scaling variable $y = 1 - E_{tag}/E_{beam}(\cos^2\theta_{tag}/2)$ is much less than 1 if the threshold for the tagged electron is set at more than half the beam energy, as it normally must be at LEP to eliminate beam-associated background from the collider, so the $y^2 F_L$ contribution is expected to be unmeasurably small [4]. The main part of $e\gamma$ deep inelastic scattering is therefore driven by the structure function $F_2(x, Q^2)$.

2.1 The QED Structure of the Photon

All of the LEP experiments have confirmed the predicted shape and size of F_2^{QED} in the singly-tagged $\gamma^*\gamma \to \mu^+\mu^-$ process [5], Figure 3. A recent L3 result [6] even claims to see signs of the slight reduction in rate expected because the average value of P^2 is not exactly zero if the second tagged electron is only vetoed down to about 35 milliradians from the beam direction. The universality of the tau coupling has been checked [7]. L3 has also measured the rates for untagged $\gamma\gamma \to e^+e^-$, $\mu^+\mu^-$ and $\tau^+\tau^-$ [8].

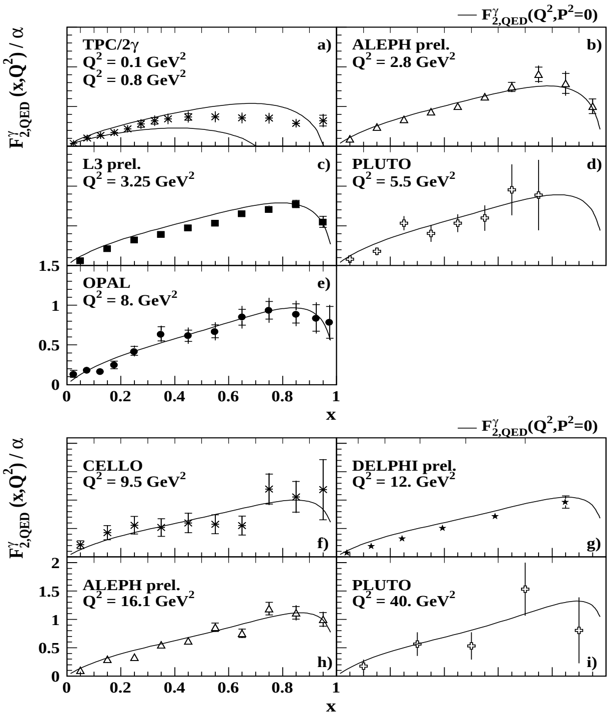


Figure 3: Measurements of F_2^{QED}.

An intriguing set of studies by three of the LEP experiments [9] has also confirmed QED predictions for a pair of more subtle structure functions, F_A^{QED} and F_B^{QED}, which relate to the azimuthal angle χ between the plane of the tagged electron and the plane of the two outgoing muons in the $\gamma\gamma$ C. of M., see Figure 4. F_A multiplies the $cos\chi$ dependence and comes from the interference between longitudinal and transverse photon scattering. F_B multiplies $cos2\chi$ and is a transverse-transverse term.

Apart from an apparent disagreement on sign conventions - an easy problem for the LEP inter-experiment $\gamma\gamma$ working group to sort out - the results agree with each other and with QED predictions.

Measurement of F_A^{QED} and F_B^{QED} is interesting, not because it tests QED but because it proves that such measurements are possible at LEP. The challenge now is to do the same thing with hadronic final states, using the plane of pairs of jets to define the plane of the outgoing quarks instead of the dimuon plane. QCD calculations of F_A and F_B involve many of the same operators as calculations of the unmeasurable F_L, which is expected to scale at lowest order in QCD.

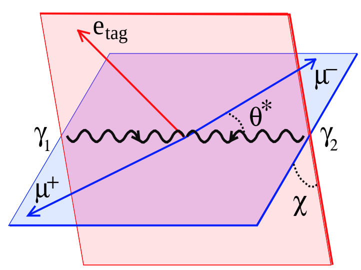


Figure 4: Definition of the angle χ in the $\gamma\gamma$ C. of M. frame.

2.2 QCD Evolution of $F_2^\gamma(x, Q^2)$ with Q^2

This classic test of QCD [10] has been complicated by both theoretical and experimental problems. The theoretical picture is complicated by the dual nature of the photon. A purely perturbative treatment, starting from the direct γq coupling, gives singularities at low x. These can be dealt with by including the pre-existent hadronic part of the photon, but the predictive power of QCD is then severely undermined by the need for a nonperturbative description of the parton distribution in the initial object – usually taken to be a vector meson with parton structure similar to that of the pion.

