Photon Structure Function Measurements at LEP II

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Abstract

The structure of the photon is studied in virtual photon-photon collisions by the four experiments at LEP. The hadronic component of the photon structure function F_2^γ becomes increasingly important at low values of the Bjorken variable. Recent results from LEP II have probed F_2^γ to the lowest values yet and are presented here. A lot of efforts have also been devoted to develop new methods to extract the true invariant mass from the visible mass seen in the detectors. The procedure of unfolding was suffering of severe model dependence, but is now getting better under control.

1 Introduction

The electron is surrounded by a cloud of virtual photons, in a two beam electron collider there is a finite probability that two of these virtual photons will collide into what is called a $\gamma\gamma$ event (Fig. 1[2]). This is an excellent system to study the virtual content of the photon, e.g. the hadronic part of the photon, which can help to improve our understanding of both perturbative and non-pertubative QCD.

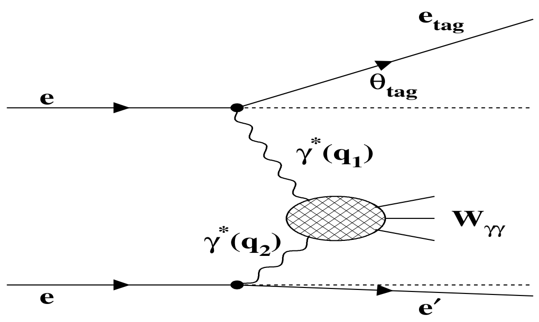

Figure 1: Deep inelastic electron photon scattering. For single tag data the second electron (from the q_2 photon) is anti-tagged and q_2 is approximately equal to 0.

$\gamma\gamma$ events are normally characterized by the invariant mass of the final state ($W_{\gamma\gamma}$) and the squared four momentum of the photons ($Q^2 = -q_1^2$ and $P^2 = -q_2^2$). The Bjorken scaling variable is used to describe the observables and is defined as x $= Q^2/(Q^2 + W_{\gamma\gamma}^2 + P^2)$. The hadronic properties of the photon become increasingly important at low x-values, which can be revealed by precise measurements in this region.

In order to get acceptable precision of the invariant mass it is necessary to detect at least one of scattered electrons. This is possible if one (or both) of the photons has a large enough virtuality $Q^2(P^2)$, and is referred to as a single or double tag event. LEP II has recently accelerated electrons to an energy over 100 GeV and the four experiments have now enough single tag statistics to produce the most accurate measurements yet at the lowest x-value obtained sofar.

2 The Photon Structure Functions

The photon can fluctuate into charged lepton-antilepton or quark-anti quark pairs, were the later for the purpose of calculations can be sub-dived into high and low virtuality fluctuations. The high virtuality part can be calculated by perturbative QCD, whereas the low-virtuality part is described in a non-perturbative phenomenological model involving the summation over vector meson states. The photon wave-function has thus a very complex structure and can be describe by:

$$|\gamma >= c_{bare}|\gamma_{bare} > + \sum_{V=\rho^0,\omega,\phi,J/\psi} v_V|V > + \sum_{q=u,d,s,c,b,t} c_q|q\overline{q} > + \sum_{l=e,\mu,\tau} c_l|l^+l^- >$$

,were the last three terms refers to virtual states. The leptonic part of the wave-function (c_l) is described by QED and will not be discussed here. The partonic content of the photon can be described by two structure functions, F_2^γ and F_L^γ. When one of the photons in the collision is quasi-real with a P^2 around zero the differential cross-section is described as:

$$\frac{d\theta_{e\gamma\to eX}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[(1+(1-y)^2F_2^\gamma(x,Q^2) - y^2F_L^\gamma(x,Q^2)],$$

$$x = \frac{Q^2}{2q_2\cdot q_1} \approx \frac{Q^2}{Q^2+W^2} \qquad , \qquad y = \frac{q_2\cdot q_1}{kq_2} \approx 1 - \frac{E_{tag}}{E_{beam}}cos^2(\frac{\Theta_{tag}}{2}).$$

y is very small in the region studied, so that the function F_2^γ can be isolated and extracted. As mentioned before special emphasis is put on the low-x behavior of F_2^γ, as it is suspected that the hadronic properties of the photon will result in a rise of F_2^γ in this region. The precision of x mainly depends of the reconstruction from the invariant mass $W_{\gamma\gamma}$, as the Q^2 is determined by the scattered electron. The hadronic system is however not always fully detected and a procedure is needed to reconstruct the true $W_{\gamma\gamma}$ from the visible tracks.