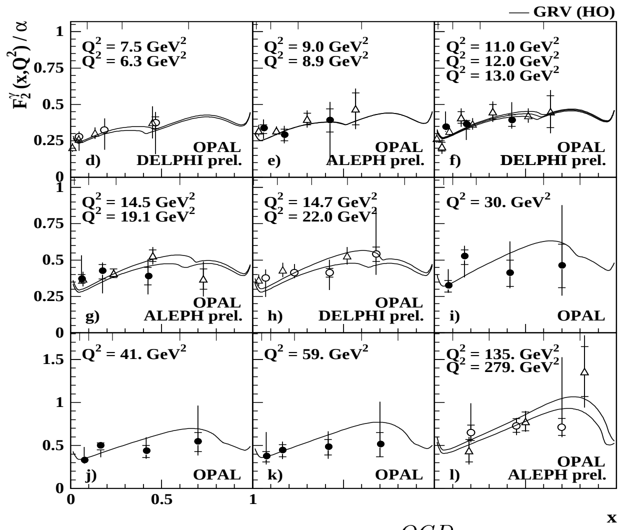


Figure 5: Measurements of F_2^{QCD}. The curves are for the GRV parameterisations of the parton density functions [17].

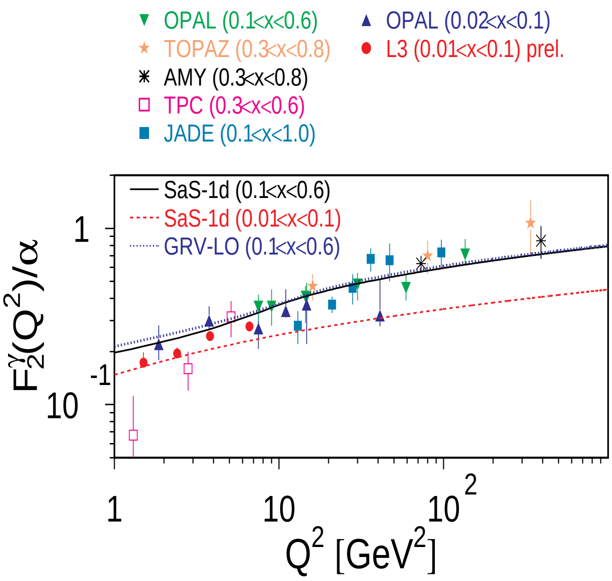


Figure 6: Q^2 evolution of F_2^{QCD}. The curves are for the SAS parameterisations [17].

Nevertheless, it has been argued [11, 12] that some sensitivity to the QCD evolution of the direct coupling does remain if measurements can be made over a wide range of Q^2. The LEP experiments [13] are making progress in measuring $F_2^\gamma(x, Q^2)$ (Figure 5), and in seeing its expected nonscaling growth with $\ln Q^2$ (Figure 6), but the error bars are enormous compared with those for F_2^p from HERA, from SLAC or from muon beams. This is partly statistical, due to the softness of the virtual photon spectrum at LEP, but the major part of the error is systematic, due to uncertainties in reconstructing the mass $W_{\gamma\gamma}$ of the hadronic final state. The LEP detectors have good hadron tracking out to a pseudorapidity $|\eta| \simeq 2.3$, but beyond that they only have electromagnetic calorimetry which samples the hadronic final state but does not measure all of the hadronic energy. It is therefore necessary to rely upon Monte Carlo simulation in an unfolding procedure [14] which corrects for the distorted x distribution caused by the biased measurement of $W_{\gamma\gamma}$. Different Monte Carlo programs [15] give very different forward energy flows (Figure 7a and b), so correlations (Figure 8) between the observed W_{vis} and the true value of W depend upon both whether the Forward Detector hadronic energy is sampled at all ("without FD", "with FD") and which Monte Carlo is used. The

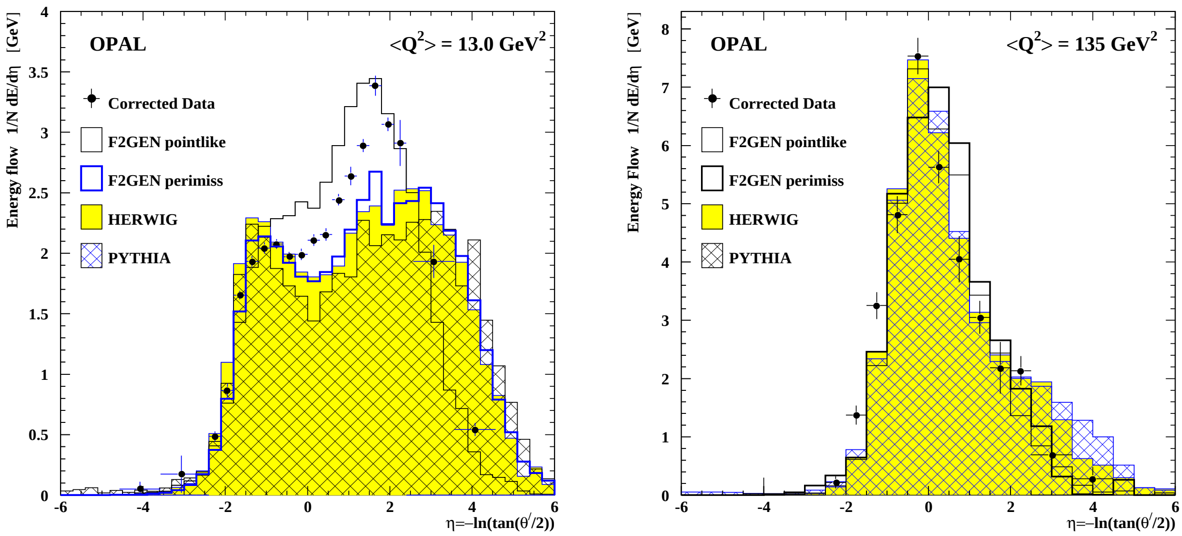


Figure 7: (a) Energy flow at $< Q^2 >$=13.0 GeV^2 and (b) $< Q^2 >$=135 GeV^2.

experimental error bars in Figures 5 and 6 are dictated primarily by the choice of the set of Monte Carlo programs used for input to the unfolding.

The all-LEP working group is making good progress on improving this situation. Better Monte Carlo generators are being provided – though there is always a danger here [16]. Many generators assume a particular parameterisation of the parton density functions inside the photon. If the parton-showering part of such a program is tuned to fit data like that in Figure 7a), then there is a chance that the unfolded $F_2^\gamma(x, Q^2)$ will not be independent from the assumed parameterisation. Fortunately, new techniques are also being devised which will make the final unfolded result less sensitive to the particular Monte Carlo used.

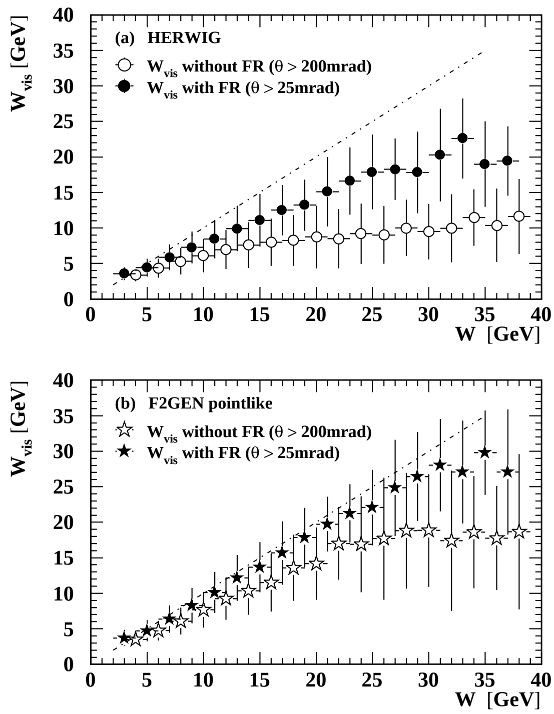


Figure 8: $W - W_{vis}$ correlation.

At large values of Q^2 the measured hadronic energy flow (Figure 7b) is much better described because the hadrons recoil against the larger transverse momentum of the tagged electron, so a larger fraction of them is caught by the central trackers. But at high Q^2 and high x there is another problem – the treatment of the charm mass, both in the Monte Carlo models and in the published parton density functions [17]. Some treat charm as massless but impose a sudden threshold cut, giving a totally unphysical sharp edge in $F_2^\gamma(x)$. Some take $m_c = 1.3GeV/c^2$, others have $m_c = 1.7GeV/c^2$. At the highest x values there may also be difficulties with simple factorisation of the effective $\gamma\gamma$

luminosity. This must all be sorted out before we can deliver the final LEP measurement of the Q^2 evolution.

LEP should generate three times more luminosity in 1998–2000 than has yet been analysed for photon structure by any single experiment. It will be at higher energies – giving an increased reach in Q^2 – and the four LEP experiments are collaborating well in understanding the problems so that their eventual results may be combined safely. Assuming we can beat down the systematic errors to match these statistics then a definitive measurement of the Q^2 evolution should be possible. It may even be possible to extract a new value of $\Lambda_{\overline{MS}}$, though probably only within the framework of a particular parameterisation of $F_2^\gamma(x,Q^2)$ like GRV or SaS. To get a truly model independent measurement may require the Compton Collider [18].

2.3 Low x QCD Evolution of $F_2^\gamma(x,Q^2)$

The rise of $F_2^p(x,Q^2)$ at low x, as seen at HERA [19], has been shown to follow from normal DGLAP evolution [20], with no need to invoke BFKL theory [21]. It is not obvious that the photon should behave in the same way, because of its dual – direct plus hadronic – nature. But the GRV parameterisation of the photonic parton densities does predict a very similar rise of $F_2^\gamma(x,Q^2)$ at low x. The LEP1 results for $Q^2 \leq 6GeV^2$ (Figure 9) are not in conflict with this. The more recent L3 result may appear to contradict OPAL [22], but this is just another manifestation of the problem of unfolding $W_{\gamma\gamma}$, discussed above. When L3 uses the same HERWIG Monte Carlo as used in the OPAL unfolding they get similar values of $F_2^\gamma(x,Q^2)$. The errors shown on both the OPAL and the L3 points are predominantly systematic and the difference between them merely reflects different choices from the range of available unfolding Monte Carlos. Both experiments disagree with the much lower values of $F_2^\gamma(x,Q^2)$ found in this region by the $TPC/2\gamma$ experiment [23]. One should not, therefore, worry too much about the fact that the GRV curves are lower than the LEP points, since GRV was constrained by the $TPC/2\gamma$ data – all that was then available.