3 Event Tagging and Background

The single tag $\gamma\gamma$ events are tagged with a number of criteria on both the hadronic system and the scattered electrons. The limits of the cuts vary slightly between the four experiments at LEP, but there are four principal tagging criteria that are used:

- The tagged lepton should have an energy greater than E_{min}, which is ranging from 50-70% of the beam energy for the different experiments.
- To assure that the opposite lepton goes in the beam-pipe an anti-tag condition is applied. A lepton with an energy greater than E_{max} (in the order of 20 GeV) is thus not allowed to be seen in the opposite direction of the tagged lepton.
- The visible hadronic mass should be in the range of 3±1 to 50±10 GeV. The limits for the OPAL experiment are shown as two lines in Fig. 2[1].
- In order to reject leptonic $\gamma\gamma$ events at least 3 charged tracks are required to be registered (marked with a line in Fig. 3[1]).

These trigger conditions isolate the $\gamma\gamma$ signal quite well, however there is still a number of background sources that has to be accounted for. The main background channel is a two-photon process going to a pair of tau's, followed by the Z_0 background. The different background types are presented in Fig. 2 and 3 along with cut criteria for the data.

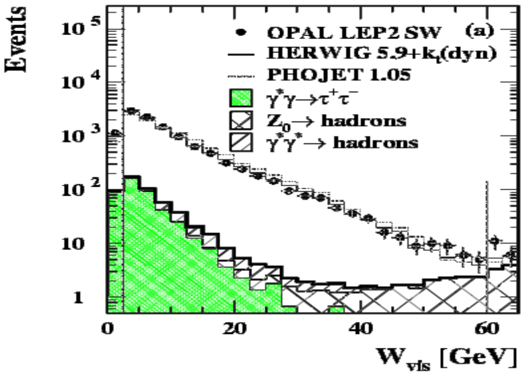

Figure 2: The background processes for $\gamma\gamma$ data. The cut on the visible mass is marked with the two vertical lines.

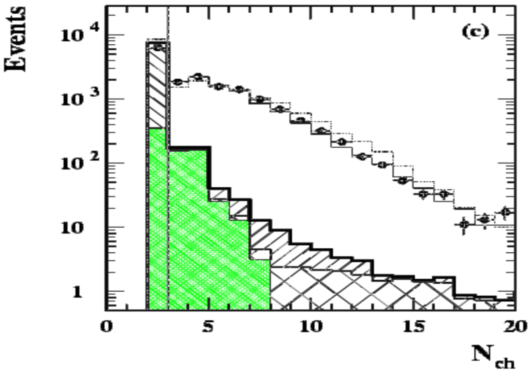

Figure 3: The number of charged tracks for data, background and Monte Carlo. A minimum of 3 tracks are required for hadronic $\gamma\gamma$ events.

4 Unfolding

The energies of the two photons in a $\gamma\gamma$-collision are normally quite different, resulting in a boosted particle system. Therefor a large part of the hadronic system created in a $\gamma\gamma$-collision goes undetected in the beam-pipe and an unfolding procedure is needed to reconstruct the true $W_{\gamma\gamma}$ from the visible. Unfolding is basically a statistical procedure to map one distribution into another. From Monte-Carlo a map is constructed with the generated invariant mass on one axis and the visible on the other (Fig. 4[4]).

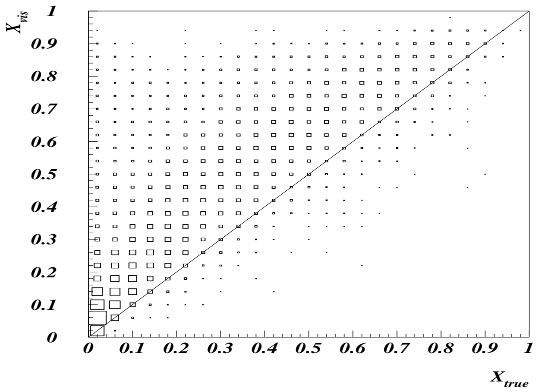

Figure 4: Monte Carlo mapping from x_{vis} onto x_{true}; the data is then unfolded with use of this map.