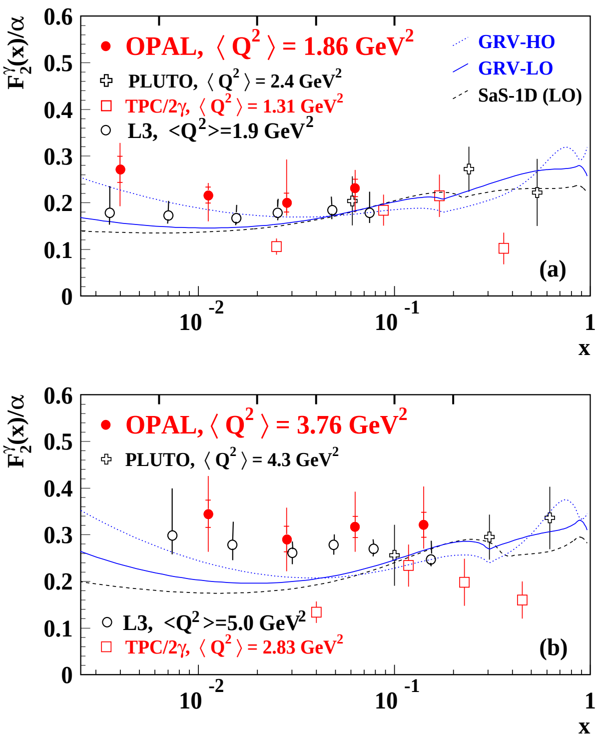
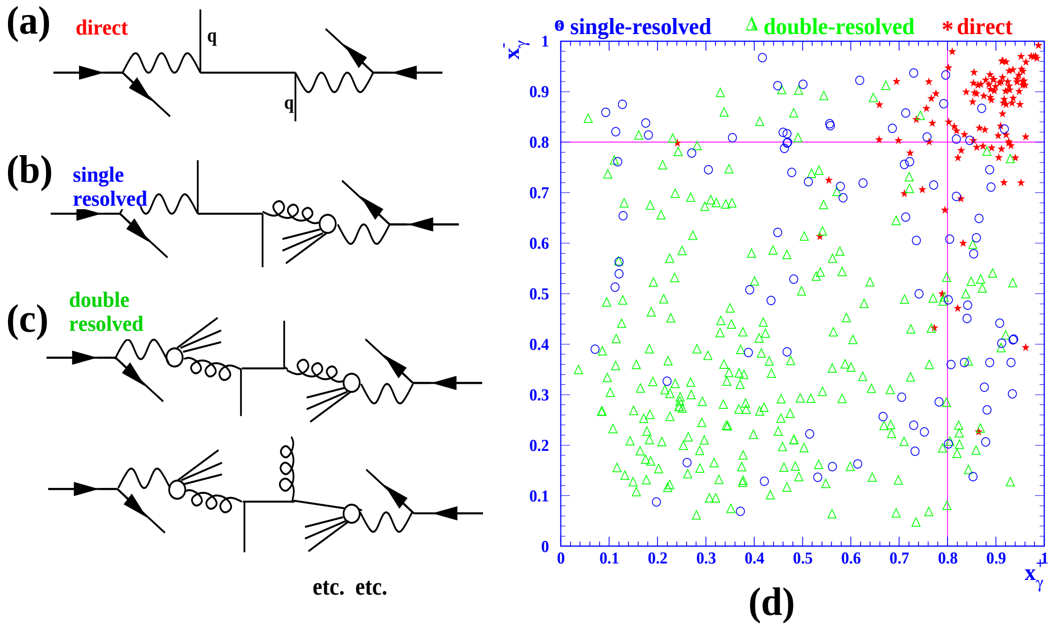


Figure 9: Measurements of F_2^γ at low x.