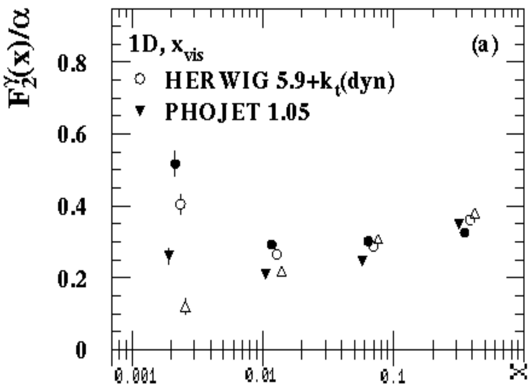

Figure 5: Result of unfolding with different models; the two extreme cases are from two older obsolete models (HERWIG 5.9 and F2GEN).

In mathematical form x is described by x(i)=$\sum_j A_{ij}x_{vis}(j) + b_j$, where A_{ij} is extracted from Monte Carlo and b_j is the expected background distribution. This procedure has the drawback of being quite dependent on which model used in the Monte Carlo generation of A_{ij} (Fig. 5[1]). At lot of effort has recently been made in an attempt to decrease this model dependence.

One approach was to use 2-dimensional unfolding, taking advantage from the fact that W_{vis} becomes more similar to W_{true} when the hadronic shower has high transverse momentum. The energy deposition in the forward direction was used as the second variable for the two dimensional unfolding. In Fig. 6[4] and 7[4] x_{vis} versus x_{true} has been plotted for two different values of E_{17} (the energy deposition below 17 degrees, used by ALEPH), and clearly the value of E_{17} has a large impact on the unfolding matrix.

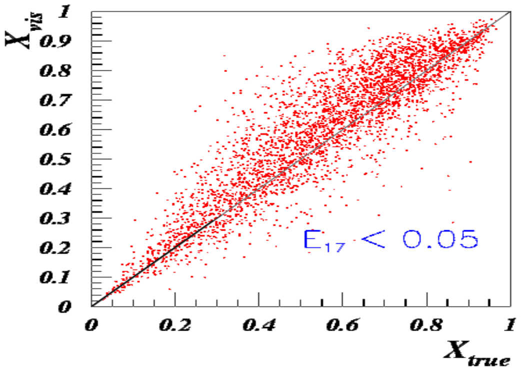

Figure 6: X_{vis} versus X_{true} with the hadronic shower far away from the beam line.

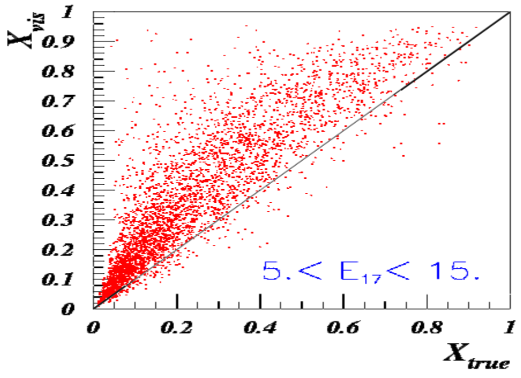

Figure 7: Hadronic shower is closer to the beam-line, and X_{vis} differs more from X_{true}

The visible invariant mass can be improved by including the kinematics of the tagged electron. If we for the hadronic system define $p_{i\pm} = E_i \pm p_{i,z}$ and $p_{i,t} = \sqrt{p_{i,x}^2 + p_{i,y}^2}$, W_{vis} can be expressed as:

$$W_{vis}^2 = (\sum_i p_{i+})(\sum_i p_{i-}) - (\sum_i p_{i,t})^2,$$

,where i runs over all tracks in the hadronic final state. Assuming that the untagged electron has zero transverse momenta, and using energy and momentum conservations, the sums over p_{i+} and $p_{i,t}$ can be replaced by measurements of the tagged electron ($(p_{beam+} - p_{tag+})$ and $p_{tag,t}$):

$$W_{rec} = (p_{beam+} - p_{tag+})(\sum_i p_{i-}) - (p_{tag,t})^2$$

In W_{rec} the hadronic energy only enters in the p_{i-} term, which is a clear improvement as the determination of the electron energy is much better than summing over the hadronic system (Fig. 8[3]). x_{rec} is then extracted from W_{rec} and inserted in the unfolding procedure. The result of the joint combination of 2-dimensional unfolding and replacing W_{vis} with W_{rec} is shown in Fig. 9[1]. From the comparison with the result of simple one-dimensional unfolding presented in Fig. 5, it is clearly seen that the model dependence has been heavily reduced.

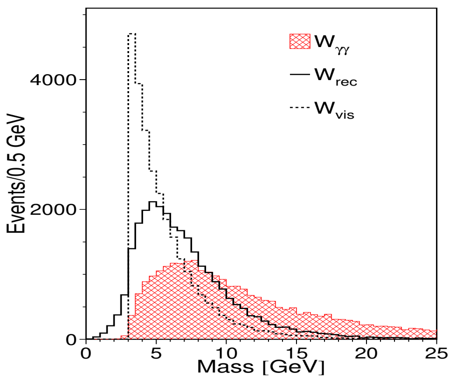

Figure 8: The true, visible and reconstructed invariant mass distribution.

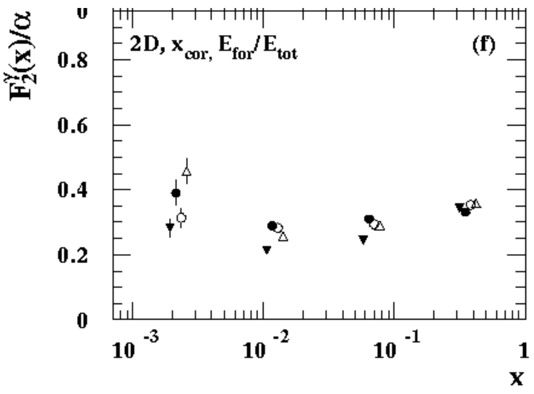

Figure 9: The result of 2-dimensional unfolding with reconstructed invariant mass.

The L3 collaboration has also adopted the method of kinematic fitting for high Q^2 data with quite promising result. DELPHI has developed the TWOGAM Monte Carlo generator with the additional resolved photon contribution model, which is less sensitive to the unfolding procedure.

5 Monte Carlo Models

A number of different Monte Carlo models have been tried in order to describe the $\gamma\gamma$ physics. More recently general purpose generators such as HERWIG and PYTHIA have also been made available for $\gamma\gamma$ studies. With the new data a number of old models, such as F2GEN, can be rejected, as they do not describe the data satisfactory. There are mainly four models presently used by the LEP experiments:

- **HERWIG 5.9** is a general-purpose QCD Monte Carlo generator to simulate hadron emission reactions with interfering gluons. The old version of HERWIG 5.9 has been replaced with HERWIG 5.9+k_t (dyn) for $\gamma\gamma$ studies. In the new version the quarks inside the photon have a modified transverse momentum distributions (k_t).
- **PHOJET 1.05** is an event generator for pp,γp and $\gamma\gamma$ interactions, described within the Dual Parton Model (DPM). This generator simulates hard interaction by perturbative QCD and uses Regge phenomenology for soft interaction.
- **TWOGAM** is a pure $\gamma\gamma$ event generator that is based on three different processes: the Quark Parton Model (QPM), the Vector Dominance Model (VDM) and the Resolved Photon Contribution (RPC). Each process is generated separately and the RPC model is unique for the TWOGAM generator.
- **PYTHIA** Very recently the general purpose PYTHIA event generator has been made available for $\gamma\gamma$ simulation. Newly obtain results look very promising, but so far no major study has been performed for single tag $\gamma\gamma$ events.

Each of the models have their own advantages and it is hard to favor any before the other. The general purpose generators are dependent on the parameterization of the F_2^γ function. The GRV LO and SaS1D are the most commonly used parameterizations, shown together with two others in Fig. 11[1].

6 Results

The LEP data have been studied by all LEP experiments in a wide range of Q^2 intervals, summarized in table here below. From theory the structure function is expected to rise linearly with log Q^2, which is clearly supported by the data of Fig. 10[5]. The additional points from $DELPHI$[6] and especially $L3$[2], seem to show a somewhat steeper rise than the other experiments and model predictions (still within error limits though).

Experiment	Q_1^2	Q_2^2	Q_3^2	Q_4^2	Q_5^2	Q_6^2
ALEPH	9.9	13.7	20.7	56.5		284
DELPHI	6.0	13.0	42.0	99	106	400
OPAL	1.9	3.7	8.9	10.7	18.0	135
L3	1.9	5.0	10.8	15.3	23.1	60
L3/OPAL	90	125	225		30	60

The different average Q^2 regions for the F_2^γ studies probed by the four LEP experiments.