No new data can be expected from LEP2 in this low Q^2 region. Both OPAL and L3 used their small-angle luminometers to tag the electrons in these events, and the definition of Q^2, above, tells us that at fixed θ_{tag} the mean value of $Q^2 \propto E_{beam}^2$. So a



$$x_\gamma^+ = \frac{\sum_{jets}(E+p_z)}{\sum_{had}(E+p_z)} \quad \text{and} \quad x_\gamma^- = \frac{\sum_{jets}(E-p_z)}{\sum_{had}(E-p_z)}$$

Figure 10: Separation of the different components of $\gamma\gamma$ scattering in the Monte Carlo sample from the PYTHIA program. [27)]

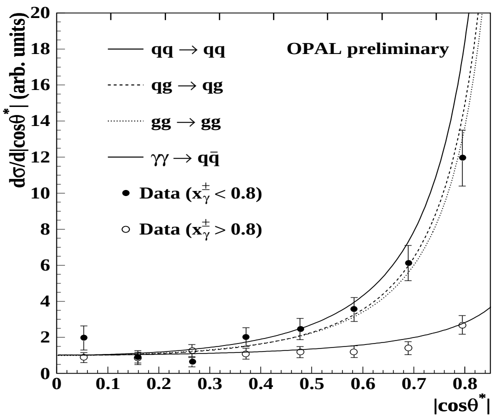


Figure 11: Angular distribution in the dijet C. of M. [27)]

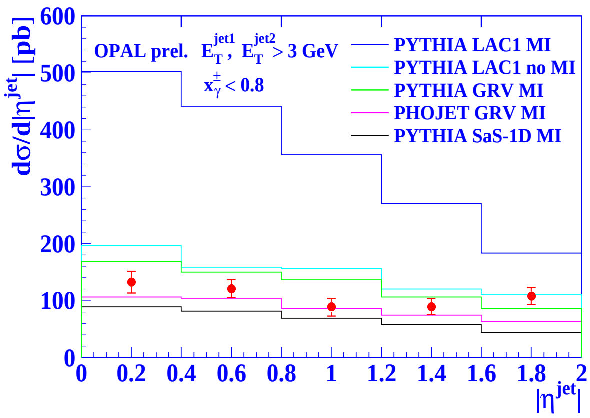


Figure 12: Dijet rate as a function of pseudorapidity η [27)].

definite statement about the low x rise of $F_2^\gamma(x,Q^2)$ is not waiting for new data. It is waiting for the all-LEP working group to sort out the $W_{\gamma\gamma}$ Monte Carlo modelling and unfolding problem so that we can reduce the systematic errors; very likely without much movement of the points already plotted in Figures 5 and 9.

2.4 QCD Gluons in the Photon

Singly tagged $e\gamma$ scattering can never give direct measurements of the distributions of uncharged partons like gluons. The only published attempts at a direct unfolding of $g^\gamma(x)$ come from H1 [24], using the distributions of high-p_T hadrons in photoproduction. But the error bars are even larger than for the LEP measurements of $F_2^\gamma(x,Q^2)$, and there is a fundamental problem with the method because the sample is contaminated by hadrons from "underlying events" in which there are interactions of other partons from the colliding proton and target photon. The uncertainty generated by such multiple interactions is the main reason why ZEUS has never attempted such an unfolding [25].

Groups at both HERA [26] and LEP are making progress in testing the parameterisations of $g^\gamma(x,Q^2)$ by studying the properties of high E_T dijets as a function of variously defined "x_γ" variables. A recent OPAL analysis of LEP2 data [27] uses an untagged $\gamma\gamma$ sample, with two identified high E_T jets in which they define x_γ^+ and x_γ^- according to the formulae on Figure 10. For direct coupling of the two photons to two quarks (Figure 10a) we expect all of the hadrons to be in just two hard quark jets, so x_γ^+ and x_γ^- should both be close to 1. In a singly resolved event [28] there should be undetected hadronic momentum going into the forward region at one end of the detector, due to the unscattered remnant of the resolved photon (Figure 10b), so one or other of x_γ^+ or x_γ^- should be significantly less than 1. In doubly resolved events (Figure 10c)) unscattered photon remnants will go into both forward regions, therefore both x_γ^+ and x_γ^- should be much less than 1. This picture is well confirmed, at least in the framework of the PYTHIA Monte Carlo program which allows events to be identified as coming from direct, singly resolved or doubly resolved processes (Figure 10d). By making cuts on both of $x_\gamma^\pm \geq 0.8$ or one of $x_\gamma^\pm < 0.8$ in the real data, OPAL has separated a "direct" and a "resolved" sample. Figure 11 shows the angular distributions in the dijet C. of M. for the two samples, compared with the predictions of various parton-parton scattering processes which match the "resolved" category, or of simple $\gamma\gamma \to q\bar{q}$ which matches the "direct" events. This work confirms the qualitative predictions of QCD, but the similarity of the different sub-processes in the resolved case is too close to give a measure of the gluon content. A more quantitative test has been made by using various parton density functions with the PYTHIA and PHOJET Monte Carlo models to predict the differential jet-pseudorapidity distributions in high E_T dijet events, Figure 12. But here again, as in the H1 attempt to unfold the gluon density, including the effects of multiple interactions (labelled "MI") makes a big difference, especially to the LAC1 case where the amount of glue in the photon is largest.

Two LEP2 untagged $\gamma\gamma$ analyses confirm the QCD picture, and may eventually allow a measurement of the glue. In the first, L3 has used high p_T final state leptons to measure the inclusive charm production rate [29], extending the work of the TRISTAN experiments and of ALEPH at LEP1 up to higher energies, Figure 13. The results can only be explained by including a large resolved contribution which grows with energy, as predicted by Krämer et al. [30] Deducing the precise amount of glue in the photon from this is difficult because, yet again, we do not know what value of m_c to use – hence the two lines for the "QCD" case which straddle most of the data points. In the second, the E_T^{jet} distributions from OPAL's dijet analysis have been compared with the predictions of a parton-level NLO calculation [31]. Again, the resolved components are essential to explain the data.

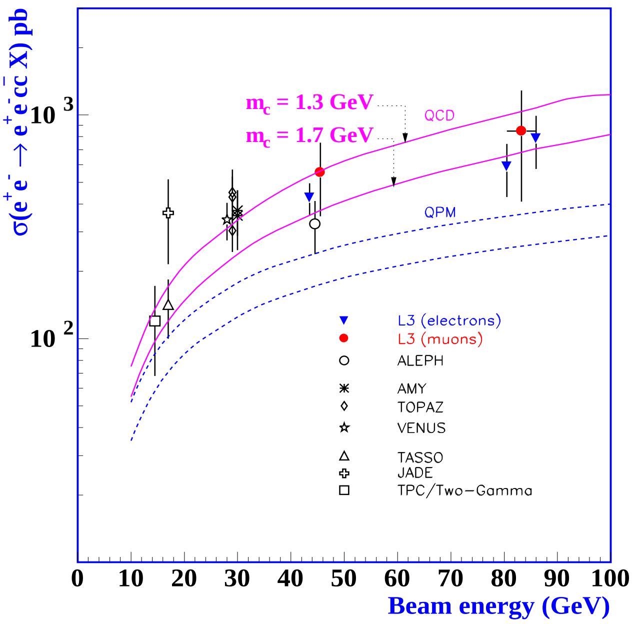


Figure 13: Cross section for $\gamma\gamma \to c\bar{c}$.

3 Other QCD $\gamma\gamma$ Processes

3.1 Hadron p_T Distributions

The special nature of the photon shows up again in the OPAL [32] data of Figure 14, where the transverse momentum distributions of individual hadrons are shown for three different initial states; $\gamma\gamma$, γp and πp, all at the same C. of M. energy. The distributions have been normalised to the same value at low p_T. They look very similar in the soft region with $p_T < 1.4 GeV/c$, but the $\gamma\gamma$ data then diverge very markedly from the other two, perhaps the clearest evidence yet for the direct $\gamma\gamma \to q\bar{q}$ process. Checks from the other LEP experiments and comparisons from HERA are needed.

3.2 Total Cross Section $\sigma_T^{\gamma\gamma}(W_{\gamma\gamma})$

This has always been the most difficult number to measure in $\gamma\gamma$ physics. Figures 7a) and b) above demonstrate for tagged events how the hadronic energy flow tends to go more and more forward, out of the efficient part of the detector, as the momentum transfer from the scattered electron and positron decreases. But the biggest contribution to the total cross section is from untagged events where both parent leptons are forward scattered and go down the beampipe, undetected, with $P^2 \simeq Q^2 \simeq 0$. And when both photons are close to the mass shell we expect a larger contribution from soft hadron-hadron scattering; diffractive processes with low p_T final state hadrons which will mostly go into the badly measured regions. This diffractive component must include the "elastic scattering" of the vector-meson-dominated photon, $\gamma\gamma \to \rho^0\rho^0$, though no one has yet succeeded in detecting it at small angles at LEP. (The analogous $\gamma p \to \rho^0 p$ channel has been seen at HERA and behaves just as vector dominance and Regge factorisation would predict.)

Extraction of $\sigma_T^{\gamma\gamma}(W_{\gamma\gamma})$ depends even more heavily upon unfolding than does the measurement of $F_2^\gamma(x, Q^2)$ described in section 2.1 above. And the Monte Carlo programs that have to be used as input to the unfolding again differ seriously from one another. OPAL sees particularly big differences between predictions from PHOJET and PYTHIA of the fraction of diffractive plus elastic events.