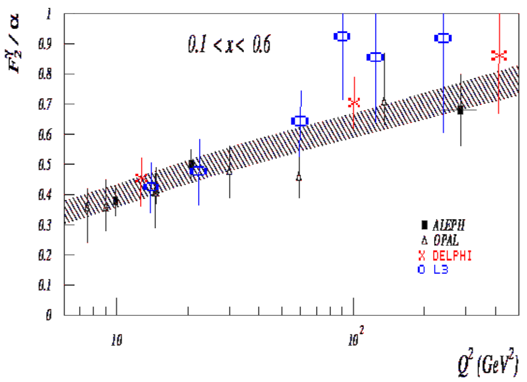

Figure 10: F_2^γ as a function of log Q^2.

The main interest is however focused on the behavior of the structure function at very low x-values. From the theory it is suspected that the hadronic content of the photon should have a rise of F_2^γ in very low x region. To get better accuracy, the x values were unfolded on a logarithmic scale rather than a linear.

The last results from these measurements are presented in Fig. 11[1], where the F_2^γ measurements have been grouped in 4 different Q^2 regions. The lowest obtained x-value comes from the OPAL experiment, which supports the predicted rise from gluons of F_2^γ in all Q^2 regions.

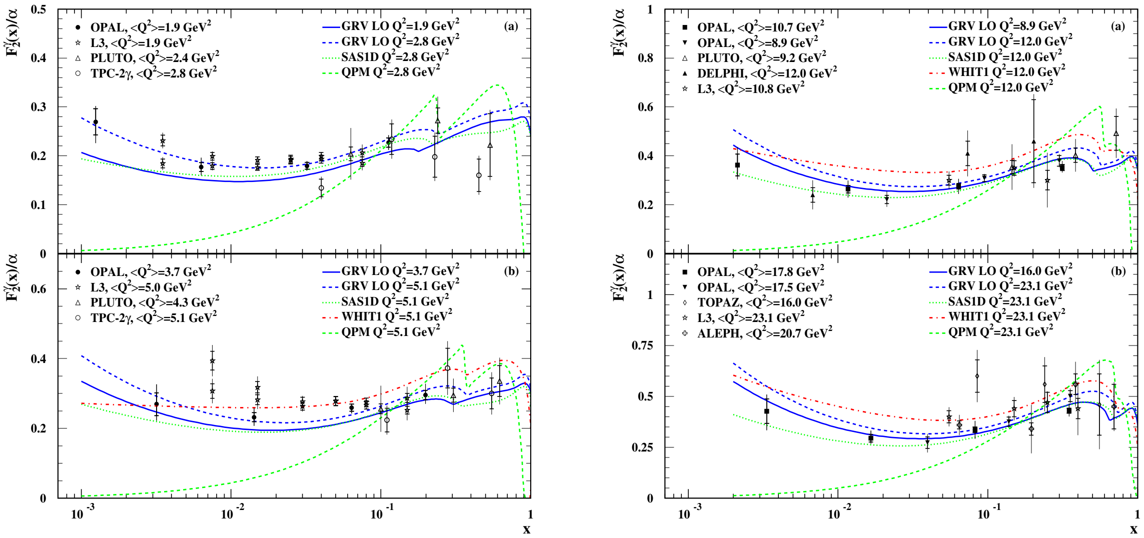

Figure 11: The F_2^γ measurements at low X, for four different Q^2 regions. The double values for each X in the L3 experiment is the result of using different Monte-Carlo models for the unfolding (the upper point is unfolded with TWOGAM the lower with PHOJET).

7 Conclusion

Existing $\gamma\gamma$ Monte Carlo generators have been developed further to fit the data better. At the same time some older models can now be excluded and new general purpose generators, such as PYHTIA, have become available for $\gamma\gamma$ simulations. The unfolding procedure has been improved, and the earlier problems of model dependent results have been reduced. This allows for better accuracy in the F_2^γ measurements and has resulted in the best low-x measurements yet. LEP I data can be considered to be more or less exhausted, whereas most of the LEP II results are still to come. With the latest measurements on the LEP II data evidence is already mounting for expected F_2^γ rise at very low-x.

References

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[3] The L3 collaboration, Study of the Hadronic Photon Structure Function F_2^γ at LEP, CERN-EP-98-98, 1998

[4] The ALEPH Collaboration, A Study of the Photon Structure Function F_2^γ using Two-Dimensional Unfolding,PHOTON99 Conference,Freiburg, 1999

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[6] The DELPHI Collaboration, F.Kapusta et al., Study of the photon structure function F_2^γ in the reaction $e^+e^- \to e^+e^- + hadrons$ at LEP2, Preliminary,2000