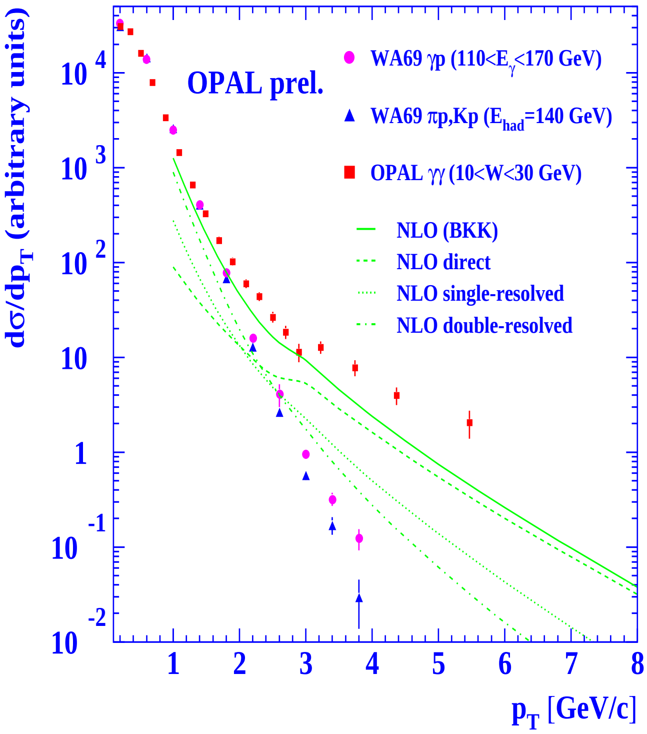


Figure 14: p_T distribution of hp, γp and $\gamma\gamma$ scattering.

Given the difficulties, it is not surprising that the first LEP measurements, from OPAL (preliminary [33]) and L3 (published [34]) and preliminary [35]) disagree with one another, Figure 15. Though the LEP measurements already agree better than did experiments at lower energy. Note that, because of unfolding, the LEP points at neighbouring values of $W_{\gamma\gamma}$ are very highly correlated. Note also that the two L3 results are significantly different from one another at low values of $W_{\gamma\gamma}$. Systematic errors dominate, and are estimated by comparing the effects of unfolding with different Monte Carlo generators. OPAL reports that no generator has yet been found which correctly predicts the observed multiplicity distribution of hadrons, especially for low numbers of hadrons where the diffractive contribution should be important. The message to theorists who want to use these results is that the spread of the data is a good indicator of the systematic errors, for the moment. Getting these errors down looks like a harder job for the all-LEP working group than sorting out F_2^γ.

One thing which both the OPAL and the L3 results have in common is a significant rise of $\sigma_T^{\gamma\gamma}(W_{\gamma\gamma})$ between $W \simeq 20\ GeV$ and $W \simeq 100\ GeV$. This rise is steeper than the simple factorisation prediction, labelled $\sigma^2_{\gamma p}/\sigma_{pp}$ on Figure 15a), based on the published ZEUS and H1 values for $\sigma_{\gamma p}$. But a recent ZEUS thesis [36] has extrapolated very low Q^2 photoproduction cross sections to $Q^2 = 0$. The resulting estimates of the total cross section are significantly higher than the published values, and they rise faster with increasing $W_{\gamma p}$. This γp evidence, together with the OPAL and L3 data on $\sigma_{\gamma\gamma}(W_{\gamma\gamma})$,

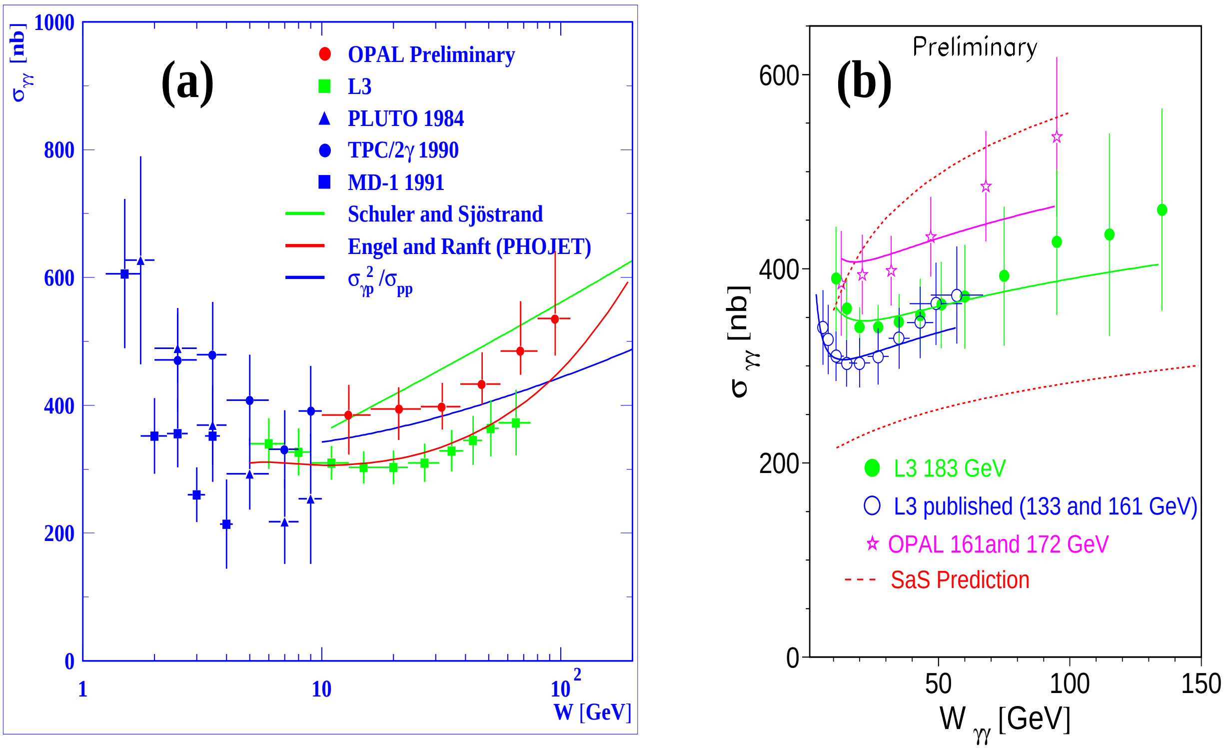


Figure 15: Total $\gamma\gamma$ cross section .

suggests that the total cross sections involving incoming photons are different from purely hadronic total cross sections. In the familiar parameterisation [37] $\sigma_{tot} = Xs^{\epsilon} + Ys^{-\eta}$ Fredj [35] has shown that the average of the OPAL and L3 results for $\sigma_{\gamma\gamma}(W_{\gamma\gamma})$ needs a larger exponent ($\epsilon \simeq 0.16 \pm 0.02$) than the accepted value ($\epsilon = 0.0790 \pm 0.0011$) which fits all hadronic total cross sections.

3.3 Doubly tagged $\gamma\gamma \to hadrons$.

All of the LEP experiments are equipped with small calorimeters beyond the first mini-beta quadrupole, capable of tagging at at finite values, $P^2 \simeq 0.3 GeV^2$, of the virtuality of the target photon. Rates at LEP1 for doubly tagged events were too low to be worthwhile (with only $\simeq 140 pb^{-1}$ of integrated luminosity), but preliminary tests at LEP2 are promising, and there are likely to be worthwhile measurements (with up to $500 pb^{-1}$) of the amount by which $F_2^{\gamma}(x, Q^2, P^2)$ is suppressed at finite P^2. Others are searching for double tags at larger angles, looking for BFKL effects [38]. No clear results have yet been reported.

4 $\gamma\gamma \to Resonances$

CLEO II has already collected more than $3 fb^{-1}$ integrated luminosity, and the beauty factory experiments BaBar and Belle expect even more. Despite their disadvantage in energy compared with LEP they will always have access to larger samples of $\gamma\gamma \to resonances$, at least up to $m_{resonance} \simeq m_{\chi_2^c}$, and their final state hadrons are better measured because they are not as strongly boosted along the beam direction as often happens at LEP. So far CLEO II has published a few gems from its great treasure of data, and the LEP experiments have checked some of them.

CLEO II's measurement of the partial width $\Gamma_{\eta_c \to \gamma\gamma} = 4.3 \pm 1.0 \pm 0.7 \pm 1.4$ [39) agrees with L3 and with the radically different Fermilab E760 measurement that uses $p\bar{p} \to \eta_c \to \gamma\gamma$. But the E760 value [40) for $\Gamma_{\chi_c^2 \to \gamma\gamma} = 0.37 \pm 0.1$ is significantly smaller than the values of around $1keV$ measured by CLEO II and L3 [41). Both sides need to look again at their systematic errors.

The "stickiness" S of a resonance X is defined as the phase-space weighted ratio of $\Gamma_{J/\psi \to X\gamma}$ to $\Gamma_{X \to \gamma\gamma}$. Glueballs should be produced copiously in radiative J/ψ decays, but should not couple directly to $\gamma\gamma$. For one particular glueball candidate, the $f_j(2220)$, CLEO II sees absolutely no signal, and has reported [42) a lower limit $S \geq 105$ – the highest ever measured. L3 also sees no sign of this resonance in $\gamma\gamma$, but with much lower significance [43).

CLEO II has also reported [44) singly tagged production of the three pseudoscalar mesons, $\gamma\gamma^* \to \pi^0$, η or η'. The Q^2 dependence is predicted to depend upon a dipole form factor, whose shape can be fitted to give an effective mass for the exchanged virtual vector meson. CLEO obtains two roughly equal values of the dipole mass, respectively $776 \pm 10 \pm 12 \pm 6 MeV/c^2$ and $774 \pm 11 \pm 16 \pm 22$ for π^0 and η production, but a significantly larger value of $859 \pm 9 \pm 18 \pm 20 MeV/c^2$ for the η' (L3 report 900 ± 50 for the η' [45)). The size of the form factor at large Q^2 can be predicted from perturbative QCD models, assuming the $q\bar{q}$ wave function of the meson. For π^0 and η the value fits the simplest model already at $Q^2 = 15 GeV^2$, but the η' form factor is about twice the size predicted by the model. Theorists [46) have suggested that this disagreement with pQCD, together with the higher dipole mass for the η', mean that its wavefunction must be more complicated than those of the lighter psuedoscalars

5 Acknowledgements

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